Muhammad Farooq
Kadambot H. M. Siddique *Editors*

Conservation Agriculture

Springer

Conservation Agriculture

Muhammad Farooq • Kadambot H. M. Siddique
Editors

Conservation Agriculture

Springer

Editors
Muhammad Farooq
Department of Agronomy
University of Agriculture
Faisalabad
Pakistan

Institute of Agriculture
The University of Western Australia
Crawley
Australia

College of Food and Agricultural Sciences
King Saud University
Riyadh
Saudi Arabia

Kadambot H. M. Siddique
Institute of Agriculture
The University of Western Australia
Crawley
Australia

ISBN 978-3-319-11619-8 ISBN 978-3-319-11620-4 (eBook)
DOI 10.1007/978-3-319-11620-4
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014955208

© Springer International Publishing Switzerland 2015
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Foreword

Conventional agriculture has largely been characterized by tillage, which leaves soil vulnerable to erosion. Continuous use of conventional farming practices with conventional tillage and burning crop residues has degraded the soil resource base and intensified soil degradation, with concomitant decreases in crop production capacity. Soil loss is expected to be a critical issue for global agricultural production under conventional farming practices. For instance, global erosion rates from conventionally ploughed agricultural fields averaged one to two orders of magnitude greater than erosion under native vegetation, long-term geological erosion and rates of soil production. Likewise, conventional tillage has also made agriculture a major contributor to global warming due to increasing greenhouse gas emissions. Soil and vegetation on the earth's land surface store three times as much carbon as is present in the earth's atmosphere. Land clearing and degradation turn this valuable carbon sink into a major source of greenhouse gas emissions.

Conservation agriculture is widely recognized as a viable approach to creating a sustainable agriculture. It is a resource-saving agricultural production system that aims to achieve production intensification and high yields while enhancing the natural resource base through compliance with four interrelated principles viz. minimal soil disturbance, permanent residue cover, planned crop rotations and integrated weed management, along with other good production practices of plant nutrition and pest management.

Conservation agriculture is environment friendly and requires less fuel, resulting in lower emissions of carbon dioxide—one of the gases responsible for global warming. In addition, conservation agriculture is very effective in reducing soil erosion. A wide range of other environmental benefits accrue in conservation agriculture, including reduced run-off, improved nutrient cycling, reduced soil degradation, reduced soil and water pollution and enhanced activities of soil biota.

Although several papers and conference proceedings are available on the subject, a comprehensive textbook on conservation agriculture was lacking. This book is a timely effort to fill the gap. The book describes various elements of conservation agriculture, highlights the associated breeding and modeling efforts, analyses the experiences and challenges in conservation agriculture in different regions and proposes some pragmatic options and new areas of research in this very important area of agriculture.

I anticipate that this volume will be a ready reference on conservation agriculture and will reinforce the understanding for its utilization to develop environmentally sustainable and profitable food production systems.

Dr. Nick Austin
Chief Executive Officer
Australian Centre for International
Agricultural Research
Canberra, Australia

Preface

The conventional mode of agriculture through intensive agricultural practices achieves production goals, but simultaneously degrades the natural resources. The growing concerns for sustainable agriculture are in response to the limitations of both low-input, traditional agriculture and intensive modern agriculture relying on high levels of inputs for crop production. Sustainable agriculture relies on practices that help to maintain ecological equilibrium and encourage natural regenerative processes such as nitrogen fixation, nutrient cycling, soil regeneration, and the protection of natural enemies of pest and diseases as well as the targeted use of inputs. Agricultural systems relying on such approaches not only support high productivity, but also preserve biodiversity and safeguard the environment. Conservation agriculture is a new paradigm for achieving sustained agricultural production and is a major step in the transition to sustainable agriculture.

Over the past few decades, resource conservation technologies, such as zero and reduced-tillage systems, better crop residue management and planting systems, have evolved to enhance water and nutrient conservation. Conservation agriculture—an array of four components including permanent soil cover, minimum soil disturbance, diversified crop rotations and integrated weed management—is now considered the principal road to sustainable agriculture and the protection of natural resources and the environment. Currently, conservation agriculture is practiced on more than 125 million ha worldwide.

While the adoption of conservation agriculture is increasing globally, in some regions it is either slow or non-existent. As a result, we felt it timely to collect and synthesize the latest developments on conservation agriculture research. The contents of this book are divided into five sections and 23 chapters as detailed below:

(1) Introduction

Chapter 1 is a brief history and overview of the components and adaptation of conservation agriculture.

(2) Elements of conservation agriculture

- Chapter 2 collates and performs a meta-analysis on existing literature on the effect of crop rotations and crop residue management on maize grain yield under conservation agriculture.

- Chapter 3 describes weed problem in conservation agriculture systems and proposes the strategies for integrated weed management.
- Chapter 4 discusses the nutrient management perspectives in conservation agriculture, and suggests the strategies for improving the nutrient use efficiency in conservation agriculture systems.
- Chapter 5 is an overview of the essential machinery requirements for the different farm operations involved in conservation agriculture. Regional-specific issues with emphasis on developing countries are also discussed, and pragmatic solutions of vital interest to researchers, academia and policy makers globally are proposed.
- Chapter 6 describes the impact of conservation agriculture on the prevalence of insects, insect biodiversity, and proposes options for integrated insect pest management in conservation agriculture.

(3) Modeling and crop improvement for conservation agriculture

- Chapter 7 covers crop breeding for conservation agriculture. Crop improvement and breeding strategies are proposed to develop improved crop genotypes better adapted to conservation agriculture.
- Chapter 8 introduces the SALUS model and its tillage component to evaluate the effects of tillage on soil water infiltration, time to ponding and soil biophysical properties.

(4) The status of conservation agriculture including some case studies

- Chapter 9 discusses the evolution and adoption of conservation agriculture in the Middle East.
- Chapter 10 discusses Syrian experiences on conservation agriculture.
- Chapter 11 describes the experiences, challenges and options regarding conservation agriculture in South Asia.
- Chapter 12 covers conservation agriculture in South East Asia and introduces the Conservation Agriculture Network for South East Asia.
- Chapter 13 discusses conservation agriculture in China, particularly in rainfed areas, including early history and progress on research and adoption for better soil and water conservation.
- Chapter 14 discusses the future of conservation farming in Australia and New Zealand, and recent advances in weed control strategies.
- Chapter 15 outlines future prospects for up-scaling of conservation agriculture in Europe, and describes the likely impact of global changes and constraints for its adoption and spread.
- Chapter 16 describes the origins and impacts of conservation agriculture in different regions of Latin America, highlights the factors limiting its adoption and outlines the innovations and strategies developed in some countries to overcome these limitations.
- Chapter 17 illustrates the diversity of conservation agriculture adoption in North America, and provides an overview of several contrasting production regions.

- Chapter 18 describes the diversity and heterogeneity of farms in sub-Saharan Africa, and highlights the experiences and constraints in conservation agriculture in the region.

(5) Conservation agriculture in agricultural systems.

- Chapter 19 covers the sustainable use of soil and other natural resources in relation to agronomic productivity and environment quality. It also addresses soil C sequestration potential through conservation agriculture, and its management in diverse soils and agro-ecosystems.
- Chapter 20 discusses the potential applications of microbiology in conservation agriculture.
- Chapter 21 discusses the experiences, challenges and opportunities of conservation agriculture in organic farming in Europe.
- Chapter 22 outlines the potential role of conservation agriculture in mitigating the impact of climate change on crop production.
- Chapter 23 discusses the factors driving the adoption of conservation agriculture and proposes some possible future directions for conservation agriculture adoption research.

Professor Kadambot Siddique's research on conservation agriculture is partly funded by the Australian Centre for International Agricultural Research (ACIAR) and is gratefully acknowledged. We thank all the authors for their contributions, and their help and cooperation during the manuscript writing and revision process. We also thank Dr. Maryse Elliott, Senior Publishing Editor and Melanie van Overbeek, Senior Publishing Assistant, Agronomy and Life Sciences Unit, Springer Dordrecht, The Netherlands.

Faisalabad, Pakistan Muhammad Farooq
Perth, Australia Kadambot H. M. Siddique

Contents

Part I Introduction

Part II Elements of Conservation Agriculture

Part III Modeling and Crop Improvement for Conservation Agriculture

Part IV Status of Conservation Agriculture: Some Case Studies

Part V Conservation Agriculture in Agricultural Systems

Contributors

M. Acutis Department of Agricultural and Environmental Sciences—Production, Landscape, Agroenergy—Via G. Celoria, University of Milano, Milano, Italy

Jam Nazeer Ahmad Integrated Genomic, Cellular, Developmental and Biotechnology Laboratory, Department of Entomology, University of Agriculture, Faisalabad, Pakistan

Abdulsattar Alrijabo University of Mosul, Ninevah, Iraq

C.F. Araujo-Junior Agricultural Research Institute of Paraná (IAPAR), Londrina, Paraná, Brazil

K.K. Barman Directorate of Weed Science Research, Jabalpur, India

G. Basch Institute of Mediterranean Agricultural and Environmental Sciences, University of Évora, ÉVORA, Portugal

Bruno Basso Department of Geological Sciences, Michigan State University, East Lansing, USA

Bill Bellotti University of Western Sydney, Parramatta, Australia

M. Bindi Department of Agri-food Production and Environmental Sciences, University of Florence -Piazzale delle Cascine, Firenze, Italy

Lorenzo Brilli Department of Agri-food Production and Environmental Sciences, University of Florence -Piazzale delle Cascine, Firenze, Italy

A. Calegari Agricultural Research Institute of Paraná (IAPAR), Londrina, Paraná, Brazil

M. Carozzi INRA, AgroParisTech, UMR 1091 Environnement et Grandes Cultures, Thiverval-Grignon, France

Marc Corbeels French Agricultural Research Centre for International Development (CIRAD), Montpellier cedex 5, France

Christos Dordas Faculty of Agriculture, Forestry and Natural Environment, School of Agriculture, Laboratory of Agronomy, Aristotle University of Thessaloniki, Thessaloniki, Greece

T. El-Shater International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria

Muhammad Farooq Department of Agronomy, University of Agriculture, Faisalabad, Pakistan

The UWA Institute of Agriculture, The University of Western Australia, Crawley, WA, Australia

College of Food and Agricultural Sciences, King Saud University, Riyadh, Saudi Arabia

David Feindel International Center for Agricultural Research in Dry Areas, Amman, Jordan

F. Fernandez University of Minnesota, Minneapolis, MN, USA

Ph. Fleury Department of Agriculture, Laboratoire d'Etudes Rurales, Food Systems and Rural Areas, ISARA-Lyon, Lyon cedex 07, France

T. Friedrich Plant Production and Protection Division, Food and Agriculture Organization, Rome, Italy

E. Gonzalez-Sanchez Rural Engineering Department, University of Córdoba, Córdoba, Spain

B. Govaerts International Maize and Wheat Improvement Centre (CIMMYT), Mexico, DF, Mexico

S. Green Arkansas State University, Jonesboro, AR, USA

J. Habig Soil Microbiology Unit, Plant Protection Research Institute, Agricultural Research Council, Pretoria, Gauteng, South Africa

Atef Haddad International Center for Agricultural Research in Dry Areas, Amman, Jordan

Atef Haddad International Center for Agricultural Research in the Dry Areas (ICARDA), Amman, Jordan

N. C. Hansen Brigham Young University, Provo, UT, USA

Brigham Young University, Rexburg, ID, USA

A. I. Hassen Biological Nitrogen Fixation Unit, Plant Protection Research Institute, Agricultural Research Council, Pretoria, Gauteng, South Africa

A. Kassam School of Agriculture, Policy and Development, University of Reading, Reading, UK

P. Kaumbutho Kenya Network for Dissemination of Agricultural Technologies, Nairobi, Kenya

Yaseen Khalil International Center for Agricultural Research in Dry Areas, Amman, Jordan

International Center for Agricultural Research in the Dry Areas (ICARDA), Amman, Jordan

Anonh Khamhoung Department of Land Management and Development of the Ministry of Agriculture and Forestry, Vientiane, Laos

Duncan Knowler School of Resource and Environmental Management, Simon Fraser University, Burnaby, British Columbia, Canada

Sumanta Kundu Central Research Institute for Dryland Agriculture, Hyderabad, Andhra Pradesh, India

Rattan Lal Carbon Management and Sequestration Center, SNER/OAR DC, The Ohio State University, Columbus, OH, USA

V. Lefevre Department of Agroeoclogy and Environment, ISARA-Lyon, Lyon cedex 07, France

Jean-Claude Legoupil Conservation Agriculture and Systems Engineering, CIRAD, Montpellier Cedex 5, France

Lingling Li Gansu Provincial Key Laboratory of Aridland Crop Science/Faculty of Agronomy, Gansu Agricultural University, Lanzhou, People's Republic of China

Pascal Lienhard Conservation Agriculture and Systems Engineering, CIRAD, Montpellier Cedex 5, France

Stephen Loss International Center for Agricultural Research in the Dry Areas (ICARDA), Amman, Jordan

Tariq Mahmood Plant Breeding Institute, The University of Sydney, Cobbitty, NSW, Australia

P. Makungu Sokoine University of Agriculture, Morogoro, Tanzania

S. Mkomwa African Conservation Tillage Network, Nairobi, Kenya

A. Mugera The UWA Institute of Agriculture & School of Agricultural and Resource Economics, The University of Western Australia, Crawley, WA, Australia

Ahmad Nawaz Integrated Pest Management Laboratory, Department of Entomology, University of Agriculture, Faisalabad, Pakistan

Ryan Nagelkirk Department of Geological Sciences, Michigan State University, East Lansing, USA

J. Peigné Department of Agroeoclogy and Environment, ISARA-Lyon, Lyon cedex 07, France

Colin Piggin Australian Centre for International Agricultural Research, Canberra, Australia

International Center for Agricultural Research in the Dry Areas (ICARDA), Amman, Jordan

M. Pisante Agronomy and Crop Sciences Research and Education Center—Via C.R.Lerici, University of Teramo, Mosciano S.Angelo, Italy

Hafeez ur Rehman Department of Crop Physiology, University of Agriculture, Faisalabad, Pakistan

Leonard Rusinamhodzi CIRAD—Agro-ecology and Sustainable Intensification of Annual Crops, c/o CIMMYT Regional Office, Harare, Zimbabwe

French Agricultural Research Centre for International Development (CIRAD), Montpellier cedex 5, France

Yashpal Singh Saharawat The Indian Agricultural Research Institute, New Delhi, India

Luigi Sartori Department of Landscape and Agroforestry Systems, University of Padua, Padua, Italy

A.R. Sharma Directorate of Weed Science Research, Jabalpur, India

Kadambot H. M. Siddique The UWA Institute of Agriculture, The University of Western Australia, Crawley, WA, Australia

Raghwendra Singh Directorate of Weed Science Research, Jabalpur, India

V.P. Singh Directorate of Weed Science Research, Jabalpur, India

A. Speratti Institute for Resources, Environment and Sustainability, University of British Columbia, Vancouver, BC, Canada

Ch. Srinivasarao Central Research Institute for Dryland Agriculture, Hyderabad, Andhra Pradesh, India

F. Stagnari Agronomy and Crop Sciences Research and Education Center—Via C.R.Lerici, University of Teramo, Mosciano S.Angelo, Italy

Valentina Di Stefano Department of Agri-food Production and Environmental Sciences, University of Florence -Piazzale delle Cascine, Firenze, Italy

W.B. Stevens USDA-ARS, Sidney Montana, MT, USA

A. Swart Nematology Unit, Plant Protection Research Institute, Agricultural Research Council, Pretoria, Gauteng, South Africa

Pravin B Thakur Central Research Institute for Dryland Agriculture, Hyderabad, Andhra Pradesh, India

Christian Thierfelder International Maize and Wheat Improvement Centre (CIMMYT), Harare, Zimbabwe

Richard Trethowan Plant Breeding Institute, The University of Sydney, Cobbitty, NSW, Australia

S. Tubbs University of Georgia, Tifton, GA, USA

M.-S. Turmel International Maize and Wheat Improvement Centre (CIMMYT), Mexico, DF, Mexico

J.F. Vian Department of Agroeoclogy and Environment, ISARA-Lyon, Lyon cedex 07, France

A. Violic Chilean Academy of Agricultural Sciences, Santiago, Chile

Abdul Wakeel Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

P. Wall International Maize and Wheat Improvement Centre (CIMMYT), Mexico, DF, Mexico

P. R. Ward CSIRO Agriculture Flagship, Wembley, WA, Australia

Y. A. Yigezu International Center for Agricultural Research in the Dry Areas (ICARDA), Amman, Jordan

Hailin Zhang College of Agronomy and Biotechnology, China Agricultural University, Beijing, People's Republic of China

Renzhi Zhang Faculty of Resource and Environment, Gansu Agricultural University, Lanzhou, People's Republic of China

Part I
Introduction

Chapter 1
Conservation Agriculture: Concepts, Brief History, and Impacts on Agricultural Systems

Muhammad Farooq and Kadambot H. M. Siddique

Abstract Conservation agriculture (CA) is characterized by minimal soil disturbance, diversified crop rotations, and surface crop residue retention to reduce soil and environmental degradation while sustaining crop production. CA involves changing many conventional farming practices as well as the mindset of farmers to overcome the conventional use of tillage operations. Although adoption of CA is increasing globally, in some regions it is either slow or nonexistent. The adoption of CA has both agricultural and environmental benefits but there is a lack of information on the effects and interactions of key CA components which affect yield and hinder its adoption. In this chapter, we discuss the basic concepts and brief history of CA, and its impacts on agricultural systems.

Keyword Adoption · Crop rotations · Crop residues · Farm machinery · Weed management

1.1 Introduction

Conventional farming practices, in particular tillage and crop residue burning, have substantially degraded the soil resource base (Montgomery 2007; Farooq et al. 2011a), with a concomitant reduction in crop production capacity (World Resources Institute 2000). Under conventional farming practices, continued loss of soil is expected to become critical for global agricultural production (Farooq et al. 2011a).

M. Farooq (✉)
Department of Agronomy, University of Agriculture, Faisalabad, Pakistan
e-mail: farooqcp@gmail.com

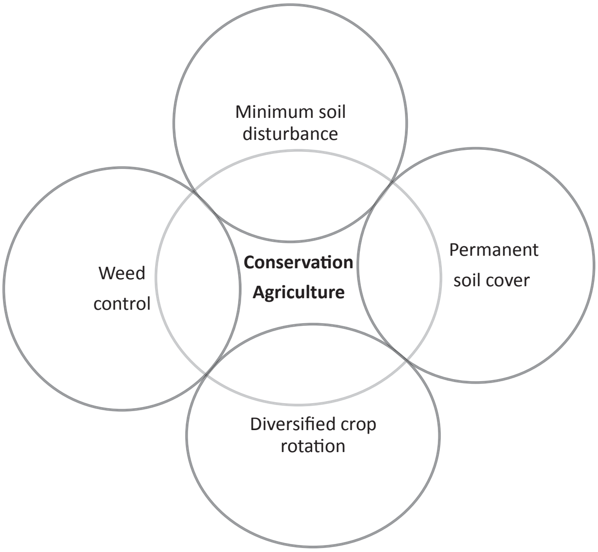
The UWA Institute of Agriculture, The University of Western Australia,
Crawley, WA 6009, Australia

College of Food and Agricultural Sciences, King Saud University,
Riyadh 11451, Saudi Arabia

M. Farooq · K. H. M. Siddique
The UWA Institute of Agriculture, The University of Western Australia,
Crawley, WA 6009, Australia

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture*,
DOI 10.1007/978-3-319-11620-4_1

Fig. 1.1 Elements of conservation agriculture



Conservation agriculture (CA) is a set of technologies, including minimum soil disturbance, permanent soil cover, diversified crop rotations, and integrated weed management (Fig. 1.1; Reicosky and Saxton 2007; Hobbs et al. 2008; Friedrich et al. 2012), aimed at reducing and/or reverting many negative effects of conventional farming practices such as soil erosion (Putte et al. 2010), soil organic matter (SOM) decline, water loss, soil physical degradation, and fuel use (Baker et al. 2002; FAO 2008). For instance, soil erosion, water losses from runoff, and soil physical degradation may be minimized by reducing soil disturbance and maintaining soil cover (Serraj and Siddique 2012). Using organic materials as soil cover and including legumes in rotations may help to address the decline in SOM and fertility (Marongwe et al. 2011). With less soil disturbance comes less fuel use, resulting in lower carbon dioxide emissions, one of the gases responsible for global warming (Kern and Johnson 1993; West and Marland 2002; Hobbs and Gupta 2004; Holland 2004; Govaerts et al. 2009). CA helps to improve biodiversity in the natural and agro-ecosystems (Friedrich et al. 2012). Complemented by other good agricultural practices, including the use of quality seeds and integrated pest, nutrient and water management, etc., CA provides a base for sustainable agricultural production intensification (Friedrich et al. 2012). Moreover, yield levels in CA systems are comparable and even higher than traditional intensive tillage systems (Farooq et al. 2011a; Friedrich et al. 2012) with substantially less production costs (Table 1.1).

CA is increasingly promoted as “a concept of crop production to a high and sustained production level to achieve acceptable profit, while saving the resources along with conserving the environment” (FAO 2006). In CA, modern and scientific agricultural technologies are applied to improve crop production by mitigating reductions in soil fertility, topsoil erosion and runoff; and improving moisture conservation and environmental footprints (Dumanski et al. 2006). CA improves soil

Table 1.1 Cost comparison of traditional (TA) and conservation agriculture (CA). (Source: Data from Hanks and Martin (2007); Meena et al. (2010); Singh and Meena (2013))

	TA (USD ha^{-1})	CA (USD ha^{-1})	Cost saving (%)
Fuel	75	25	66.67
Depreciation	115	65	43.47
Maintenance	22	10	54.55
Pesticides	35	45	−28.57
Total costs	247	145	41.30

water-use efficiency, enhances water infiltration, and increases insurance against drought (Colmenero et al. 2013). CA is thus an eco-friendly and sustainable management system for crop production (Hobbs et al. 2008; Govaerts et al. 2009) with potential for all agroecological systems and farm sizes. This chapter provides a brief history and overview of the components and adaptation of CA.

1.2 History and Adoption of Conservation Agriculture

Tillage is defined as the mechanical manipulation of soil. Tillage started millions of years ago when man shifted from hunting to more sedentary and conventional agriculture especially in the Euphrates, Nile, Tigris, Yangste, and Indus valley (Hillel 1991). The idea to plough or till the soil began in Mesopotamia around 3000 BC (Hillel 1998). Lal (2001) identified tillage as a major component of husbandry practices in agriculture. After the industrial revolution in the nineteenth century, agricultural machinery became available to carry tillage operations. More recently, a range of equipment has become available for tillage operations in agricultural production (Hobbs et al. 2008). Traditionally, tillage was aimed to soften the soil, prepare the seedbed to ensure good and uniform seed germination, manage weeds, help in the release of soil nutrients needed for crop growth through mineralization and oxidation, and incorporate crop residues and soil amendments (fertilizers, organic or inorganic) into the soil (Hobbs et al. 2008). Moreover, tillage helps to modify soil's physical, chemical, and biological properties, which improves conditions for crop growth resulting in higher crop yields (Farooq et al. 2011a).

Tillage, particularly in fragile ecosystems, was questioned for the first time in the 1930s by Edward H. Faulkner, in a manuscript called "Plowman's Folly" (Faulkner 1943) when dust bowls devastated wide areas of the Midwestern USA (Friedrich et al. 2012). With time, the concept of protecting soil, by reducing tillage and keeping the soil covered, gained popularity. This system of soil protection was then named conservation tillage (Friedrich et al. 2012). Economic and ecological sufferings caused by disastrous droughts in the USA during the 1930s drove the shift towards CA (Haggblade and Tembo 2003). The development of seeding machinery during the 1940s made sowing possible without soil tillage (Friedrich et al. 2012). Moreover, increased fuel prices during the 1970s attracted farmers to shift towards resource-saving farming systems (Haggblade and Tembo 2003). In this scenario, commercial farmers adapted CA to combat drought-induced soil erosion together with the fuel saving (Haggblade and Tembo 2003).

During the early 1970s, no-tillage farming reached Brazil; and no-tillage and mulching were tested in West Africa (Table 1.2; Greenland 1975; Lal 1976). The CA experience in the USA helped motivate the CA movement in South Africa and South America (Haggblade and Tembo 2003). Nonetheless, CA took more than 20 years to reach significant adoption levels in South America (Friedrich et al. 2012). During this time, farm equipment and agronomic practices in no-tillage systems were improved and developed to optimize crop performance and machinery, and field operations (Friedrich et al. 2012).

In the early 1990s, the spread of CA hastened, which revolutionized farming systems in Argentina, southern Brazil, and Paraguay (Friedrich et al. 2012). During this time, several international organizations became interested in the promotion of CA. Participation of these organizations in the promotion of these conservation farming systems led to the adoption of these systems in Africa (Tanzania, Zambia, and Kenya) and some parts of Asia (Kazakhstan, China, India, and Pakistan). CA systems then made their way to Canada, Australia, Spain, and Finland.

Today, CA is practiced on millions of hectares across the globe (FAO 2011a) including the USA, Argentina, Bolivia, Brazil, Chile, China, Colombia, Falkland Islands, Finland, Kazakhstan, Kenya, Malvinas, Morocco, Uganda, Western Australia, and Zambia (Friedrich et al. 2012) on soils varying from 90 % sand (e.g., Australia) to 80 % clay (e.g., Brazil's Oxisols and Alfisols). Derpsch and Friedrich (2009) reported that any crop can be grown effectively under CA including tuber and root crops. In recent years, the spread of CA has been quite rapid. In 1973–1974, CA was practiced on 2.8 M ha globally, increasing to 6.2 M ha in a decade; by 1996–1997, this area had reached 38 M ha, and by 2003, it was 72 M ha. More recently, CA has been practiced on 125 M ha (Friedrich et al. 2012).

CA has positive effects in terms of yield, income, sustainability of land use, ease of farming, and the timeliness of ecosystem services and cropping practices. As a result, its adoption rate has increased by 7 M ha per year in the past decade (Friedrich et al. 2012). Of the total area under CA systems worldwide, 45 % is in South America, 32 % in USA and Canada, 14 % in Australia and New Zealand, and 9 % in the rest of the world including Asia, Europe, and Africa (Table 1.3; Friedrich et al. 2012). In Canada, CA adoption has seen a pragmatic eco-friendly approach as that helped to decrease the dust storms and increase the biodiversity (Lindwall and Sonntag 2010). Carbon payment schemes have been introduced in Alberta and Canada, which have resulted in the rapid uptake of CA in these areas (Friedrich et al. 2012).

Despite the continued effort of international organizations and local NGOs, the total area under CA is only 9 % of the total cropped area (Friedrich et al. 2012). A lack of CA extension programs is one reason for its slow uptake. In addition, regional traditions and mindset, along with a lack of technical knowledge, institutional support, CA machinery, and suitable herbicides to facilitate weed management are major constraints in the wide-scale adoption of CA systems (FAO 2008; Friedrich and Kassam 2009; Friedrich et al. 2012). Certain other issues related to natural assets of the farm also hinder CA adoption worldwide (Dixon et al. 2001; Govaerts et al. 2009). However, in Asia, many agricultural lands may adopt CA systems

Table 1.2 History of conservation agriculture

Year	Development	Reference
1930	Great dust bowl and start of conservation agriculture in the USA	Hobbs et al. (2008)
1940	Development of direct seeding machinery, first no-till sowing	Friedrich et al. (2012)
1943	Book on no-till in modern agriculture entitled “Plowman’s Folly” by Faulkner	Faulkner (1943)
1950	No-till, direct-sowing of crops was first successfully demonstrated in the USA	Harrington (2008)
1956	Experiments on various combinations of tillage and herbicides were initiated	Lindwall and Sonntag (2010)
1960	Commercial adoption of no-till in the USA	Lindwall and Sonntag (2010); Friedrich et al. (2012)
1962	Paraquat was registered as first herbicide for broad-spectrum weed control	Lindwall and Sonntag (2010)
1962	Long-term no-till experiments were started in Ohio, USA; the experiments are still running	Perszewski (2005)
1964	First no-till experiments in Australia	Barret et al. (1972)
1966	Demonstration trials on direct drilling systems in Germany	Bäumer (1970)
1967	Demonstration trials on direct drilling systems in Belgium	Cannel and Hawes (1994)
1968	First no-tillage trials in Italy	Sartori and Peruzzi (1994)
1969	Introduction of CA in West Africa	Greenland (1975); Lal (1976)
1970	First no-till demonstration in Brazil	Borges (1993)
1970	Long-term no-till experiments were started in France	Boisgontier et al. (1994)
1970	First report on the development of herbicide resistance in weeds	Ryan (1970)
1973	Phillips and Young published the book “No-Tillage Farming.” This publication was a milestone in no-tillage literature, being the first one of its kind in the world	Derpsch (2007)
1974	First no-till demonstration in Brazil and Argentina	Friedrich et al. (2012)
1975	Book on CA entitled “One straw revolution” by Fukuoka	Fukuoka (1975)
1976	Glyphosate was registered for general broad-spectrum weed control	Lindwall and Sonntag (2010)
1980	Introduction and on-farm demonstration of CA in subcontinent	Harrington (2008)
1980	Introduction of CA in Zimbabwe	Friedrich et al. (2012)
1981	The first National No-till Conference held in Ponta Grossa, Paraná, Brazil	Derpsch (2007)
1982	Introduction of no-till in Spain	Giráldez and González (1994)
1982	Development of first glyphosate-resistant transgenic crops	Fraley et al. (1983)
1990	Development and commercial release of reliable seeding machines	Lindwall and Sonntag (2010)
1990	Commercial adaptation of CA in southern Brazil, Argentina, and Paraguay	Friedrich et al. (2012)
1990	Introduction of CA in India, Pakistan, and Bangladesh	Friedrich et al. (2012)

Table 1.2 (continued)

Year	Development	Reference
1992	Start of CA research in China	Derpsch and Friedrich (2009)
1996	Commercial launch of transgenic glyphosate-resistant soybean	Dill (2005)
1997	Commercial launch of transgenic glyphosate-resistant crops in China	Paarlberg (2001)
1998	Identification of weed (rigid ryegrass) resistant to glyphosate	Powles et al. (1998)
2002	Introduced no-tillage systems in Kazakhstan	Derpsch and Friedrich (2009)

CA conservation agriculture

Table 1.3 Continent-wise area under conservation agriculture in the world. (Source: Friedrich et al. 2012)

Continent	Area (M ha)	Percent of total
Africa	1.01	1
Asia	4.72	4
Australia and New Zealand	17.16	14
Europe	1.35	1
South America	55.46	45
North America	39.98	32
Russia and Ukraine	5.1	3
Total	124.78	

especially in Kazakhstan, China, and India in the next two decades (Friedrich et al. 2012). In the Indo-Gangetic Plains (Pakistan, India, Bangladesh, and Nepal), no-tilled wheat plantations have reached 5 M ha in recent years especially in the rice–wheat cropping system (Friedrich et al. 2012) and are expected to expand further.

In a nutshell, since the 1930s, farming communities have gradually shifted towards no-tillage systems for potential fossil-fuel savings, reduced erosion, and run-off, and to minimize SOM loss. The first 50 years was the start of the conservation tillage movement and, today, a large percentage of agricultural land is cropped following CA principles (Hobbs et al. 2008). Sustained governmental policies and institutional support may play a key role in the promotion of CA both in rainfed and irrigated cropped lands by providing incentives and required services to farmers to adopt CA practices and advance them over time (FAO 2008; Friedrich and Kassam 2009; Friedrich et al. 2009; Kassam et al. 2009, 2010; Friedrich et al. 2012).

1.3 Permanent or Semi-permanent Organic Soil Cover

In CA, crop residues—the principal element of permanent soil cover—must not be removed from the soil surface or burned. The residue is left on the soil surface to protect the topsoil enriched with organic matter from erosion. At the same time, fresh residues must be added to the soil when existing residues decompose. Burning not only increases mineralization rates which rapidly depletes nutrients and organic matter from the soil but also causes air pollution (Magdoff and Harold 2000). In CA, plants are either left in the field or killed, with their residues left in the field to decompose *in situ*. This practice is primarily aimed at protecting the enriched topsoil against chemical and physical weathering. Plant residues slow down the speed of falling raindrops, provide a barrier against strong winds and temperature, decrease surface evaporation, and improve water infiltration (Thierfelder and Wall 2009).

Cover crops/green manure crops are grown to increase or maintain soil fertility and productivity. They increase SOM content either by adding fresh plant residues to the soil or by reducing soil erosion. Legume cover crops can fix nitrogen from the atmosphere into the soil increasing N availability to crop plants. Cover crops are mowed or killed before or during soil preparation for the next economic crop. A gap of 1 or 2 weeks before planting the next crop is needed to allow some decomposition and reduction in allelopathic effects of the residues, and to minimize nitrogen immobilization (Miguel et al. 2011; Farooq and Nawaz 2014).

CA improves soil biodiversity, soil biological activity, water quality and soil aggregation, and increases soil carbon sequestration through maintenance of crop residues. By keeping residues on the surface and using cover crops, permanent soil cover is maintained during fallow periods as well as during crop growth phases. Giller et al. (2009) opined that the benefits of each principle need to be properly evaluated as trade-offs exist and some farmers have not adopted all of CA components. Retaining crop residues has positive and negative effects; researchers should develop strategies to enhance the positive effects (Kumar and Goh 2000).

1.4 Minimal Soil Disturbance

CA promotes minimal soil disturbance through no- or reduced tillage, careful management of residues and organic wastes, and a balanced use of chemical inputs; all aimed at decreasing soil erosion, water pollution and long-term dependence on external inputs, improving water quality and water-use efficiency, and minimizing greenhouse gas emissions by reducing the use of fossil fuels (Kumar and Goh 2000). Zero-tillage systems need minimal mechanical soil disturbance and permanent soil cover to achieve sufficient living and/or residual biomass to control soil erosion which ultimately improves water and soil conservation (Li et al. 2007). CA emphasizes the importance of soil as a living body, particularly the most active zone in the top 0–20 cm, to sustain the quality of life on this planet; yet this zone is most vulnerable to degradation and erosion. Most environmental functions and services—essential to support terrestrial life on this planet—are concentrated in the macro-, micro-, and meso-flora and fauna, which live and interact in this zone. Human activities with regard to land management have the most immediate and potentially maximum impact in this zone (Hobbs et al. 2008). By protecting this fragile zone, the vitality, health, and sustainability of life on this planet may be ensured.

A recent modeling analysis, for three sites with fine-textured soils and different crop rotations in North America (Conant et al. 2007), simulated zero tillage until equilibrium was reached and ran experimental models for 220 years thereafter. The model demonstrated a substantial decrease (~27 %) in soil C content due to a shift to conventional tillage from zero tillage (Conant et al. 2007).

1.5 Diversified Crop Rotations

Crop rotations play a critical role in determining the success of crop production enterprises, but are most important in determining the success of crop production systems using conservation tillage. CA addresses the problems of insect, pests, and diseases by integrating crop rotations, which help break the cycle that perpetuates crop diseases such as wheat rust and pest infestations (Witmer et al. 2003), resulting in higher yield. A well-planned systematic crop rotation helps farmers to avoid many problems linked with conservation tillage, such as increased soil compaction, plant diseases, perennial weeds, and slow early season growth (Tarkalson et al. 2006).

Continuous maize planting in a no-till system may cause several problems such as perennial weeds, leaf diseases, inoculum buildup in residues, and wetter and cooler soils at planting due to heavy maize residues (Fischer et al. 2002). These residues interfere with seed placement resulting in uneven stand establishment; while allelopathic effects from decomposing maize residues on young plants may slow the growth of maize early in the season (Fischer et al. 2002). In such situations, a maize–hay rotation—as an alternative to continuous maize—is gaining popularity on dairy farms in Pennsylvania. Many problems linked to continuous no-till maize may be eliminated in this rotation when the sod is killed in autumn. The residue level will be manageable, the flux of perennial weeds will be less, insect problems will be less, and the soil structure usually will be excellent resulting in higher yields. Inclusion of *Sesbania* in direct-seeded rice as a green manure intercrop and then knocking it down with broadleaf herbicide has been effective in suppressing weeds and improving soil fertility in rice–wheat cropping systems (Yadav 2004; Hobbs et al. 2008).

With systematic crop rotations, the benefits of CA can be achieved on soils or at locations where success is often difficult. Combining the timeliness and reduced-labor benefits of CA with advantages of higher yield and reduced inputs when associated with a better crop rotation significantly increased profit levels (Linden et al. 2000).

1.6 Weed Control

Weed control is considered a serious problem in CA systems and its success largely depends on effective weed control. Multiple tillage operations are required to control perennial weeds by reducing the energy reserves in different storage organs or roots of weeds (Todd and Derksen 1986; Fawcett 1987). Weed control in CA depends upon agronomic practices, herbicides, and level of tillage used (Lafond et al. 2009). In CA systems, small-seeded weed species are favored (Chauhan et al. 2006a; Farooq and Nawaz 2014), while dormant weed seeds present in the soil do not move to the soil surface (Cardina et al. 1991). In CA, crop residues are maintained on the soil surface that keeps the soil moist and cool, which increases the survival of germinated small weed seeds compared with conventional agriculture. In conventional tillage systems, weed seeds are buried in the soil, while in CA more weed seeds are left on the soil surface (Chauhan et al. 2006b), which are generally more susceptible to decay (Gallandt et al. 2004).

Chemical weed control is the most effective weed management option in CA; however, its effectiveness depends upon several factors including application of appropriate herbicides, time of application (postemergence vs. preemergence), and the amount of crop residue present on the soil surface. Crop residues directly affect weed germination and the bioavailability of herbicides such as trifluralin (Chauhan et al. 2006c). Residue retention strongly impacts weed emergence; several factors determine the extent of this influence including type and quantity of residue, nature of the residue, soil type, weather conditions, and prevailing weed flora (Buhler 1995; Chauhan et al. 2006d). Phenolics in the surface residue may reduce the weed infestation (Farooq et al. 2011b) in CA system. Nonetheless, the presence of plant residues may reduce the persistence and efficacy of soil-applied herbicides, which do not require incorporation into the soil and also intercept and bind the chemical before it reaches the soil surface (Potter et al. 2008).

The availability of transgenic crops with resistance to nonselective herbicides, such as glyphosate and glufosinate, can effectively control weed species while decreasing labor demands and repeated applications of herbicides (Cerdeira and Duke 2006). By using transgenic crops in CA, growers have boosted profitability by reducing labor expenses. The introduction of herbicide-tolerant transgenic crop varieties in CA systems provided effective weed control with substantial yield increases (Duke and Powles 2008). A new challenge to develop herbicide-resistant weed biotypes is threatening the use of herbicide-tolerant transgenic crops in CA systems (Farooq et al. 2011a; Heap 2014). Several weeds have developed resistance against herbicides. The first case was reported in 1970 in common groundsel (*Senecio vulgaris* L.), which developed triazine resistance (Ryan 1970). Worldwide, the number of herbicide-resistant weed biotypes has reached 432, which demands continued research to control the resistance and avoid the future spread of resistant weeds (Appleby 2005; Heap 2014).

Kirkegaard et al. (2014) opined that herbicide rotation, green/brown manures, and harvesting and destruction of weed seeds may help in weed management under CA systems. They further proposed to include strategic tillage as a component of integrated weed management approach where applicable and safe (with respect to erosion risk; Kirkegaard et al. 2014). This may help to reduce the incidences of development of herbicide-resistant weed biotypes.

1.7 The Role of Policy and Institutional Support

CA is a multi-dimensional approach ensuring the sustainability of resource use and food security. Principally, CA offers resistance to the irrational use of natural reserves through good management practices such as minimal soil disturbance using optimized tillage operations, check on soil exposure to environmental calamities, and biodiversity maintenance through diversified crop rotations. With the ever-increasing global population and urbanization reducing the amount of land under agriculture, food security has become a conundrum (Hobbs et al. 2008); the sustainable use of available resources is a key element of CA systems.

Adoption of CA is a paradigm shift requiring huge efforts and trade-offs at individual and institutional levels. In the long run, CA should be the ultimate solution to agricultural problems in small landholding farming communities (Derpsch 2003; Giller et al. 2009). CA research has progressed but adoption at the farmer level is a serious concern. Many factors hinder the uptake of CA by farmers and authorities: lack of proper information, poor knowledge dissemination, lack of demonstration, the need for long-term hard work, temporary decline in economic returns, hesitation, vague policies, lack of institutional support and natural disasters. Institutional support, innovative policy making, organizational collaboration, motivated think tanks, and government supervision are critical to develop a strong system for proliferation of CA (Kassam et al. 2012).

Policy making involves the realization of the available resources and serious approach to rethink the issue and options. Ecological, social, and political activism on the issue of natural resource depletion and sustainability has been ignited for 20–30 years at a global level. Understanding this problem provides the foundation for structural development and promotion of sustainable approaches along with an awareness campaign (Kassam et al. 2012). One important policy is “Save and Grow” coined by the Food and Agriculture Organization. It covers the idea of a two-way process of sustainable production and economical usage, which has simplified and clarified the theme of CA. Policy formation strengthens the expression, adoption, and promotion of this approach (FAO 2011b). Effective policies offer pragmatic solutions to a number of challenges (Kienzler et al. 2012) such as:

- Useful practices to improve food production under limited inputs and thus sustainable promotion of food production and the supply chain.
- Lowering the intensity of environmental damage through eco-friendly approaches.
- Economizing the production chain via improved cultural practices, judicious input use, and reduced exploitation of on-farm resources.
- Preserving ecological hierarchy by maintaining biodiversity and natural habitats.
- Offering a wide range of adjustments, adaptations, and rehabilitation after frequent natural and secondary disasters.

Plenty of evidence on the serious concerns, issues, and threats necessitating the adoption of CA are available (Foresight 2011); however, intensified production is still possible under a conservation regime with benefits including lower capital costs, reduced inputs, flexibility in terms of adaptation, aggrandized ecosystem efficiency, and environmental protection. In some parts of the world, conservation tillage has been termed under transformed tillage packages like zero tillage, reduced tillage, minimum tillage, etc.

Institutions are the main hubs for information gathering, knowledge sharing, and technology transfer. The role of institutional development in agriculture is significant. Linkage between research organizations, educational institutes, and extension wings must be very strong to launch any technology. Considerable work is being undertaken on the adoption of CA on national and international fronts. Governments are sensing the vitality of the system and reinforcing the approach through multi-actions. In developed countries, the scientific community is leading the task by innovating and modifying the steps for sustainability. Strict implication of the rules and regulations has confirmed the success of CA in different cases.

Authorities are sensing their responsibilities, and public sector movements regarding CA adoption are flourishing. Different institutions support farming communities to trial subsidized conservation packages. Incentives and visual economic profitability help to promote adoption and reduce farming community concerns (Kassam et al. 2012). Adoption of zero tillage in the rice–wheat cropping system in the Indo-Gangetic Plains is a successful example of CA adoption in the developing world. It is the result of consistent efforts by global institutions and organizations in collaboration with local governments and NGOs. Similarly, successful progress is being made in Central Asia, Africa, and other regions. Conservation approaches are not only becoming popular but also being adopted at the farmer level, which could improve with further institutional support and the right policy making in the future.

1.8 Conclusion

CA is a complex suite of technologies, including wise soil manipulation, retention of crop residues as soil cover, planned and diversified crop sequences, and effective weed management, for eco-friendly sustainable crop production. CA has proved beneficial in terms of yield, income, sustainability of land use, ease of farming, and the timeliness of ecosystem services and cropping practices. CA systems are being increasingly adopted worldwide; however, in some countries, its adoption is either slow or nonexistent. Sustained governmental policies and institutional support may play a key role in the promotion of CA through the provision of required services for farming communities and certain incentives. On-farm participatory research and demonstration trials may help accelerate the adoption of CA. The development and introduction of herbicide-tolerant transgenic crops resulted in the rapid spread of CA systems; however, the development of herbicide-resistant weed biotypes is posing a new threat. This invites attention of researchers to develop economically viable innovative alternative tools to prevent and manage herbicide-resistance development in weeds and weed management strategies. The use of *Sesbania* in direct-seeded rice as a manure intercrop and then using that as mulch with the application of broadleaf killer herbicide is a good option for weed and fertility management.

Developing crop genotypes with strong allelopathic potential against associated weeds is another option in this regard.

References

Appleby AP (2005) A history of weed control in the United States and Canada a sequel. Weed Sci 53:762–768

Baker CJ, Saxton KE, Ritchie WR (2002) No-tillage seeding: science and practice, 2nd edn. CAB, Oxford

Barret DWA, Wiles TL, Barker MR (1972) Spray-seed with the bipyridyls in Western Australia. In: Proceedings no-tillage systems symposium, Columbus, 21–22 Feb 1972, pp 83–92

Bäumer K (1970) First experiences with direct drilling in Germany. Neth J Agric Sci 18:283–292

Boisgontier D, Bartholomy P, Lescar L (1994) Feasibility of minimum tillage practices in France. In: Proceedings of the EC-Workshop-I-, Giessen, 27–28 June, 1994, Experience with the applicability of no-tillage crop production in the West-European countries, Wissenschaftlicher Fachverlag, Giessen, pp 81–91

Borges G de O (1993) Resumo histórico do plantio direto no Brasil. In: EMBRAPA, Centro Nacional de Pesquisa de Trigo (Passo Fundo, RS). Plantio direto no Brasil. EMBRAPA-CNPT/Fundacep Fecotrigo/Fundação ABC/Aldeia Norte, pp 13–17

Buhler DD (1995) Influence of tillage systems on weed population dynamics and management in corn and soybean in the central USA. Crop Sci 35:1247–1258

Cannel RQ, Hawes JD (1994) Trends in tillage practices in relation to sustainable crop production with special reference to temperate climates. Soil Till Res 30:245–282

Cardina J, Regnier E, Harrison K (1991) Long-term tillage effects on seed banks in three Ohio soils. Weed Sci 39:186–194

Cerdeira AL, Duke SO (2006) The current status and environmental impacts of glyphosate resistant crops: a review. J Environ Qual 35:1633–1658

Chauhan BS, Gill GS, Preston C (2006a) Seedling recruitment pattern and depth of recruitment of 10 weed species in minimum tillage and no-till seeding systems. Weed Sci 54:658–668

Chauhan BS, Gill GS, Preston C (2006b) Influence of tillage systems on vertical distribution, seedling recruitment and persistence of rigid ryegrass (*Lolium rigidum*). Weed Sci 54:669–676

Chauhan BS, Gill GS, Preston C (2006c) Tillage systems affect trifluralin bio-availability in soil. Weed Sci 54:941–947

Chauhan BS, Gill GS, Preston C (2006d) Tillage system effects on weed ecology, herbicide activity and persistence: a review. Aust J Exp Agric 46:1557–1570

Colmenero MR, Bienes R, Eldridge DJ, Marques MJ (2013) Vegetation cover reduces erosion and enhances soil organic carbon in a vineyard in the central Spain. Soil Till Res 104:153–160

Conant RT, Easter M, Paustian K, Swan A, Williams S (2007) Impacts of periodic tillage on soil C stocks: a synthesis. Soil Till Res 95:1–10

Derpsch R (2003) Conservation tillage, no-tillage and related technologies. In: Luis GT, José B, Armando MV, Antonio HC (eds) Conservation agriculture: environment, farmers experiences, innovations, socio-economy, policy. Springer Netherlands, pp 181–190

Derpsch R (2007) Historical review of no- tillage cultivation of crops. http://www.rolf-derpsch.com/notill.htm#1#1. Accessed 19 May 2014

Derpsch R, Friedrich T (2009) Development and current status of no-till adoption in the world. In: Proceedings on CD, 18th triennial conference of the International Soil Tillage Research Organization (ISTRO), Izmir, Turkey, 15–19 June 2009

Dill GM (2005) Glyphosate-resistant crops: history, status and future. Pest Manage Sci 61:219–224

Dixon J, Gulliver A, Gibbon D (2001) Farming systems and poverty: improving farmers' livelihoods in a changing world. FAO and World Bank, Rome

Duke SO, Powles SB (2008) Glyphosate: a once-in-a-century herbicide. Pest Manage Sci 64:319–325

Dumanski J, Peiretti R, Benetis J, McGarry D, Pieri C (2006) The paradigm of conservation tillage. In: Proceedings of world association of soil and water conservation, pp 58–64

FAO (2006) Agriculture and consumer protection department. Rome, Italy. http://www.fao.org/ag/magazine/0110sp.htm. Accessed 18 May 2014

FAO (2008) Investing in sustainable crop intensification: the case for soil health. Report of the international technical workshop, FAO, Rome, July. Integrated crop management, vol 6. FAO, Rome. http://www.fao.org/ag/ca/. Accessed 18 May 2014

FAO (2011a) CA adoption worldwide, FAO-CA website. http://www.fao.org/ag/ca/6c.html. Accessed 11 April 2014

FAO (2011b) Save and grow: a policymaker's guide to the sustainable intensification of smallholder crop production. FAO, Rome

Farooq M, Nawaz A (2014) Weed dynamics and productivity of wheat in conventional and conservation rice-based cropping systems. Soil Till Res 141:1–9

Farooq M, Flower K, Jabran K, Wahid A, Siddique KHM (2011a) Crop yield and weed management in rainfed conservation agriculture. Soil Till Res 117:172–183

Farooq M, Jabran K, Cheema ZA, Wahid A, Siddique KHM (2011b) The role of allelopathy in agricultural pest management. Pest Manage Sci 67:494–506

Faulkner EH (1943) Plowman's folly. Michael Joseph, London

Fawcett RS (1987) Overview of paste management for conservation tillage systems. In: Logan TJ, Davidson JM, Baker L, Overcash MR (eds) Effects of conservation tillage on groundwater quality: nitrtes and pesticides. Lewis, Chelsea, pp 19–37

Fischer RA, Santiveri F, Vidal IR (2002) Crop rotation, tillage and crop residue management for wheat and maize in the sub-humid tropical highlands. II maize and system performance. Field Crops Res 79:123–137

Foresight (2011) The future of food and farming. The Government Office for Science, London

Fraley RT, Stephen GR, Robert BH, Patricia RS, Jeffery SF, Steven PA, Michael LB, Leslie AB, Cynthia LF, Joyce SF, Gerald RG, Sarah BG, Nancy LH, Sherry CW (1983) Expression of bacterial genes in plant cells. Proc Natl Acad Sci U S A 80:4803–4807

Friedrich T, Kassam AH (2009) Adoption of conservation agriculture technologies: constraints and opportunities. In: Proceedings of the IV world congress on conservation agriculture, ICAR, New Delhi, India, 4–7 Feb 2009

Friedrich T, Kassam AH, Shaxson F (2009) Conservation agriculture. In: Agriculture for developing countries. Science and Technology Options Assessment (STOA) Project, European technology assessment group, Karlsruhe, Germany

Friedrich T, Derpsch R, Kassam AH (2012) Global overview of the spread of conservation agriculture. Field Actions Sci Rep 6:1–7

Fukuoka M (1975) One straw revolution, Rodale, Tokyo, p 138

Gallandt ER, Fuerst EP, Kennedy AC (2004) Effect of tillage, fungicide seed treatments and soil fumigation on seed bank dynamics of wild oat (*Avena fatua*). Weed Sci 52:597–604

Giller KE, Witter E, Corbllels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: the heritics view. Field Crop Res 114:23–34

Giráldez JV, González P (1994) No-tillage in clay soils under Mediterranean climate: physical aspects. In: Proceedings of the EC-workshop-I-, Giessen, 27–28 June 1994, Experience with the applicability of no-tillage crop production in the West-European countries, Wissenschaftlicher Fachverlag, Giessen, 1994, pp 111–117

Govaerts B, Verhulst N, Castellanos-Navarrete A, Sayre KD, Dixon J, Dendooven L (2009) Conservation agriculture and soil carbon sequestration; between myth and farmer reality. Crit Rev Plant Sci 28:97–122

Greenland DJ (1975) Bringing the green revolution to the shifting cultivators. Science 190:841–844

Haggblade S, Tembo G (2003) Conservation farming in Zambia EPTD. Discussion Paper No. 108, International Food Policy Research Institute, Washington

Hanks J, Martin SW (2007) Economic analysis of cotton conservation tillage practices in the Mississippi Delta. J Cotton Sci 11:75–78

Harrington LW (2008) A brief history of conservation agriculture in Latin America, South Asia and Sub-Saharan Africa. PACA, 1st Floor, NASC Complex, DPS Marg, Pusa, New Delhi–110 012, India

Heap I (2014) The international survey of herbicide resistant weeds. http://www.weedscience.com. Accessed 18 May 2014

Hillel D (1991) Out of the earth: civilization and the life of the oil. Free, New York

Hillel D (1998) Environmental soil physics. Academic, San Diego

Hobbs PR, Gupta RK (2004) Problems and challenges of no-till farming for the rice–wheat systems of the Indo-Gangetic Plains in South Asia. In: Lal R, Hobbs P, Uphoff N, Hansen DO (eds) Sustainable agriculture and the rice–wheat system. Ohio State University/Marcel Dekker, Columbus, pp 101–119

Hobbs RP, Sayre K, Gupta R (2008) The role of conservation agriculture in sustainable agriculture. Phil Trans R Soc B 363:543–555

Holland JM (2004) The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric Ecosyst Environ 103:1–25

Kassam AH, Friedrich T, Shaxson F, Pretty J (2009) The spread of conservation agriculture: justification, sustainability and uptake. Int J Agric Sustain 7:1–29

Kassam AH, Friedrich T, Derpsch R (2010) Conservation agriculture in the 21st century: a paradigm of sustainable agriculture. In: Proceedings of the European Congress on conservation agriculture, Madrid, October 2010

Kassam A, Friedrich T, Derpsch R, Lahmar R, Mrabet R, Basch G, González-Sánchez E, Serraj R (2012) Conservation agriculture in the dry Mediterranean climate. Field Crops Res 132:7–17

Kern JS, Johnson MG (1993) Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Sci Soc Am J 57:200–210

Kienzler KM, Lamers JPA, McDonald A, Mirzabaev A, Ibragimov N, Egamberdiev O, Ruzibaev E, Akramkhanov A (2012) Conservation agriculture in Central Asia—what do we know and where do we go from here? Field Crops Res 132:95–105

Kirkegaard JA, Conyers MK, Hunta JR, Kirkby CA, Watt M, Rebetzke GJ (2014) Sense and nonsense in conservation agriculture: principles, pragmatism and productivity in Australian mixed farming systems. Agric Ecosys Environ 187:133–145

Kumar K, Goh KM (2000) Crop residues and management practices: effects on soil quality, soil nitrogen dynamics, crop yield and nitrogen recovery. Adv Agron 68:198–279

Lafond GP, McConkey BG, Stumborg M (2009) Conservation tillage models for small scale farming: linking the Canadian experience to the small farms of Inner Mongolia Autonomous Region in China. Soil Till Res 104:150–155

Lal R (1976) No tillage effects on soil properties under different crops in western Nigeria. Soil Sci Soc Am Proc 40:762–768

Lal R (2001) Managing world soils for food security and environmental quality. Adv Agron 74:155–192

Li H, Gao H, Wu H, Li W, Wang X, He J (2007) Effects of 15 years of conservation tillage on soil structure and productivity of wheat cultivation in northern China. Aust J Soil Res 45:344–350

Linden DR, Clapp CE, Dowdy RH (2000) Long term grain and stover yields as a function of tillage and residue removal in east central Minnesota. Soil Till Res 56:167–174

Lindwall CW, Sonntag B (2010) Landscape transformed: the history of conservation tillage and direct seeding, knowledge impact in society. University of Saskatchewan, Saskatoon, Saskatchewan S7 N 5B8, Canada

Magdoff F, Harold VE (2000) Building soils for better crops. 2nd edn. Sustainable Agriculture, Burlington

Marongwe LS, Kwazira K, Jenrich M, Thierfelder C, Kassam A, Friedrich T (2011) An African success: the case of conservation agriculture in Zimbabwe. Int J Agric Sustain 9:153–161

Meena MS, Singh KM, Singh SS (2010) Conservation agriculture: adoption strategies. Agric Ext Rev 22:20–24

Miguel AF, Peñalva M, Calegari A, Derpsch R, McDonald, MJ (2011) Green manure/cover crops and crop rotation in conservation agriculture on small farms. Plant Production and Protection Division, FAO, Rome

Montgomery DR (2007) Soil erosion and agricultural sustainability. Proc Natl Acad Sci U S A 104:13268–13272

Paarlberg RL (2001) The politics of precaution: genetically modified crops in developing countries. Johns Hopkins University Press, Balitmore

Perszewski R (2005) Ideas leading to no-till's second revolution. http://www.no-tillfarmer.com/pages/Feature-Articles---Ideas-Leading-To-No-Tills-Second-Revolution.php. Accessed 2 June 2014

Potter TL, Truman CC, Strickland TC, Bosch DD, Webster TM (2008) Herbicide incorporation by irrigation and tillage impact on runoff loss. J Environ Qual 37:839–847

Powles SB, Lorraine-Colwill DF, Dellow JJ, Preston C (1998) Evolved resistance to glyphosate in rigid ryegrass. Weed Sci 46:604–607

Putte AV, Govers G, Diels J, Gillijns K, Demuzere M (2010) Assessing the effect of soil tillage on crop growth: a meta-regression analysis on European crop yields under conservation agriculture. Eur J Agron 33:231–241

Reicosky DC, Saxton KE (2007) The benefits of no-tillage. In: Baker CJ, Saxton KE, Ritchie WR, Chamen WCT, Reicosky DC, Ribeiro MFS, Justice SE, Hobbs PR (eds) No-tillage seeding in conservation agriculture. 2nd edn. CABI, Wallingford, pp 11–20

Ryan GF (1970) Resistance of common groundsel to simazine and atrazine. Weed Sci 18:614–616

Sartori L, Peruzzi P (1994) The evolution of no-tillage in Italy: a review of the scientific literature. In: Proceedings of the EC-Workshop-I-, Giessen, 27–28 June, 1994, Experience with the applicability of no-tillage crop production in the West-European countries, Wissenschaftlicher Fachverlag, Giessen, 1994, pp 119–129

Serraj R, Siddique KHM (2012) Conservation agriculture in dry areas. Field Crops Res 132:1–6

Singh KM, Meena MS (2013) Economics of conservation agriculture: an overview. Munich Personal RePEc Archive, MPRA Paper No. 49381. http://mpra.ub.uni-muenchen.de/49381/. Accessed 19 May 2014

Tarkalson DD, Hergert GW, Cassman KG (2006) Long term effects of tillage on soil chemical properties and grain yields of a dryland winter wheat-sorghum/corn-fallow rotation in the Great Plains. Agron J 98:26–33

Thierfelder C, Wall PC (2009) Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. Soil Till Res 105:217–227

Todd BC, Derksen DA (1986) Perennial weed control in wheat in western Canada. In: Slinkard AE, Fowler DB (ed) Wheat production in Canada—a review. University of Saskatchewan, Saskatoon, pp 391–404

West TO, Marland G (2002) A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agric Ecosyst Environ 91:217–232

Witmer JE, Hough-Goldstein JA, Pesek JD (2003) Ground-dwelling and foliar arthropods in four cropping systems ground-dwelling and foliar arthropods in four cropping systems. Environ Entomol 32:366–376

World Resources Institute (2000) People and ecosystems, the frayling web of life. World Resources Institute, United Nations Development Programme, World Bank, Washington, USA, p 36. http://www.wri.org/wr2000/pdf/summary.pdf. Accessed 14 May 2014

Yadav RL (2004) Enhancing efficiency of fertilizer N use in rice–wheat systems of Indo-Gangetic Plains by intercropping *Sesbania aculeata* in direct seeded upland rice for green manuring. Bioresour Technol 93:213–215

Part II
Elements of Conservation Agriculture

Chapter 2
Crop Rotations and Residue Management in Conservation Agriculture

Leonard Rusinamhodzi

Abstract Yield increases and sustainability of conservation agriculture (CA) systems largely depend on systematic crop rotations and *in situ* crop harvest residue management coupled with adequate crop nutrition. In this chapter, the beneficial effects of crop residue management and crop rotations on maize (*Zea mays* L.) grain yield in CA systems under rainfed conditions are explained through a meta-analysis. The effects of crop residue management are most beneficial under rainfed conditions as rainfall distribution is often erratic and seasonal dry spells common. The meta-analysis was based on the weighted mean difference (WMD) effect size using the random effects model. Yield advantages of CA systems over conventional tillage systems were only significant when in rotation, under low rainfall conditions and with large N fertiliser inputs. The WMD for CA with continuous maize ranged from -1.32 to 1.27 with a mean of -0.03 t ha^{-1}, and when rotation was included the WMD ranged from -0.34 to 1.92 with a mean of 0.64 t ha^{-1}. Mulch retention under low rainfall (<600 mm) had a WMD between -0.2 and 1.0 with a mean of 0.4 t ha^{-1} while high rainfall (>1000 mm per season) reduced the yield advantage with the WMD ranging from -1.2 to 0.02 with a mean of -0.59 t ha^{-1}. CA is likely to have the largest impact in low-rainfall environments where increased infiltration of rainfall and reduced evaporative losses are achieved by retaining crop residues. However, it is in these areas that achieving sufficient crop residues is a challenge, particularly in mixed crop–livestock systems where crop residues are needed for livestock feed in the dry season. The results suggest that CA needs to be targeted and adapted to specific biophysical as well as socioeconomic circumstances of farmers for improved impact. The ability of farmers to purchase fertiliser inputs, achieve sufficient biomass production as well as produce alternative feed will allow them to practise CA and possibly achieve large yields.

Keywords Crop rotation · Crop residues · Conservation agriculture · Maize grain yield · Meta-analysis · Weighted mean difference · Rainfed conditions

---

L. Rusinamhodzi (✉)
CIRAD—Agro-ecology and Sustainable Intensification of Annual Crops, c/o CIMMYT Regional Office, Mt Pleasant, Harare, Zimbabwe
e-mail: leonard.rusinamhodzi@gmail.com

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_2

2.1 Introduction

Systematic crop rotations and *in situ* crop harvest residue management are the pillars of conservation agriculture (CA). Yet, they are also the most pronounced barriers to its widespread practice especially on smallholder farms in the tropics. A crop rotation is the sequence of crop types grown in succession on a specific field (Wibberley 1996; Castellazzi et al. 2008). Crop rotations play a key role in CA systems where they facilitate soil fertility replenishment while at the same time minimising pest and disease build-up (Trenbath 1993). Crop rotations with leguminous crops have the potential to increase soil nitrogen (N) concentration through biological nitrogen fixation (BNF; Giller 2001). Research results have shown that synthetic fertilisers or organic manure do not solve the challenges of soil degradation and fertility decline except when used in combination (Chivenge et al. 2009, 2011). The use of mineral fertiliser is needed and should be combined with management practices that build up organic carbon and achieve sustainability in the longer term. The underlying hypothesis of this chapter is that yield increases in CA over conventional agriculture systems are underpinned by successful crop residue management and crop rotation, and such yield increases differ according to fertiliser inputs by farmers and the amount and distribution of seasonal rainfall.

The importance of crop residue retention to sustainability of crop production is widely acknowledged. *In situ* retention of crop harvest residues coupled with no tillage has the potential to increase substantially soil organic carbon (SOC) although current data and knowledge are inconclusive (Govaerts et al. 2009). However, there is consensus that consistent and sufficient C inputs are the major determinants of SOC changes in soil and not so much the type of tillage (Chivenge et al. 2007). Reduced tillage is important in reducing decomposition rates but this is only relevant if sufficient organic inputs have been applied (Chivenge et al. 2007). The absence of soil inversion may lead to SOC accumulation in the top layers of the soil (Franzluebbers and Arshad 1996). Carbon increases are expected over time if the amount of crop residue retained is more than that dissipated by the oxidation process. Current literature suggests that the importance of crop residue retention in the short term might be related to the maintenance of SOC rather than its absolute increase.

Crop residues provide soil cover which decreases run-off and soil loss especially on low slopes but it is less effective on steep slopes (Adekalu et al. 2007). In a study on a utisol in Nigeria, Adekalu et al. (2007) reported that water infiltration increased with increasing levels of mulch cover (giant elephant grass) and decreased with increasing slope. The authors suggested that to improve infiltration and reduce run-off and soil erosion, up to 90 % cover may be necessary especially if organic matter is low and sand content is high. Other researchers have suggested mulch application rates of 4–6 t ha^{-1} as adequate (Lal 1976; De Silva and Cook 2003) but what these quantities translate to in terms of soil cover for different crops is not well known (Morrison et al. 1985). Some authors suggest that mulch rates of up to 6 t ha^{-1} may completely eliminate soil loss (Fig. 2.1, Lal 1998; Adekalu et al. 2006, 2007). Understanding the interactions between the type and rate of mulch application, the

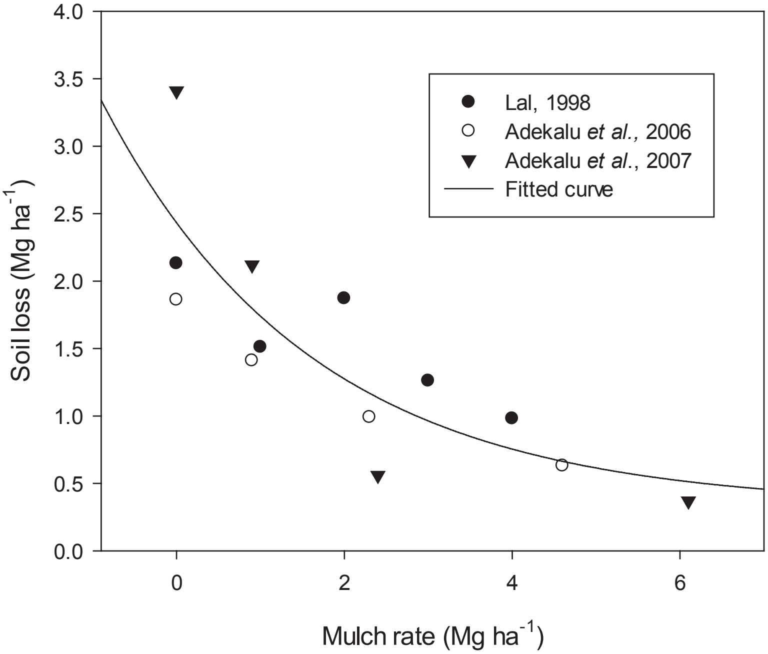


Fig. 2.1 The relationship between the amount of crop residue retained and soil loss. (Data used were reported by Adekalu et al. 2006, 2007; Lal 1998)

contribution to nutrient enhancement in soil and the potential for crop yield improvement are needed (Cook et al. 2006). Crop residues have low thermal conductivity such that mulching can reduce soil temperature for optimal germination and root development in hot environments (Lal 1978; Riddle et al. 1996). They insulate the soil surface and increase resistance to heat and vapour transfer leading to increased available soil water (Hatfield and Prueger 1996; Dexter 1997; Cook et al. 2006). Mulch is also important for intercepting rainfall energy and reduces erosion. In areas of relatively short duration and low-intensity rainfall, mulching may reduce soil water recharge; this could be crucial in areas with frequent and small amounts of rainfall because it can be intercepted before it recharges the topsoil (Sadler and Turner 1993; Savabi and Stott 1994). It has also been suggested that the crop residue thickness has a direct effect on total interception of rainfall (Savabi and Stott 1994). Thus, mulch application is not always positive and may be detrimental to crop productivity.

In cereal-based systems which dominate the tropics, most crop residues are derived from maize, millet and sorghum, which are rich in lignin and have high C/N ratios that are generally greater than 60 (Cadisch and Giller 1997; Handayanto et al. 1997). Although crop residues are often on the soil surface, they are more likely to partially incorporate and decompose as the season progresses adding to SOC (Parker 1962). However, the wide C/N ratio leads to prolonged N immobilization by microorganisms, rendering N unavailable for crop growth in the short term (Giller et al. 1997). Thus, high N inputs are required when poor-quality crop residues are used as mulch cover.

This chapter collates and performs a meta-analysis on existing literature on the effect of crop rotations and crop residue management on maize grain yield under CA. Meta-analysis allows combined quantitative analyses of experimental yield data reported in the literature and estimation of effect sizes (Glass 1976; Rosenburg et al. 2000; Ried 2006; Borenstein et al. 2009). The analysis increases the statistical power available to test hypotheses and can help unravel differences in responses between treatments under different environments (Gates 2002; Borenstein et al. 2009). The effect size for each individual study is considered an independent estimate of the underlying true effect size, subject to random variation. All studies contribute to the overall estimate of the treatment effect whether the result of each study is statistically significant or not thus reducing publication bias. Data from studies with more precise measurements or larger studies (many cases) are given more weight, so they have more influence on the overall estimate (Gates 2002). However, meta-analysis has potential weaknesses due to publication bias and other biases that may be introduced in the process of locating, selecting and combining studies (Egger et al. 1997; Noble 2006). Publication bias arises when researchers, reviewers and editors submit or accept manuscripts for publication based on the direction or strength of the study findings (Dickersin 1990). This means that studies reporting contradictory or neutral results are likely to be omitted from publications. To reduce publication bias, data searches were carried out online to find results from all parts of the world under rainfed conditions. Some researchers were also contacted to provide some grey literature. Moderators, i.e. factors likely to influence effect sizes such as mean annual precipitation (MAP) and N fertiliser input, were identified during data collation and the random effects model was used during the analysis (Ried 2006).

2.2 Meta-analysis

Maize grain yield data were obtained from studies on the effect of crop residue management and crop rotation. Due to the voluminous nature of the search results, meta-analysis was restricted to rainfed conditions in semiarid and subhumid environments where the effects of mulch on crop productivity would be better assessed. Data searches were predominantly online and obtained from refereed journals, book chapters or peer-reviewed conference proceedings. The following keywords and their combinations were searched: crop rotations, legumes, CA, mulch cover, no tillage, maize yield, corn yield, subhumid, semiarid and rainfed. The treatments from which maize grain yield data were collated are described in Table 2.1. Nutrient inputs needed to be the same across the treatments tested in each study. Unpublished data or grey literature was obtained from researchers working on CA. Result moderators or factors likely to influence the meta-analysis outcome such as annual rainfall and N input as reported in the literature were included in the analysis. Fifty publications met the selection criteria and were used in the meta-analysis (Table 2.2).

Table 2.1 Tillage treatments used in the meta-analysis

Tillage management option	Short description
Conventional tillage (CT)	Mouldboard ploughing without crop residue retention. The most widely practised tillage technique used by communal farmers with animal draught power in southern Africa
No tillage + mulch (NTM)	Practice of minimising soil disturbance plus previous crop residues to achieve soil cover after planting. Weed control is accomplished primarily with herbicides
No tillage + mulch + rotation (NTMR)	As described above for NTM. Main crop of maize in a rotation sequence with legumes such as soybean (*Glycine max* L.) or cowpea (*Vigna unguiculata* (L.) Walp)

The meta-analysis procedure and calculation followed that described by Rusinamhodzi et al. (2011) as presented below. Data required for the meta-analysis were in the form of treatment mean ($\bar{X}$), standard deviation ($SD_{\bar{X}}$), and number of replicates (n) mentioned in the experimental design. Several authors presented statistical data in different formats such as standard error $SE_{\bar{X}}$ and coefficient of variation ($CV\%$). These were converted to standard deviation ($SD_{\bar{X}}$) using the following equations: $SD_{\bar{X}} = SE_{\bar{X}} \times \sqrt{n}$ and $SD_{\bar{X}} = \left(\frac{CV\%}{100}\right) \times \bar{X}$. Effect size was obtained by computing the weighted mean difference (WMD) using the random effects model (DerSimonian and Laird 1986; Borenstein et al. 2009). The mean difference (Eq. 2.1) in yield between the treatment and control was used due to its ease of interpretation and the relevance for comparing potential gains (Ried 2006; Sileshi et al. 2008). To obtain overall treatment effects across studies, the differences between treatment and control were weighted (Eq. 2.3). The weight given to each study was calculated as the inverse of the variance (Eq. 2.2). The random effects model assumed that the true effect of CA on crop yield varied from site to site and from season to season; thus, contributions of each study to the overall effect size were considered independent. Nitrogen input and amount of seasonal rainfall were chosen as the most important moderators and their effect tested on the magnitude of the responses (mean differences). Nitrogen input and MAP classes were categorized as reported by Rusinamhodzi et al. (2011) with MAP classes as low (<600 mm), medium (600–1000 mm) and high (>1000 mm), and N fertiliser input as low (<100 kg ha^{-1}) and high (>100 kg ha^{-1}):

$$\text{Mean difference (MD)} = \text{mean}_{\text{treated}} - \text{mean}_{\text{control}} \tag{2.1}$$

$$\text{weight}_i = \frac{1}{\text{variance}_i} = \frac{1}{\text{SD}_i^2} \tag{2.2}$$

$$\text{Weighted mean difference (WMD)}_{\text{overall}} = \sum_{i=1}^{i=n} (\text{weight}_i * \text{MD}) / \sum_{i=1}^{i=n} \text{weight}_i \tag{2.3}$$

$$\text{CI}_{95\%} = \text{mean}_{\text{overall}} \pm (1.96 * (\text{variance}_{\text{overall}})^{0.5}) \tag{2.4}$$

Table 2.2 Site information for experiments used in the meta-analysis

Country	Treatments	Reference
Madagascar	CT, NT, NTR	Djigal et al. (2012)
USA	CT, NT	Wilhelm and Wortmann (2004)
USA	CT, NT	Karlen et al. (1991)
USA	CT, NT	Griffith et al. (1988)
USA	CT, NT, NTM	Linden et al. (2000)
Nigeria	CT, NT, NTM	Lal (1997)
Zimbabwe	CT, NT	Vogel (1993)
Zimbabwe	CT, NT	Moyo (2003)
Zimbabwe	CT, NT	Nehanda (2000)
USA	CT, NT	Olson et al. (2004)
USA	CT, NT	Wilhelm et al. (1987)
Australia	CT, NT	Thiagalingam et al. (1996)
USA	CT, NT	Iragavarapu and Randall (1995)
India	CT, NT, NTM	Acharya and Sharma (1994)
Brazil	CT, NT	Sisti et al. (2004)
China	CT, NTM	Jin et al. (2007)
USA	CT, NT	Karunatilake et al. (2000)
Italy	CT, NT	Mazzoncini et al. (2008)
Canada	CT, NT, NTM	Dam et al. (2005)
Mexico	CT, NT, NTM	Fischer et al. (2002)
USA	CT, NT	Rice et al. (1986)
India	CT, NTR	Ghuman and Sur (2001)
USA	NT, NTR	Karlen et al. (1994b)
USA	CT, NT, NTR	Ismail et al. (1994)
Zimbabwe	CT, NT	Nyagumbo (2002)
USA	CT, NT	Dick and Van Doren (1985)
Zimbabwe, Zambia	CT, NT	Marongwe et al. (2011)
Malawi	CT, NT, NTR	Ngwira et al. (2012a)
Malawi	CT, NT, NTR	Ngwira et al. (2012b)
Malawi, Mozambique, Zambia, Zimbabwe	CT, NT, NTR	Thierfelder et al. (2012a)
Zimbabwe	CT, NT, NTR	Thierfelder et al. (2012b)
Malawi	CT, NT, NTR	Thierfelder et al. (2013a)
Zambia	CT, NT, NTR	Thierfelder et al. (2013c)
Malawi, Mozambique, Zambia, Zimbabwe	CT, NT	Thierfelder et al. (2013b)
Zimbabwe	CT, NT	Thierfelder and Wall (2012)
Kenya	CT, NT, NTM	Paul et al. (2013)
Nigeria	CT, NT	Osuji (1984)
Zimbabwe	CT, NT, NTR	Mupangwa et al. (2007)
Zimbabwe	CT, NT, NTR	Mupangwa et al. (2012)
Nigeria	CT, NT	Mbagwu (1990)
Kenya	CT, NT, NTR	Kihara et al. (2012)

CT conventional tillage, *NT* no tillage, *NTM* no tillage with mulch

$$\text{Variance}_{\text{overall}} = \frac{1}{\sum_{i=1}^{i=n} \text{weight}_i}. \tag{2.5}$$

2.3 Yield Data from Different Mulch and Crop Rotations

The WMD of CA with continuous maize cropping was almost zero but ranged from −1.32 to 1.27 t ha^{-1} (Fig. 2.2). Including the rotation into the CA system increased the WMD which ranged from −0.34 to 1.92 t ha^{-1} with a mean of 0.64 t ha^{-1}. Retention of mulch alone without crop diversification does not necessarily lead to improved crop productivity. The overall effect of mulch on crop productivity could be considered neutral in this case. These results agree with Kapusta et al. (1996) who observed no significant yield difference between no tillage and conventional ploughing on poorly drained soils after 20 years of continuous no tillage. Similarly, Dam et al. (2005) reported that, after 11 years, maize yields were more affected by the amount of rainfall and temperature across years than tillage and crop residue management. Rotations especially with legumes often have positive effects on maize yield across soil fertility regimes (Karlen et al. 1991, 1994a). The larger yield in rotation compared with continuous monocropping was attributed to reduced pest infestations, improved water-use efficiency, good soil quality as shown by increased organic carbon, greater soil aggregation, increased nutrient availability and greater soil biological activity (Van Doren et al. 1976; Hernanz et al. 2002; Kureh et al. 2006). In the Highlands of Madagascar, Djigal et al. (2012) observed CA systems that supported comparable or better yields in the long term than conventional tillage if crop rotation was correctly managed.

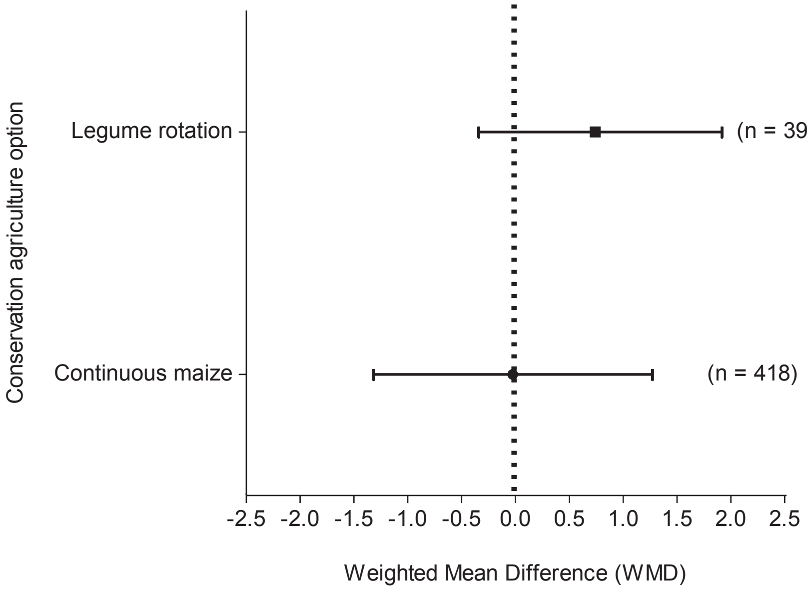


Fig. 2.2 The weighted mean difference (*WMD*) for continuous maize under conservation agriculture (*CA*) and for maize in rotation with legumes under CA. The WMD were computed as the difference in yield of the CA options over continuous maize cropped using conventional tillage

Subgroup analysis of continuous maize production with mulch suggested that the amount of seasonal rainfall and fertiliser inputs are important yield moderators. The most yield advantage (WMD between −0.2 and 1.0 t ha^{-1}) from mulch retention was obtained in environments where seasonal precipitation did not exceed 600 mm, with an overall effect of 0.4 t ha^{-1} (Fig. 2.3). The yield advantages from mulch application decreased with increasing seasonal rainfall as expected; above 600 mm, there was no yield advantage from mulch retention over conventional tillage. The retention of mulch increases rainfall infiltration into the soil and reduces evaporative losses resulting in waterlogging. In other studies, yields under CA practices were 5–20 % less than under conventional tillage practices in wet years, but 10–100 % higher in relatively dry years (Hussain et al. 1999). Similarly, Lueschen et al. (1991) reported larger crop yields with CA practices than conventional tillage in a relatively dry year.

Retention of mulch requires a concomitant increase in N inputs to ensure larger yields. WMD for systems where N input was less than 100 kg ha^{-1} indicated that conventional systems would yield more than CA options tested (Fig. 2.4). When N fertiliser input was raised beyond 100 kg ha^{-1}, the WMD had a yield advantage for CA over conventional tillage. The results agree with Vanlauwe et al. (2014) who identified adequate nutrient management in CA systems as another critical factor, i.e. the need for a fourth principle. Similarly, Díaz-Zorita et al. (2002) reported that maize yields increased more with nitrogen fertilisation than tillage under subhumid

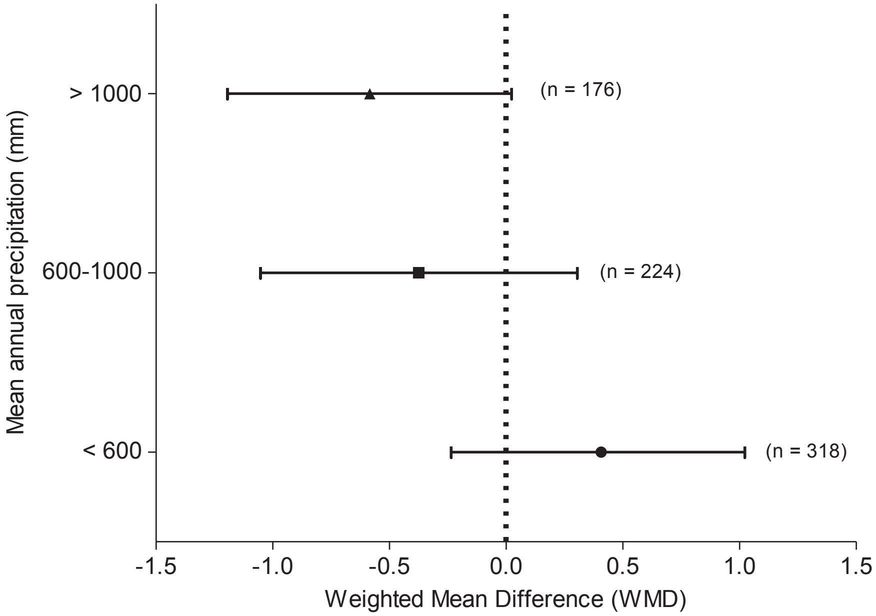


Fig. 2.3 The weighted mean difference (WMD) for continuous maize under conservation agriculture (CA) under different rainfall categories. The WMD were computed as the difference in yield of the CA over continuous maize cropped using conventional tillage

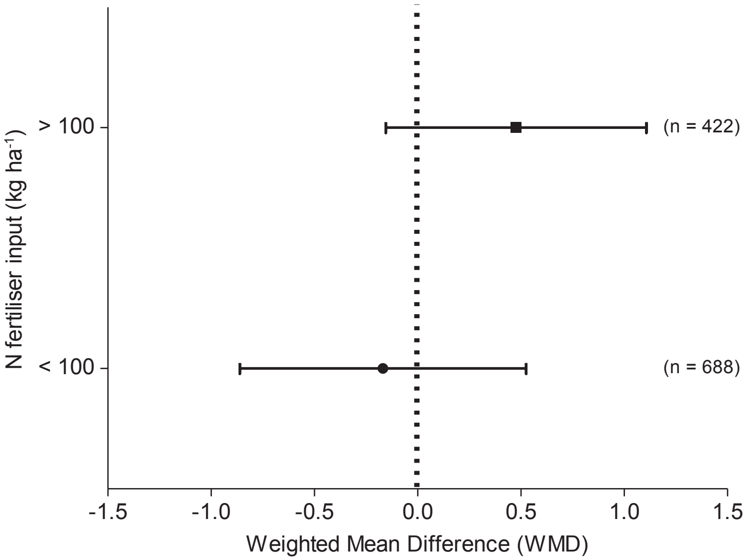


Fig. 2.4 The weighted mean difference (WMD) for continuous maize under conservation agriculture (CA) under different N fertiliser categories. The WMD were computed as the difference in yield of the CA over continuous maize cropped using conventional tillage

and semiarid regions of Argentina. The most notable crop residues in semiarid areas are those of maize, millet and sorghum of poor quality due to high C/N ratios, generally greater than 60, which immediately immobilizes N (Cadisch and Giller 1997; Handayanto et al. 1997). Thus, high N inputs are required when poor-quality crop residues are used as mulch.

2.4 Constraints to Systematic Crop Rotations

Poorly developed markets, minimal household food contributions and limited land sizes are the major impediments to successful crop rotations by smallholder farmers. Widespread poverty prevents farmer access to credits and inputs such as fertiliser, seed and pesticides (Graham and Vance 2003; Sanginga and Woomer 2009). Specialized agrifood markets such as those in Laos limit the integration of grasses and legumes into diversified crop rotations (Lestrelin et al. 2012). Limited landholdings are becoming a major problem due to the rising population pressure—a classic example is in Malawi where land sizes are often below 1 ha limiting the number of crops farmers can grow in a season (Ellis et al. 2003; World Bank 2007). Soil fertility decline is another major challenge in the field where deficiencies of phosphorus (P), potassium (K), sulphur (S) and micronutrients such as zinc (Zn), molybdenum (Mo) and boron (B) may limit legume growth and N_2 fixation (O'Hara et al. 1988). P availability is often regarded as the most limiting factor (Giller and

Cadisch 1995). At the farm level, it is important that grain legumes provide multiple benefits especially as a food and are acceptable to farmers (Giller 2001). Formal seed systems are poorly developed with limited varieties of maize seed available, often open-pollinated varieties. Most farmers use retained seed, informal seed exchanges with other farmers and seed bought from local markets. They see their local seed as better adapted to their conditions but lack of quality uniformity means they are less preferred at the market (cf. Rohrbach and Kiala 2007). Widespread adoption of legume production will be achieved by strengthening seed systems, improving farmer access to input markets for improved, short-season and disease-resistant varieties and P fertiliser and output markets for better prices and trade terms.

2.5 Constraints to Crop Residue Management

A comprehensive appraisal of the benefits and constraints related to crop residue management has been explored (Erenstein 2002; Lal 2005). Major constraints to successful crop residue management in CA systems are related to the small baseline crop productivity and other alternative economic uses of crop residues such as livestock feed, fuel, bedding in kraals (animal paddocks) during the rainy season and construction (fencing and thatching) for some farming households (Mazvimavi et al. 2008; Erenstein 2011; Rufino et al. 2011; Johansen et al. 2012). Crop and livestock production are closely integrated in mixed smallholder farming systems in much of the tropics (Thornton and Herrero 2001; Rufino et al. 2011). Crop residues are needed to provide livestock feed during the dry season where feed is severely limited while manure is needed for crop production (Rufino et al. 2011; Rusinamhodzi et al. 2013). The application of livestock manure has been shown to increase crop productivity especially targeted to responsive fields (Zingore et al. 2008; Rusinamhodzi et al. 2013). Such yield benefits derived from manure, whose quantity and quality partly depends on crop harvest residues (Nzuma and Murwira 2000; Lekasi et al. 2003; Rufino et al. 2007), suggest that farmers face trade-offs in crop residue management and it might be beneficial for them to follow the manure production pathway than apply crop residues as mulch (Naudin et al. 2012; Valbuena et al. 2012; Rusinamhodzi 2013). Moreover, livestock provides a source of cash income and spreads the risk (Sumberg 2002; Rufino et al. 2006). In most situations, alternative grazing does not exist as communal rangelands are often degraded and characterized by poor-quality fodder (Rufino et al. 2011). Although development agents have made potential legume, grass and other agroforestry trees available for use as a fodder, farmers reject them because they do not contribute directly to food security despite the enormous labour inputs required (Giller 2001). The unimodal nature of the cropping seasons suggest that farmers concentrate all their limited resources to major food production and other crops are considered much later in the season leading to small productivity.

On the other hand, the availability of crop residues is not a technological panacea. The overall effect depends on the local biophysical and socioeconomic environment; i.e. they differ substantially between the agricultural settings of developed and developing countries (Erenstein 2002). In South Asia, Aulakh et al. (2012) concluded after a 4-year study that future efforts are required to develop new technologies to alleviate the negative effects of relatively cooler environments created by surface-retained crop residues especially during germination and initial growth in the subtropical region. In the Trans-Gangetic plains of India, crop residue management practices are largely incompatible with year-round mulch retention needed in CA despite significant biomass production (Erenstein 2011) due to other important activities for the household.

2.6 Future Outlook

Much of the research on CA has been conducted at plot level, focusing on the effects of CA on soil quality, with little effort on how CA fits into broader farming systems (Giller et al. 2009; Baudron et al. 2012). Retention of crop residues as a mulch in the field is not feasible for most farmers due to competition for livestock feed and the need for more fertiliser, making CA unattractive for most farmers. Retention of crop residues will lead to depressed yields in the short term due to immobilization of N which contrasts sharply with farmers' needs. Therefore, the short-term needs of farmers may be a threat to CA uptake. While the short-term crop yield response to CA is highly variable, yields often improve in the long term when the continued accumulation of crop residue increases the availability of SOC and nutrients for crop growth.

Until recently, the discourse around CA has been the inadequate amounts of crop residue produced against multiple important uses, i.e. creating trade-offs for their use. The success of CA was considered directly related to the ability to provide enough soil cover, and little attention has been paid to adequate nutrient management, firstly to offset the N deficit caused by immobilization due to poor-quality residues and secondly to provide a balanced nutrient supply to the growing crop. Recently, Vanlauwe et al. (2014) suggested the need for a fourth principle to add to the principles of no till, mulch retention and crop rotation. Optimum fertiliser application may help to increase biomass production which may allow both the retention of crop harvest residues for mulch as well as providing livestock feed. Both crop rotations and fertiliser inputs are important for improved yields in CA systems. Future research needs should be devoted to identifying appropriate nutrient management strategies in CA systems together with crop residue retention and crop rotations to boost crop productivity (Vanlauwe et al. 2014). Efforts are needed to increase fertiliser use by smallholder farmers especially in Africa where figures as low as 8 kg ha^{-1} are often mentioned (Groot 2009; Sanginga and Woomer 2009).

2.7 Conclusions

The meta-analysis suggested that to achieve any meaningful yield increases in CA systems, crop residues must be retained in situ coupled with crop rotations and increased N fertiliser inputs to offset the immobilization effect of crop residues. Moreover, CA is likely to have the largest impact in low-rainfall environments where increased infiltration of rainfall and reduced evaporative losses will be achieved by retaining crop residues. However, it is in these areas where achieving sufficient crop residues is also a challenge, particularly in mixed crop–livestock systems where crop residues are needed for livestock feed in the dry season. CA needs to be targeted and adapted to specific biophysical as well as socioeconomic circumstances of farmers for improved impact. The ability of farmers to purchase fertiliser inputs, achieve sufficient biomass production as well as produce alternative feed will allow them to practise CA and achieve large yields. Considerable efforts are needed in the future to develop nutrient management strategies tailored for the practice of CA.

References

Acharya CL, Sharma PD (1994) Tillage and mulch effects on soil physical environment, root growth, nutrient uptake and yield of maize and wheat on an Alfisol in north-west India. Soil Tillage Res 32:291–302

Adekalu KO, Okunade DA, Osunbitan JA (2006) Compaction and mulching effects on soil loss and run-off from two southwestern Nigeria agricultural soils. Geoderma 137:226–230

Adekalu KO, Olorunfemi IA, Osunbitan JA (2007) Grass mulching effect on infiltration, surface runoff and soil loss of three agricultural soils in Nigeria. Bioresour Technol 98:912–917

Aulakh MS, Manchanda JS, Garg AK, Kumar S, Dercon G, Nguyen ML (2012) Crop production and nutrient use efficiency of conservation agriculture for soybean-wheat rotation in the Indo-Gangetic Plains of Northwestern India. Soil Tillage Res 120:50–60

Baudron F, Tittonell P, Corbeels M, Letourmy P, Giller KE (2012) Comparative performance of conservation agriculture and current smallholder farming practices in semi-arid Zimbabwe. Field Crops Res 132:117–128

Borenstein M, Hedges LV, Higgins JPT, Rothstein HR (2009) Introduction to meta-analysis. Wiley, Chichester

Cadisch G, Giller KE (1997) Driven by nature: plant residue quality and decomposition. CABI, Wallingford

Castellazzi MS, Wood GA, Burgess PJ, Morris J, Conrad KF, Perry JN (2008) A systematic representation of crop rotations. Agric Syst 97:26–33

Chivenge PP, Murwira HK, Giller KE, Mapfumo P, Six J (2007) Long-term impact of reduced tillage and residue management on soil carbon stabilization: implications for conservation agriculture on contrasting soils. Soil Tillage Res 94:328–337

Chivenge P, Vanlauwe B, Gentile R, Wangechi H, Mugendi D, van Kessel C, Six J (2009) Organic and mineral input management to enhance crop productivity in central Kenya. Agron J 101:1266–1275

Chivenge P, Vanlauwe B, Six J (2011) Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. Plant Soil 342:1–30

Cook HF, Valdes GSB, Lee HC (2006) Mulch effects on rainfall interception, soil physical characteristics and temperature under Zea mays. Soil Tillage Res 91:227–235

Dam RF, Mehdi BB, Burgess MSE, Madramootoo CA, Mehuys GR, Callum IR (2005) Soil bulk density and crop yield under eleven consecutive years of corn with different tillage and residue practices in a sandy loam soil in central Canada. Soil Tillage Res 84:41–53

De Silva SHSA, Cook HF (2003) Soil physical conditions and performance of cowpea following organic matter amelioration of sand. Commun Soil Sci Plant Anal 34:1039–1058

DerSimonian R, Laird N (1986) Meta-analysis in clinical trials. Control Clin Trials 7:177–188

Dexter AR (1997) Physical properties of tilled soils. Soil Tillage Res 43:41–63

Díaz-Zorita M, Duarte GA, Grove JH (2002) A review of no-till systems and soil management for sustainable crop production in the subhumid and semiarid Pampas of Argentina. Soil Tillage Res 65:1–18

Dick WA, Van Doren DM Jr (1985) Continuous tillage and rotation combinations effects on corn, soybean, and oat yields. Agron J 77:459–465

Dickersin K (1990) The existence of publication bias and risk factors for its occurrence. J Am Med Assoc 263:1385–1389

Djigal D, Saj S, Rabary B, Blanchart E, Villenave C (2012) Mulch type affects soil biological functioning and crop yield of conservation agriculture systems in a long-term experiment in Madagascar. Soil Tillage Res 118:11–21

Egger M, Smith GD, Phillips AN (1997) Meta-analysis: principles and procedures. BMJ 315:1533–1537

Ellis F, Kutengule M, Nyasulu A (2003) Livelihoods and rural poverty reduction in Malawi. World Dev 31:1495–1510

Erenstein O (2002) Crop residue mulching in tropical and semi-tropical countries: an evaluation of residue availability and other technological implications. Soil Tillage Res 67:115–133

Erenstein O (2011) Cropping systems and crop residue management in the Trans-Gangetic Plains: issues and challenges for conservation agriculture from village surveys. Agric Syst 104:54–62

Fischer RA, Santiveri F, Vidal IR (2002) Crop rotation, tillage and crop residue management for wheat and maize in the sub-humid tropical highlands: II. Maize and system performance. Field Crops Res 79:123–137

Franzluebbers AJ, Arshad MA (1996) Soil organic matter pools during early adoption of conservation tillage in northwestern Canada. Soil Sci Soc Am 60:1422–1427

Gates S (2002) Review of methodology of quantitative reviews using meta-analysis in ecology. J Anim Ecol 71:547–557

Ghuman BS, Sur HS (2001) Tillage and residue management effects on soil properties and yields of rainfed maize and wheat in a subhumid subtropical climate. Soil Tillage Res 58:1–10

Giller KE (2001) Nitrogen fixation in tropical cropping systems. CABI, Wallingford

Giller KE, Cadisch G (1995) Future benefits from biological nitrogen fixation: an ecological approach to agriculture. Plant Soil 174:255–277

Giller KE, Cadisch G, Ehaliotis C, Adams E, Sakala WD, Mafongoya PL (1997) Building soil nitrogen capital in Africa. In: Buresh RJ, Sanchez PA, Calhoun F (eds) Replenishing soil fertility in Africa. Soil Science Society of America Special Publication No. 51, Madison, pp 81–95

Giller KE, Witter E, Corbeels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crops Res 114:23–34

Glass GV (1976) Primary, secondary, and meta-analysis of research. Educ Res 5:3–8

Govaerts B, Verhulst N, Castellanos-Navarrete A, Sayre KD, Dixon J, Dendooven L (2009) Conservation agriculture and soil carbon sequestration: between myth and farmer reality. Crit Rev Plant Sci 28:97–122

Graham PH, Vance CP (2003) Legumes: importance and constraints to greater use. Plant Physiol 131:872–877

Griffith DR, Kladivko EJ, Mannering JV, West TD, Parsons SD (1988) Long-term tillage and rotation effects on corn growth and yield on high and low organic matter, poorly drained soils. Agron J 80:599–605

Groot JJR (2009) Update of fertiliser supply and demand—sub Saharan Africa., IFA Africa Forum. IDFC, Cairo

Handayanto E, Giller KE, Cadisch G (1997) Regulating N release from legume tree prunings by mixing residues of different quality. Soil Biol Biochem 29:1417–1426

Hatfield JL, Prueger JH (1996) Microclimate effects of crop residues on biological processes. Theor Appl Climatol 54:47–59

Hernanz JL, López R, Navarrete L (2002) Long-term effects of tillage systems and rotations on soil structural stability and organic carbon stratification in semiarid central Spain. Soil Tillage Res 66:129–141

Hussain I, Olson KR, Ebelhar SA (1999) Impacts of tillage and no-till on production of maize and soybean on an eroded Illinois silt loam soil. Soil Tillage Res 52:37–49

Iragavarapu TK, Randall GW (1995) Yield and nitrogen uptake of monocropped maize from a long-term tillage experiment on a poorly drained soil. Soil Tillage Res 34:145–156

Ismail I, Blevins RL, Frye WW (1994) Long-term no-tillage effects on soil properties and continuous corn yields. Soil Sci Soc Am J 58:193–198

Jin H, Hongwen L, Xiaoyan W, McHugh AD, Wenying L, Huanwen G, Kuhn NJ (2007) The adoption of annual subsoiling as conservation tillage in dryland maize and wheat cultivation in northern China. Soil Tillage Res 94:493–502

Johansen C, Haque ME, Bell RW, Thierfelder C, Esdaile RJ (2012) Conservation agriculture for small holder rainfed farming: opportunities and constraints of new mechanized seeding systems. Field Crops Res 132:18–32

Kapusta G, Krausz RF, Matthews JL (1996) Corn yield is equal in conventional, reduced, and no tillage after 20 years. Agron J 88:812–817

Karlen DL, Berry EC, Colvin TS, Kanwar RS (1991) Twelve-year tillage and crop rotation effects on yields and soil chemical properties in northeast Iowa. Commun Soil Sci Plant Anal 22:1985–2003

Karlen DL, Wollenhaupt NC, Erbach DC, Berry EC, Swan JB, Eash NS, Jordahl JL (1994a) Long-term tillage effects on soil quality. Soil Tillage Res 32:313–327

Karlen DL, Wollenhaupt NC, Erbach DC, Berry EC, Swan JB, Eash NS, Jordahl JL (1994b) Crop residue effects on soil quality following 10-years of no-till corn. Soil Tillage Res 31:149–167

Karunatilake U, van Es HM, Schindelbeck RR (2000) Soil and maize response to plow and no-tillage after alfalfa-to-maize conversion on a clay loam soil in New York. Soil Tillage Res 55:31–42

Kihara J, Bationo A, Waswa B, Kimetu JM, Vanlauwe B, Okeyo J, Mukalama J, Martius C (2012) Effect of reduced tillage and mineral fertilizer application on maize and soybean productivity. Exp Agric 48:159–175

Kureh I, Kamara AY, Tarfa BD (2006) Influence of cereal-legume rotation on Striga control and maize grain yield in farmers' fields in the Northern Guinea savanna of Nigeria. J Agric Rural Dev Trop Subtrop 107:41–54

Lal R (1976) No-tillage effect on soil properties under different crops in western Nigeria. Soil Sci Soc Am J 40:762–768

Lal R (1978) Importance of tillage system in soil and water management in the tropics. Soil tillage and crop production. IITA, Ibadan, pp 25–32

Lal R (1997) Long-term tillage and maize monoculture effects on a tropical alfisol in western Nigeria. I. Crop yield and soil physical properties. Soil Tillage Res 42:145–160

Lal R (1998) Soil erosion impact on agronomic productivity and environment quality. Crit Rev Plant Sci 17:319–464

Lal R (2005) World crop residues production and implications of its use as a biofuel. Environ Int 31:575–584

Lekasi JK, Tanner JC, Kimani SK, Harris PJC (2003) Cattle manure quality in Maragua district, central Kenya: effect of management practices and development of simple methods of assessment. Agric Ecosyst Environ 94:289–298

Lestrelin G, Quoc HT, Jullien F, Rattanatray B, Khamxaykhay C, Tivet F (2012) Conservation agriculture in Laos: diffusion and determinants for adoption of direct seeding mulch-based cropping systems in smallholder agriculture. Renew Agric Food Syst 27:81–92

Linden DR, Clapp CE, Dowdy RH (2000) Long-term corn grain and stover yields as a function of tillage and residue removal in east central Minnesota. Soil Tillage Res 56:167–174

Lueschen WE, Evans SD, Ford JH, Hoverstad TR, Kanne BK, Orf JH, Stienstra WC, Warnes DD, Hicks DR (1991) Soybean production as affected by tillage in a corn and soybean management system: I. Cultivar response. J Product Agric 4:571–579

Marongwe LS, Kwazira K, Jenrich M, Thierfelder C, Kassam A, Friedrich T (2011) An African success: the case of conservation agriculture in Zimbabwe. Int J Agric Sustain 9:153–161

Mazvimavi K, Twomlow S, Belder P, Hove L (2008) An assessment of the sustainable uptake of conservation farming in Zimbabwe. International Crops Research Institute for the Semi-Arid Tropics: global theme on agroecosystems report no. 39. Bulawayo

Mazzoncini M, Di Bene Coli CA, Risaliti R, Bonari E (2008) Long-term tillage and nitrogen fertilisation effects on maize yield and soil quality under rainfed Mediterranean conditions: a critical perspective. In: Christensen BT, Petersen J, Schacht M (eds) Proceedings of 407 NJF Long-term field experiments—a unique platform, Askov, Denmark, pp 13–17

Mbagwu JSC (1990) Maize *(Zea mays)* response to nitrogen fertiliser on an ultisol in Southern Nigeria under two tillage and mulch treatments. J Sci Food Agric 52:365–376

Morrison JV, Prunty L, Giles JF (1985) Characterizing strength of soil crusts formed by simulated rainfall. Soil Sci Soc Am J 49:423–431

Moyo A (2003) Assessment of the effect of soil erosion on nutrient loss from granite-derived sandy soils under different tillage systems in Zimbabwe. Ph.D. thesis, University of Zimbabwe, Harare, Zimbabwe

Mupangwa W, Twomlow S, Walker S, Hove L (2007) Effect of minimum tillage and mulching on maize (*Zea mays* L.) yield and water content of clayey and sandy soils. Phys Chem Earth 32:1127–1134

Mupangwa W, Twomlow S, Walker S (2012) Reduced tillage, mulching and rotational effects on maize (*Zea mays* L.), cowpea (*Vigna unguiculata* (Walp) L.) and sorghum (*Sorghum bicolor* L. (Moench)) yields under semi-arid conditions. Field Crops Res 132:139–148

Naudin K, Scopel E, Andriamandroso ALH, Rakotosolofo M, Andriamarosoa Ratsimbazafy NRS, Rakotozandriny JN, Salgado P, Giller KE (2012) Trade-offs between biomass use and soil cover. The case of rice-based cropping systems in the Lake Alaotra region of Madagascar. Exp Agric 48:194–209

Nehanda G (2000) The effects of three animal-powered tillage systems on soil-plant-water relations and maize cropping in Zimbabwe. Department of Soil Science and Agricultural Engineering, University of Zimbabwe, Harare, p 260

Ngwira AR, Aune JB, Mkwinda S (2012a) On-farm evaluation of yield and economic benefit of short term maize legume intercropping systems under conservation agriculture in Malawi. Field Crops Res 132:149–157

Ngwira AR, Thierfelder C, Lambert DM (2012b) Conservation agriculture systems for Malawian smallholder farmers: long-term effects on crop productivity, profitability and soil quality. Renew Agric Food Syst 28(4):350–363

Noble JH (2006) Meta-analysis: methods, strengths, weaknesses, and political uses. J Lab Clin Med 147:7–20

Nyagumbo I (2002) The effects of three tillage systems on seasonal water budgets and drainage of two Zimbabwean soils under maize. PhD thesis, University of Zimbabwe, Harare, Zimbabwe

Nzuma JK, Murwira HK (2000) Improving the management of manure in Zimbabwe. IIED-Drylands Programme, London

O'Hara G, Boonkerd N, Dilworth M (1988) Mineral constraints to nitrogen fixation. Plant Soil 108:93–110

Olson KR, Ebelhar SA, Lang JM (2004) Impacts of conservation tillage systems on maize and soybean yields of eroded illinois soils. J Agron 3:31–35

Osuji GE (1984) Water storage, water use and maize yield for tillage systems on a tropical alfisol in Nigeria. Soil Tillage Res 4:339–348

Parker DT (1962) Decomposition in the field of buried and surface-applied cornstalk residue. Soil Sci Soc Am J 26:559–562

Paul BK, Vanlauwe B, Ayuke F, Gassner A, Hoogmoed M, Hurisso TT, Koala S, Lelei D, Ndabamenye T, Six J, Pulleman MM (2013) Medium-term impact of tillage and residue management on soil aggregate stability, soil carbon and crop productivity. Agric Ecosyst Environ 164:14–22

Rice CW, Smith MS, Blevins RL (1986) Soil nitrogen availability after long-term continuous no-tillage and conventional tillage corn production. Soil Sci Soc Am J 50:1206–1210

Riddle WC, Gillespie TJ, Swanton CJ (1996) Rye mulch characterization for the purpose of microclimatic modelling. Agric For Meteorol 78:67–81

Ried K (2006) Interpreting and understanding meta-analysis graphs: a practical guide. Aust Fam Phys 35:635–638

Rohrbach D, Kiala D (2007) Development options for local seed systems in Mozambique. J SAT Agric Res 3:1–28

Rosenburg MS, Adams DC, Gurevitch J (2000) Metawin. Statistical software for meta-analysis, version 2. Sinauer Associates Inc, Sunderland

Rufino MC, Rowe EC, Delve RJ, Giller KE (2006) Nitrogen cycling efficiencies through resource-poor African crop-livestock systems. Agric Ecosyst Environ 112:261–282

Rufino MC, Tittonell P, van Wijk MT, Castellanos-Navarrete A, Delve RJ, de Ridder N, Giller KE (2007) Manure as a key resource within smallholder farming systems: analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. Livest Sci 112:273–287

Rufino MC, Dury J, Tittonell P, van Wijk MT, Herrero M, Zingore S, Mapfumo P, Giller KE (2011) Competing use of organic resources, village-level interactions between farm types and climate variability in a communal area of NE Zimbabwe. Agric Syst 104:175–190

Rusinamhodzi L (2013) Nuances and nuisances: crop production intensification options for smallholder farming systems of southern Africa. Plant Sciences, Wageningen Univerity, The Netherlands, S.l., p 222

Rusinamhodzi L, Corbeels M, Van Wijk MT, Rufino MC, Nyamangara J, Giller KE (2011) A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agron Sustain Dev 31:657–673

Rusinamhodzi L, Corbeels M, Zingore S, Nyamangara J, Giller KE (2013) Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe. Field Crops Res 147:40–53

Sadler EJ, Turner NC (1993) Water relationships in a sustainable agriculture system. In: Hatfield JL, Karlen DL (eds) Sustainable agriculture systems. Lewis, Boca Raton, pp 21–46

Sanginga N, Woomer PL (2009) Integrated Soil Fertility Management in Africa: Principles, Practices and Developmental Process. CIAT, Nairobi, Kenya

Savabi MR, Stott DE (1994) Effect of rainfall interception by plant residues on the soil water. Trans Am Soc Agric Eng 37:1093–1098

Sileshi G, Akinnifesi FK, Ajayi OC, Place F (2008) Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. Plant Soil 307:1–19

Sisti CPJ, dos Santos HP, Kohhann R, Alves BJR, Urquiaga S, Boddey RM (2004) Change in carbon and nitrogen in soil under 13 years of conventional or zero tillage in southern Brazil. Soil Tillage Res 76:39–58

Sumberg J (2002) The logic of fodder legumes in Africa. Food Policy 27:285–300

Thiagalingam K, Dalgliesh N, Gould N, McCown R, Cogle A, Chapman A (1996) Comparison of no-tillage and conventional tillage in the development of sustainable farming systems in the semi-arid tropics. Aust J Exp Agric 36:995–1002

Thierfelder C, Wall PC (2012) Effects of conservation agriculture on soil quality and productivity in contrasting agro-ecological environments of Zimbabwe. Soil Use Manage 28:209–220

Thierfelder C, Cheesman S, Rusinamhodzi L (2012a) Benefits and challenges of crop rotations in maize-based conservation agriculture (CA) cropping systems of southern Africa. Int J Agric Sustain 11(2):108–124

Thierfelder C, Cheesman S, Rusinamhodzi L (2012b) A comparative analysis of conservation agriculture systems: benefits and challenges of rotations and intercropping in Zimbabwe. Field Crops Res 137:237–250

Thierfelder C, Chisui JL, Gama M, Cheesman S, Jere ZD, Bunderson WT, Eash NS, Rusinamhodzi L (2013a) Maize-based conservation agriculture systems in Malawi: long-term trends in productivity. Field Crop Res 142:47–57

Thierfelder C, Mombeyarara T, Mango N, Rusinamhodzi L (2013b) Integration of conservation agriculture in smallholder farming systems of southern Africa: identification of key entry points. Int J Agric Sustain 11 (4):317–330

Thierfelder C, Mwila M, Rusinamhodzi L (2013c) Conservation agriculture in eastern and southern provinces of Zambia: long-term effects on soil quality and maize productivity. Soil Tillage Res 126:246–258

Thornton PK, Herrero M (2001) Integrated crop-livestock simulation models for scenario analysis and impact assessment. Agric Syst 70:581–602

Trenbath BR (1993) Intercropping for the management of pests and diseases. Field Crops Res 34:381–405

Valbuena D, Erenstein O, Homann-Kee Tui S, Abdoulaye T, Claessens L, Duncan AJ, Gérard B, Rufino MC, Teufel N, van Rooyen A, van Wijk MT (2012) Conservation agriculture in mixed crop–livestock systems: scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. Field Crops Res 132:175–184

Van Doren DM Jr, Triplett GB Jr, Henry JE (1976) Influence of long term tillage, crop rotation, and soil type combinations on corn yield. Soil Sci Soc Am 40:100–105

Vanlauwe B, Wendt J, Giller KE, Corbeels M, Gerard B, Nolte C (2014) A fourth principle is required to define conservation agriculture in sub-Saharan Africa: the appropriate use of fertilizer to enhance crop productivity. Field Crops Res 155:10–13

Vogel H (1993) Tillage effects on maize yields, rooting depth and soil water and water content on sandy soils in Zimbabwe. Field Crops Res 33:367–384

Wibberley J (1996) A brief history of rotations, economic considerations and future directions. Aspects Appl Biol 47:1–10

Wilhelm WW, Wortmann CS (2004) Tillage and rotation interactions for corn and soybean grain yield as affected by precipitation and air temperature. Agron J 96:425–432

Wilhelm WW, Schepers JS, Mielke LN, Doran JW, Ellis JR, Stroup WW (1987) Dryland maize development and yield resulting from tillage and nitrogen fertilization practices. Soil Tillage Res 10:167–179

World Bank (2007) International development association on a country assistance strategy of the World Bank for the Republic of Malawi. Washington, DC

Zingore S, Delve RJ, Nyamangara J, Giller KE (2008) Multiple benefits of manure: the key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms. Nutr Cycl Agroecosyst 80:267–282

Chapter 3
Weed Management in Conservation Agriculture Systems

V.P. Singh, K.K. Barman, Raghwendra Singh and A.R. Sharma

Abstract Conservation agriculture (CA) does have several advantages over conventional tillage (CT)-based agriculture in terms of soil health parameters. However, weeds are the major biotic constraint in CA, posing as a great challenge towards its adoption. The presence of weed seeds on the upper soil surface, due to no tillage operation, leads to higher weed infestation in CA, and so far, herbicides are the only answer to deal with this problem. Overreliance of herbicide use showed its consequence in terms of environmental pollution, weed shift and herbicide resistance development in weeds. Growing herbicide-tolerant crops using nonselective herbicides could be a broad-spectrum weed management technique to tackle weed shift, but the same is being resulted in the evolution of more problematic 'super weed'. These observations indicate the need of integrated weed management technologies involving the time tested cultural practices, viz. competitive crop cultivars, mulches, cover crops, intercrops with allelopathic potential, crop diversification, planting geometry, efficient nutrient, water management, etc., along with limited and site-specific herbicide application. The modern seeding equipment, e.g. 'Happy Seeder' technology, that helps in managing weeds through retention of crop residues as mulches, besides providing efficient seeding and fertilizer placement, shows the promise of becoming an integral part of CA system.

Keywords Allelopathy · Herbicide-tolerant crop · Herbicide · Soil seed bank · Weed shift · Weed ecology · Intercropping · Crop cultivar · Mulch

3.1 Introduction

The rapid increase in the use of chemical fertilizers and pesticides, farm mechanization, along with high-yielding crop varieties accelerated modern agriculture and initiated the 'green revolution' era. However, this growth in conventional agriculture was based on capital depletion and massive additions of external inputs, e.g. energy, water, chemicals, etc. Consequently, the transformation of 'traditional

---

V.P. Singh (✉) · K.K. Barman · R. Singh · A.R. Sharma
Directorate of Weed Science Research, 482004 Jabalpur, India
e-mail: vpsinghnrcws@gmail.com

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_3

animal-based subsistence farming' to 'intensive chemical- and tractor-based conventional agriculture' led to a multiplicity of issues associated with sustainability of these production practices. Clean cultivation involving removal or burning of residues after harvesting led to continuous mining of nutrients and moisture from the soil profile under conventional agriculture systems. Intensive tillage, bare soil with no soil cover, indiscriminate use of insecticides and pesticides, and excessive and imbalanced use of chemical fertilizers further deteriorated soil health leading to declining input-use efficiency and factor productivity. These concerns compelled researchers to critically look at the agronomic management in conventional crop production systems with an overall strategy of (i) producing more food with reduced risks and costs, (ii) increasing input-use efficiency, viz. land, labour, water, nutrients and pesticides, (iii) improving and sustaining the quality of the natural resource base and (iv) mitigating emissions and improving resilience to changing climates. These have led to the innovations of conservation agriculture (CA)-based crop management technologies, which are said to be more efficient as they address the emerging problems and improve production and income (Gupta and Seth 2007). CA has increased crop yields compared with conventional tillage (CT) in many countries, viz. the USA, Australia, Mexico, Canada and Brazil (Dick et al. 1991; D'Emden et al. 2009; Govaerts et al. 2005; Malhi and Lemke 2007; Saturnino and Landers 2001). For example, a sizable yield increases and income stability have led to wide-scale adoption of CA among farming community in Brazil (Saturnino and Landers 2001). Similarly, farmers in developing countries, like India and Pakistan, have also started to practice some CA technologies. For example, zero-till (ZT) wheat in the rice–wheat system is currently being practiced on >3 million ha in north-western parts of the Indo-Gangetic Plains. Globally, the concepts and technologies for CA are being practiced on more than 154 million ha with the major countries being the USA, Brazil, Argentina, Canada and Australia (FAO 2014).

Farmers have benefited from the adoption of this technology in many ways, viz. (i) reduced cost of production (Malik et al. 2005; RWC-CIMMYT 2005); (ii) enhanced soil quality, i.e. soil physical, chemical and biological conditions (Hoyle and Murphy 2006; Hobbs et al. 2008; Govaerts et al. 2009; Jat et al. 2009a; Kaschuk et al. 2010; Gathala et al. 2011b); (iii) increased C sequestration and build-up in soil organic matter (Blanco-Canqui and Lal 2009; Saharawat et al. 2012); (iv) reduced incidence of weeds (Malik et al. 2005; Chauhan et al. 2007b); (v) increased water and nutrient-use efficiencies (Blanco-Canqui and Lal 2009; Kaschuk et al. 2010; Jat et al. 2012; Saharawat et al. 2012); (vi) increased system productivity (Gathala et al. 2011a); (vii) advances in sowing date (Malik et al. 2005; Hobbs et al. 2008); (viii) greater environmental sustainability (Sidhu et al. 2007; Pathak et al. 2011); (ix) increased residue breakdown with legumes in the rotation (Fillery 2001); (x) reduced temperature variability (Blanco-Canqui and Lal 2009; Jat et al. 2009b; Gathala et al. 2011b) and (xi) opportunities for crop diversification and intensification (Jat et al. 2005).

CA addresses the complete agricultural system—the 'basket' of conservation-related agricultural practices. Three key principles have been identified, viz. minimal soil disturbance, permanent residue cover and planned crop rotations, which are considered essential to its success (Hobbs et al. 2008; Reicosky and Saxton 2007). Weeds being one of the most difficult management issues within this system in several countries (Lafond et al. 2009; Giller et al. 2009), it was advocated to include integrated weed management as a fourth component that is crucial for successful implementation of CA (Farooq et al. 2011a). A study on the adoption and impacts of ZT wheat in the rice–wheat systems of Pakistan's Punjab province showed not only a stagnation in diffusion but also there has been a significant proportion of disadoption (Farooq et al. 2007). It was noted that the ZT adopters, non-adopters and disadopters differ significantly in terms of their resource bases; and disadopters also had more problems in controlling weeds. About 39 % ZT users of this region had the perception often increased in weed problems due to ZT, with 37 % reporting no effect and 24 % a decrease (Tahir and Younas 2004). Crop–weed competition and management strategies also affect CA yields and sustainability; as it was argued by Giller et al. (2009), weeds are the 'Achilles heel' of CA.

3.2 Weed Problems in CA

Tillage affects weeds by uprooting, dismembering and burying them deep enough to prevent emergence. Ploughing also moves weed seeds both vertically and horizontally, and changes the soil environment, thereby promoting or inhibiting weed seed germination and emergence. Compared to CT, the presence of weed seeds is more in the soil surface under ZT, which favours relatively higher weed germination. Hence, reduction in tillage intensity and frequency, as practiced under CA, generally increases weed infestation. Further, changes from conventional to conservation farming practices often lead to a weed flora shift in the crop field, which in turn dictate the requirements of new weed management technologies involving various approaches, viz. preventive measures, cultural practices (tillage, crop residues as mulches, intercropping, competitive crop cultivars, herbicide-tolerant cultivars, planting dates, crop rotations, etc.) and herbicides, is of paramount importance in diversified cropping systems. It may be noted that weed control in CA depends upon herbicides and agronomic practices, and limited tillage in minimum till systems (Lafond et al. 2009).

3.2.1 Weed Ecology

In CA systems, the presence of residue on the soil surface may influence soil temperature and moisture regimes that affect weed seed germination and emergence patterns over the growing season (Spandl et al. 1998; Teasdale and Mohler 2000; Bullied et al. 2003). There is mounting evidence that retention of preceding crop residues suppresses the germination and development of weeds in minimum tillage systems, thus enhancing system productivity. Gill et al. (1992) advocated residue

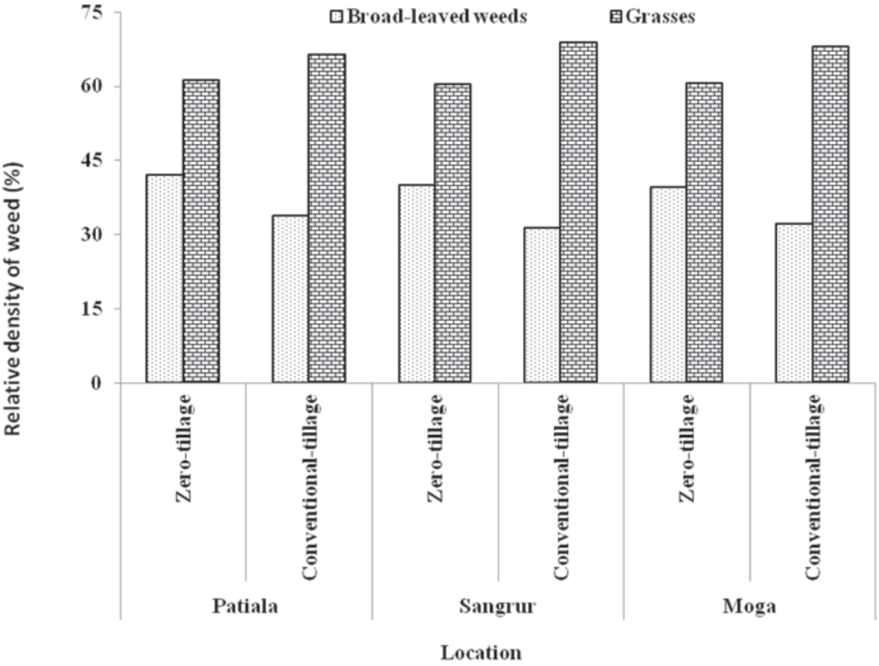


Fig. 3.1 The effect of tillage on the relative density of grasses and broad-leaved weeds in different geographical locations of Punjab, India. (Source: Brar and Walia 2007)

mulching as a practical method for early season weed control in minimum tillage systems for smallholder farmers in Zambia. Similarly, in Zimbabwe, retention of the previous season's maize residues significantly suppressed weed biomass in ripped plots compared to the un-mulched treatment (Vogel 1994). In the USA, work by Buhler et al. (1996) showed that retaining maize residue often reduced the density of some annual weeds in untilled soils, except during the drought year when maize residue retention resulted in increased weed growth. Thus, the changes in the soil microenvironment that result from surface mulching (Erenstein 2003) can result in either suppression in germination of annual weeds (Bilalis et al. 2003) or increased weed growth of some weed species (Chauhan et al. 2006). The composition of weed species and their relative time of emergence differ between CA systems and soil-inverting CT systems. Brar and Walia (2007) reported that CT favoured the germination of grassy weeds in wheat compared with ZT in a rice–wheat system across different geographical locations of Indian Punjab, while the reverse was true in respect to broad-leaved weeds (Fig. 3.1).

Some weed seeds require scarification and disturbance for germination and emergence, which may be enhanced by the types of equipment used in soil-inverting tillage systems than by conservation tillage equipment. The timing of weed emergence also seems to be species dependent. Bullied et al. (2003) found that species such as common lamb's quarters (*Chenopodium album* L.), field pennycress (*Thlaspi arvense* L.),

Table 3.1 Infestation of various weed species under ZT compared to CT

Weed species	Relative infestation	Reference
Awnless barnyard grass	Increase	Mishra and Singh (2012a), Chauhan and Johnson (2009), Kumar and Ladha (2011)
Rice flat sedge	Increase	Mishra and Singh (2012a), Kumar and Ladha (2011)
Indian sorrel	Increase	Chhokar et al. (2007)
Nut sedge	Increase	Curran et al. (1996), Kumar and Ladha (2011)
Field bindweed	Increase	Shrestha et al. (2003)
Johnson grass	Increase	Curran et al. (1996)
Common knotgrass	Increase	Gill and Arshad (1995)
Crabgrass	Increase	Tuesca et al. (2001), Chauhan and Johnson (2009)
Burclover	Increase	Mishra and Singh (2012a)
Goat weed	Increase	Chauhan and Johnson (2009)
Crowfoot grass	Increase	Chauhan and Johnson (2009)
Little canary grass	Decrease	Chhokar et al. (2007, 2009), Franke et al. (2007), Malik et al. (2002)
Wild oat	Decrease	Mishra and Singh (2012a)
Lamb's quarters	Decrease	Mishra and Singh (2012a)
Bermuda grass	Decrease	Bhattacharyya et al. (2009)
Italian ryegrass	Decrease	Scursoni et al. (2014)
Yellow starthistle	Decrease	Scursoni et al. (2014)

green foxtail (*Setaria viridis* (L.) Beauv.), wild buckwheat (*Polygonum convolvulus* L.) and wild oat (*Avena ludoviciana* L.) emerged earlier in a CA system than in a CT system. However, redroot pigweed (*Amaranthus retroflexus* L.) and wild mustard (*Sinapis arvensis* L.) emerged earlier in the CT system. Changes in weed flora make it necessary to study the composition of weed communities under different environmental and agricultural conditions.

3.2.2 *Weed Dynamics*

Certain weed species germinate and grow more profusely than others under a continuous ZT system. As a consequence, a weed shift occurs due to the change from a CT to a ZT system (Table 3.1). Mishra and Singh (2012a) observed a higher emergence of awnless barnyard grass (*Echinochloa colona* (L.) Link) and rice flatsedge (*Cyperus iria* L.) under continuous zero tillage (ZT–ZT) than continuous conventional (CT–CT) systems due to their small seed size, which failed to germinate when buried deeply in CT. A shift in weed populations towards small-seeded annuals is generally observed under conservation tillage systems (Childs et al. 2001). Contrary to this, in spite of small seed size, little canary grass has shown a remarkable reduction in their population under ZT compared to CT system in the Indo-Gangetic Plains. This may be attributed to (i) higher soil strength in ZT because of crust development in the absence of tillage, which can mechanically impede seedling emergence (Chhokar et al. 2007), (ii) less soil temperature fluctuation under ZT (Gathala et al. 2011b) or (iii) relatively lower levels of light stimuli, N mineralization and gas exchange under ZT, all of which are known to stimulate germination of many weed species under CT system (Franke et al. 2007).

Shifts in weed populations towards perennials have also been observed in conservation tillage systems (Derksen et al. 1993; Froud-Williams 1988). Perennial weeds thrive in reduced or no-tillage (NT) systems (Curran et al. 1996) because the root system is not disturbed and herbicides used to control annual weeds are not effective on perennial weeds. Perennial monocots are considered a greater threat than perennial dicots in the adoption of reduced tillage systems. Unlike annuals, many perennial weeds can reproduce from several structural organs other than seeds. For example, purple nutsedge (*Cyperus rotundus* L.), tiger grass (*Saccharum spontaneum* L.) and Johnson grass (*Sorghum halepense* (L.) Pers.) generally reproduce from underground plant storage structures, i.e. tubers or nuts and rhizomes. Conservation tillage may encourage these perennial reproductive structures by not burying them to depths that are unfavourable for emergence or by failing to uproot and kill them. Weed species shifts and losses in crop yield as a result of increased weed density have been cited as major hurdles to the widespread adoption of CA. Crop yield losses in CA due to weeds may vary depending on weed dynamics and weed intensity.

3.2.3 Weed Seed Bank

The success of the CA system depends largely on a good understanding of the dynamics of the weed seed bank in the soil. A weed seed bank is the reserve of viable weed seeds present in the soil. The seed bank consists of new seeds recently shed by weed plants as well as older seeds that have persisted in the soil for several years. The seed bank builds up through seed production and dispersal, while it depletes through germination, predation and decay. Different tillage systems disturb the vertical distribution of weed seeds in the soil, in different ways. Under ZT, there is little opportunity for the freshly rained weed seeds to move downwards in the soil and hence remain mostly on the surface, with the highest concentration in the 0–2 cm soil layer, and no fresh weed seed is observed below 5 cm soil depth (Fig. 3.2). Under conventional and minimum tillage systems, weed seeds are distributed throughout the tillage layer with the highest concentration of weed seeds in the 2–5 cm soil layer. Mouldboard ploughing buries most weed seeds in the tillage layer, whereas chisel ploughing leaves the weed seeds closer to the soil surface. Similarly, depending on the soil type, 60–90 % of weed seeds are located in the top 5 cm of the soil in reduced or NT systems (Swanton et al. 2000). As these seeds are at a relatively shallow emergence depth, they are likely to germinate and emerge more readily with suitable moisture and temperature than when buried deeper in conventional systems.

A small percentage of the fresh weed seeds that shattered in the crop field actually emerge as seedlings due to seed predation (Westerman et al. 2003). Therefore,

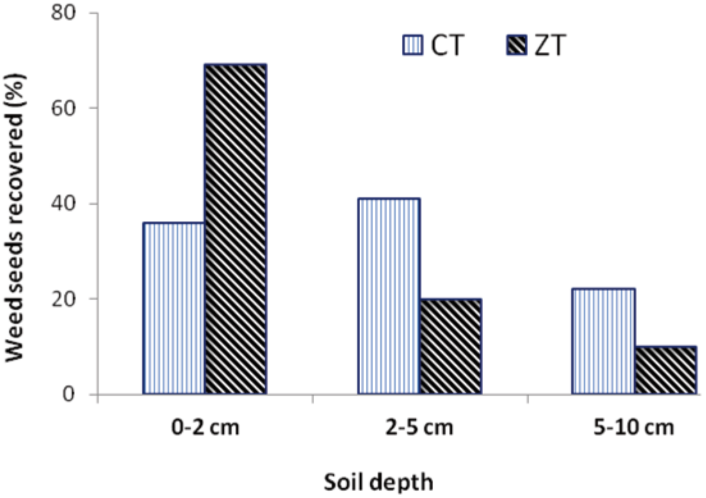


Fig. 3.2 Vertical distribution of weed seeds in soil under different tillage systems. *CT* conventional tillage, *ZT* zero tillage

unlike in conventional practice of burial that makes weed seeds largely unavailable, seed predation could be important in NT systems where newly produced weed seeds remain on the soil surface and are most vulnerable to surface-dwelling seed predators like mouse, ants and other insects (Hulme 1994; Baraibar et al. 2009; Chauhan et al. 2010). For example, reduced seed input from 2000 to 360 seeds m^{-2} as a result of post-dispersal predation of barnyard grass (*Echinochloa crus galli* P. Beauv.) was reported by Cromar et al. (1999). Further, CA systems may favour population growth of harvester ants by not damaging the nests, and may minimize the redistribution of weed seeds stored in superficial chambers (Baraibar et al. 2009).

Weed seed predation can be encouraged to manage weeds in CA as it can substantially reduce the size of the weed seed bank. Such approaches are possible with no additional costs to growers. Predators prefer certain kinds of seeds, e.g. the ant species; the tropical fire ant (*Solenopsis geminate*) prefers grass weed seeds over broadleaf weed seeds (Risch and Carroll 1986). Vertebrate and large invertebrate predators usually prefer larger seeds. Such selectivity in seed consumption may result in shifts in weed population. The seed size and ease of consumption are factors influencing the preference of granivores, particularly ants.

3.3 Weed Management

It is important to understand weed management as it is the major hindrance in CA-based production systems (Lafond et al. 2009; Giller et al. 2009). Weed control in CA is a greater challenge than in conventional agriculture because there is no weed seed burial by tillage operations (Chauhan et al. 2012). The behaviour of weeds and their interaction with crops under CA is complex and not fully understood. The weed species that germinate in response to light are likely to be more problematic in CA. In addition, perennial weeds become more challenging in this system (Vogel 1994; Shrestha et al. 2006). In the past, attempts to implement CA have often resulted in a yield penalty because reduced tillage failed to control weed interference (Muliokela et al. 2001). However, the recent development of post-emergence broad-spectrum herbicides provides an opportunity to control weeds in CA (Nalewaja 2001). Crop yields can be similar for conventional and conservation tillage systems if weeds are controlled and crop stands are uniform (Mahajan et al. 2002). Various approaches that may be employed to successfully manage weeds in CA systems are described here.

3.3.1 Preventive Measures

Preventive weed control encompasses all measures taken to prevent or arrest the introduction and arrest of weeds (Rao 2000). Weed seeds resembling the shape and size of crop seeds are often the major source of contamination in crop seeds. Contamination usually occurs at crop harvesting if the life cycle of crop and weeds is of similar duration. Preventive measures are the first and most important steps to manage weeds, in general and especially under CA, as the presence of even a small quantity of weed seeds may cause a serious infestation in the forthcoming seasons. The various preventive measures (Das 2014) include the following:

- Use weed-free crop seed.
- Prevent the dissemination of weed seeds/propagules from one area to another or from one crop to another by using clean machinery/implements, screens to filter irrigation water and restricting livestock movement.
- Use well-decomposed manure/compost so that it does contain any viable weed seeds.
- Remove weeds near irrigation ditches, fencerows, rights of way, etc. prior to seed setting.
- Mechanically cut the reproductive part of weeds prior to seed rain.
- Implement stringent weed quarantine laws to prevent the entry of alien invasive and obnoxious weed seeds/propagules into the country.

3.3.2 Cultural Practices

A long-term goal of sustainable and successful weed management is not to merely control weeds in a crop field, but rather to create a system that reduces weed establishment and minimizes weed competition with crops. Further, since environmental protection is a global concern, the age-old weed management practices, viz. tillage, mulching, inter-cultivation, intercropping, cover crops, crop rotation/diversification and other agro-techniques—once labelled as uneconomical or impractical—should be relooked and given due emphasis in managing weeds under CA. One of the pillars of CA is ground cover with dead or live mulch, which leaves less time for weeds to establish during fallow or a turnaround period. Some other common problems under CA include emergence from recently produced weed seeds that remain near the soil surface, lack of disruption of perennial weed roots, interception of herbicides by thick surface residues and a change in the timing of weed emergence. Shrestha et al. (2002) concluded that long-term changes in weed flora are driven by an interaction of several factors, including tillage, environment, crop rotation, crop type and timing and type of weed management practice.

3.3.2.1 Tillage

Tillage has long been an essential component of conventional agricultural systems and it is the most important among the traditional means of weed management in agriculture. The effect of primary tillage on weeds is mainly related to the type of implement used and to tillage depth. These factors impact the weed seed and propagule distribution over the soil profile, and therefore directly affect the number of weeds that can emerge in a field. Differential distribution of seeds in the soil profile subsequently leads to changes in weed population dynamics. Weed seeds buried deep germinate but fail to emerge due to the thick soil layer above it, resulting in death of the weed seedling. Tillage stimulates weed germination and emergence of many weed seeds through brief exposure to light (Ballard et al. 1992). ZT wheat in a rice–wheat system reduces little seed canary grass (*Phalaris minor* Retze) infestation, which is highly competitive and can cause drastic wheat yield reductions under heavy infestation (Fig. 3.3), but it favours the infestation of toothed dock (*Rumex dentatus* L.) and cheeseweed mallow (*Malva parviflora* L.; Chhokar et al. 2007) and wild oat (Mishra et al. 2005). Cheeseweed mallow is favoured by shallow seed burial and scarification (Chauhan et al. 2007a; Chhokar et al. 2007) leading to more weed population under a ZT system.

A reduction in weed density occurs if the weed seed bank depletion is greater than weed seed shedding. However, this situation is rarely achieved with NT. Therefore, weed densities in NT systems are generally higher (Table 3.2) than in plough-based systems (Cardina et al. 1991; Spandl et al. 1999, Mishra et al. 2012). The findings of a long-term experiment with four tillage systems adopted for 12 consecutive years in a continuous winter wheat or a pigeon bean–winter wheat rotation showed that total weed seedling density in NT, minimum tillage using rotary harrow (15 cm depth) and chisel ploughing (45 cm depth) was relatively higher in the 0–15-, 15–30-, and 30–45-cm soil layers, respectively (Bàrberi and Lo Cascio 2001). But NT may affect seedling emergence of some particular weed species under a particular cropping system.

The impact of tillage on weed infestation varies depending upon the weed seed morphology vis-a-vis agro-climatic situations. For example, infestation of little seed

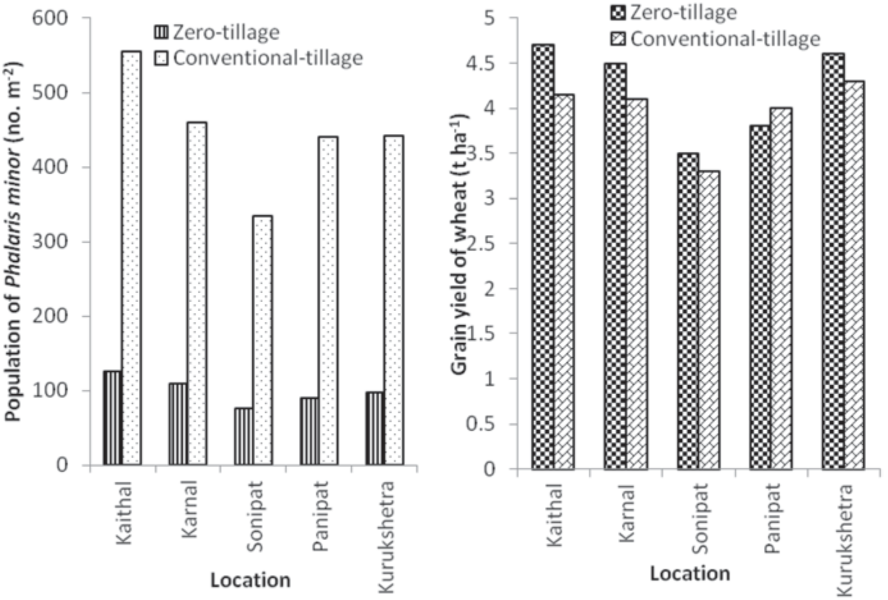


Fig. 3.3 The effect of tillage on wheat yield and population of *Phalaris minor* at different locations in Haryana, India. (Source: Gupta and Seth 2007)

canary grass in the crop sown with ZT was 21–33 % less compared to the conventional method of sowing (Singh 2007). However, the benefit of ZT in reducing the *P. minor* population was relatively lower under late-sown conditions (Lathwal and Malik 2005). In a black cotton soil, ZT planting reduced the infestation of little seed canary grass and lamb's quarter but increased the problem of wild oat under transplanted rice–wheat system (Mishra et al. 2005). On the other hand, a DSR–wheat system with continuous ZT reduced the population of wild oat and lamb's quarter in wheat (Mishra and Singh 2012a). Some authors (e.g. Derksen et al. 1993) observed a small difference in weed populations between conventional and ZT fields, while relatively less weeds were reported in ZT wheat from the Indo-Gangetic Plains (Hobbs and Gupta 2013; Singh et al. 2001; Malik et al. 2002). Variation in the composition of the soil seed bank and prevailing agro-climatic conditions among the site is responsible for such observations. Mulugeta and Stoltenberg (1997) noticed a several-fold increase in weed seedling emergence due to tillage. The impact of tillage vis-à-vis weed infestation in the crop field is influenced by the previous cropping systems. Continuous ZT increased the population density of awnless barnyard grass and rice flatsedge in rice, but rotational tillage systems significantly reduced the seed density of these weeds. Continuous ZT with effective weed management using recommended herbicide + hand weeding was more remunerative and energy efficient (Mishra and Singh 2012b). Similarly, ZT with effective weed control was more remunerative in soybean–wheat system (Mishra and Singh 2009).

Table 3.2 Effect of tillage on total weed density, dry matter of weeds in different locations in India

Location	Weed density (no. m^{-2})			Weed dry weight (g m^{-2})			Reference
	CT	ZT	FIRB	CT	ZT	FIRB	
Faizabad	–	–	–	14.40	20.2	–	Yadav et al. (2005)
Palampur	270.0	283.3	241.0	131.3	139.4	107.3	Chopra and Angiras (2008a)
Palampur	228.0	245.0	203.0	113.0	126.0	91.0	Chopra and Angiras (2008b)
Karnal	83.2	62.0	–	18.1	20.7	–	Chopra and Chopra (2010)
Delhi	137.9	168.5	–	15.6	19.1	–	Tuti and Das (2011)
Jabalpur	155.0	213.0	–	–	–	–	Mishra and Singh (2012b)
Hisar	89.3	87.4	96.1	30.1	26.5	32.4	Jat et al. (2013b)

CT conventional tillage, *ZT* zero till, *FIRB* furrow-irrigated raised-bed system

Furrow-irrigated raised-bed system (FIRBS) and ridge tillage systems are the form of reduced and conservation tillage, respectively, that appear to overcome weed control problems associated with conventional and NT systems (e.g. Chopra and Angiras 2008a, b; Mishra and Singh 2012a; Sharma et al. 2004). Besides improved weed management, FIRBS has been found to improve input-use efficiency. Chauhan et al. (1998) obtained reasonably good control of little seed canary grass in wheat on raised beds but broad-leaved weeds in furrows were not controlled. The problem with little seed canary grass was less as the weed seeds lying on top of the raised beds failed to germinate as the top of bed dried quickly. This method also facilitated mechanical weeding as the area in the furrows could easily be cultivated and even manual weeding could be done. When crop plants are 40 cm tall, soil is excavated from the furrows and is moved back to the ridge crest, thereby affecting weeds, weed control and the crop–weed interaction (Forcella and Lindstorm 1998). However, changes in weed communities were influenced more by location and year than by tillage systems (Derksen et al. 1993).

3.3.2.2 Stale Seedbed

Seedbed preparation can contribute to weed management by affecting weed seed dynamics and seedling densities at planting (Buhler et al. 1997). In CT, disking or ploughing at intervals achieves control of initial weed populations before crop sowing. Cultivation for seedbed preparation affects the weeds in two ways: (i) it destroys the emerged vegetation after primary tillage and (ii) it stimulates weed seed germination and consequent seedling emergence and reallocation of seeds towards the soil surface; this phenomenon could be exploited to manage weeds through application of the stale (false) seedbed technique.

NT stale seedbed practice can help to reduce weed pressure in CA systems. In this technique, the field is irrigated 10–15 days prior to actual seeding to favour the germination of weed seeds lying on the soil surface. Emerged weeds are then destroyed by the application of non-selective herbicides like glyphosate, paraquat or ammonium glufosinate. It depletes the seed bank in the surface layer of the soil and reduces subsequent weed emergence. Where light rains occur for an extended period before the onset of the monsoon or irrigation is available, it may be possible to kill several flushes of weed growth before planting. To ensure success, cropping should be delayed until the main flush of emergence has passed. However, this practice may not be exploited where the season available for crop growth is short, which may reduce the yield potential of the crop. The main advantage of the stale seedbed practice is that the crop emerges in a weed-free environment, with a competitive advantage over late-emerging weed seedlings. The practice of false seedbed technique may decrease weed infestation in crops by 80 % or more compared to standard seedbed preparation (Van der Weide et al. 2002).

The stale seedbed technique is widely used in many countries to manage weedy rice and awnless barnyard grass in rainfed rice (Fischer 1996). Stale seedbeds reduce weed populations in direct-seeded rice (Rao et al. 2007) and may be especially effective when combined with NT practices (Chauhan et al. 2006). Pittelkow et al. (2012) reported that NT stale seedbed practice was effective at reducing the population of sedges and grasses, but not for controlling redstem weeds. This practice is very effective in ZT wheat in the north-western Indo-Gangetic Plains (Mahajan et al. 1999).

3.3.2.3 Crop Residues

Crop residues present on the soil surface can influence weed seed germination and seedling emergence by interfering with sunlight availability and creating physical impedance, as well as improving soil and moisture conservation and soil tilth (Locke and Bryson 1997). Residues on the soil surface can vary greatly in dimension, structure, distribution pattern and spatial heterogeneity. Weed biology, and the quantity, position (vertical or flat, and below- or above-weed seeds) and allelopathic potential of the crop residues may influence weed germination (Chauhan et al. 2006).

Soil cover using crop residues is a useful technique to manage weeds. Weed emergence generally declines with increasing residue amounts. However, the emergence of certain weed species is also favoured by some crop residue at low amounts (Mohler and Teasdale 1993). For example, germination and growth of wild oat and animated oat (*Avena sterilis* L.) may get stimulated with low levels of wheat residue. High amounts of crop residues have implications for weed management in CA through reduced and delayed weed emergence. The crop gets competitive advantage over weeds due to delayed weed emergence, which results in relatively less impact on crop yield loss. Further, late emerging weed plants produce less number of seeds than the early emerging ones (Chauhan and Johnson 2010). For example, the residue of Russian vetch (*Vicia villosa* Roth) and rye (*Secale cereale* L.) reduced total weed density by more than 75 % compared with the treatments with no residue (Mohler and Teasdale 1993). The presence of rye mulch in corn significantly reduced the emergence of white lamb's quarter, hairy crabgrass (*Digitaria sanguinalis* (L.) Scap.), common purslane (*Portulaca oleracea* L.) (Mohler and Calloway 1992) and total weed biomass (Mohler 1991). However, crop residues alone may not be able to fully control weeds, e.g. hairy-vetch residue suppressed

Table 3.3 Some important weed biomass reducing intercropping systems

Main crop(s) + smother crop	Weed suppression effect stronger than main crop(s) alone
Alfalfa + barley	Moyer (1985)
Alfalfa + oats	Lanini et al. (1991)
Faba bean + red clover	Palada et al. (1983)
Maize + Italian ryegrass/perennial ryegrass	Samson et al. (1990)
Maize + red clover/hairy vetch	Palada et al. (1983)
Maize/cassava + cowpea/peanut/sweet potato	Unamma et al. (1986), Dubey (2008)
Pigeonpea + urdbean/mungbean/soybean/cowpea/sorghum	Ali (1988)
Rice + *Azolla pinnata*	Janiya and Moody (1984)
Sorghum + cowpea/mungbean/peanut/soybean	Abraham and Singh (1984)
Chickpea + mustard	Rathi et al. (2007)

weeds early in the growing season but herbicide was needed to achieve season-long weed control (Teasdale 1993). The effectiveness of crop residue to reduce weed emergence also depends upon the nature of weed species to be controlled. Chauhan and Abugho (2012) reported that 6 t ha^{-1} crop residues reduced the emergence of jungle rice, crowfoot grass and rice flatsedge by 80–95 % but only reduce the emergence of barnyard grass by up to 35 %.

The increased moisture content and decreased temperature of soil due to the presence of crop residue may increase the germination of some weed species (Young and Cousens 1999). In dry land areas, the amount of available crop residue may be insufficient to substantially suppress weed germination and growth (Chauhan et al. 2006; Chauhan and Johnson 2010). Further, certain crops like oilseeds and pulses produce less biomass than cereals. Therefore, the effects of crop residue on the weed population depend on the region, crop and rainfall. There is a need to integrate herbicide use with residue retention to achieve season-long weed control. In high-residue situations, it is important that residue does not hinder crop emergence.

3.3.2.4 Intercropping

Intercropping involves growing a smother crop between rows of the main crop such that the competition for water or nutrients does not occur. Intercrops help to effectively pre-empt resources used by weeds and suppress weed growth (Table 3.3), and hence can be used as an effective weed control strategy in CA. Intercropping of short-duration, quick-growing and early-maturing legume crops with long-duration and wide-spaced crops leads to quick ground cover, with higher total weed suppressing ability than sole cropping. This technique enhances weed control by increasing shade and crop competition. Like cover crops, intercrops increase the ecological diversity in a field. In addition, they often compete better with weeds for light, water and nutrients. Success of intercropping relies on the best match between the requirements of the component species for light, water and nutrients, which increases resource use. Many short-duration pulses like cowpea, greengram and soybean effectively smother weeds without reducing the yield of the main crop. For instance, total weed growth reduced under intercropping combinations of chickpea + mustard over the sole chickpea crop without losing productivity of the main crop (Rathi et al. 2007). Similar observations were also recorded by Dubey (2008) under a maize + cowpea intercropping system. Compared with the sole crop, increased canopy cover and decreased light availability for weeds in maize–legume intercropping was responsible for the reduction in weed density and dry matter (Kumar et al. 2010). However, intercropping cowpea in maize under CA had the greatest impact on weeding activities in the farmer's field, with labour hours increasing by 40 % due to the additional precision required for weeding compared with maize-only fields (Lai et al. 2012).

One of the principles of CA is to include green manuring, with its bioherbicidal characteristics (Lazzeri and Manici 2000) and weed-smothering capabilities, along with an additional benefit of adding biomass to soil. Sesbania can be grown with rice as a coculture to suppress weeds (Torres et al. 1995), and in addition to weed control it can also fix large amounts of N (Ladha et al. 2000). *Sesbania* intercropping for 25–30 days in a dry-seeded rice under CA followed by killing of *Sesbania* using 2,4-D or mechanical means was effective in controlling weeds, but the contribution from N fixation was small because of intercropping and short growth duration (Singh et al. 2007). This practice was also a highly beneficial resource conservation technology for soil and water conservation, weed control and nutrient supplementation in maize (Sharma et al. 2010). The *Sesbania* option also provides an alternative to crop residue.

3.3.2.5 Cover Cropping

Ground cover with dead or live mulch, allowing less time for weeds to establish during fallow or turnaround period, is an important component of CA technology. The inclusion of cover crops in a rotation between two main crops is a good preventive measure when developing a weed management strategy. Cover crops are fundamental and sustainable tools to manage weeds, optimize the use of natural resources and reduce water runoff, nutrient leaching and soil erosion (Lal et al. 1991). Competition from a strong cover crop can virtually shut down the growth of many annual weeds emerging from seeds. Aggressive cover crops can even substantially reduce growth and reproduction of perennial weeds that emerge or regenerate from roots, rhizomes or tubers, and are more difficult to suppress. Cover crop effects on weeds largely depend upon the species and weed community composition. Weed suppression is exerted partly through resource competition for light, nutrients and water during the cover crop growing cycle, and partly through physical and chemical effects that occur when cover crop residues are left on the soil surface as a dead mulch or ploughed down (Mohler and Teasdale 1993; Teasdale and Mohler 2000).

Weed pressure in CA can be reduced by including short-duration legume crops, e.g. cowpea, greengram, *Sesbania*, etc., during the fallow period between harvesting wheat and planting rice. This practice facilitates emergence of weeds during the legume period (stale seedbed effects) and reduces the population during the rice season (Kumar et al. 2012). The density of annual ryegrass plants in a wheat crop decreased to one third after green-manured lupins compared with the harvested lupin crop, and to <20% after green manured oats and mustard (Gill and Holmes 1997; Anderson 2005). In India, *Sesbania* grown as a cover crop produced green biomass up to 30 t ha^{-1} in 60 days, and controlled most of the weeds (Mahapatra et al. 2004).

Growing green manure or cover crops in the summer season or as a relay crop to efficiently suppress weed growth is a cost and labour efficient practice. Therefore, green manures are sometimes also called the herbicides of small farmers. Perennial grasses such as cogon grass (*Imperata cylindrical* (L.) P. Beauv.) and Bermuda grass (*Cynodon dactylon* (L.) Pers.), and other problem weeds like *Striga* spp. and Siam weed (*Chromolaena odorata* (L.) King & H. E. Robins.) can be suppressed by one or two seasons of cover crops. In CA, a number of cover crops, including legumes (alfalfa, *Sesbania,* sunhemp, clover, soybean, lupin and cowpea) and non-legumes (sunflower, rapeseed, rye, buckwheat and sudan grass), could be exploited to suppress and smother various weeds.

3.3.2.6 Crop Diversification

Crop rotation involves alternating different crops in a systematic sequence on the same land. It limits the build-up of weed populations and prevents weed shifts as the weed species tend to thrive in a crop with similar growth requirements. Different crops require different cultural practices, which help to disrupt the growing cycle of weeds and prevent any weed species to dominate. Johnson grass was the predominant weed in a continuous maize system but could be controlled by rotating with cotton (Dale and Chandler 1979). In monocropping systems, several weed species persist and expand rapidly. Cropping sequences provide varying patterns of resource competition, allelopathic interference, soil disturbance and mechanical damage, and thus provide an unstable environment that prevents the proliferation and dominance of a particular weed, and discourages growth and reproduction of troublesome weed species. The prolonged cultivation of the rice–wheat system in north-western India has resulted in increased population of sedges and grassy weeds. The diversification of the system even for a short period and intensification by including summer legumes/green manuring decreased the weed menace (Singh et al. 2008).

Certain crop-associated weed species, e.g. barnyard grass in rice, wild oat and little seed canary grass in wheat, dodder (*Cuscuta* spp.) in alfalfa, etc., may be discouraged by following a rotation of crops with contrasting growth and cultural requirements. Crop rotation is an effective practice for management of little seed canary grass because selection pressure is diversified by changing patterns of disturbances (Bhan and Kumar 1997; Chhokar and Malik 2002). Changing from rice–wheat to any other sequence not involving rice reduces the population of little seed canary grass in wheat. In the case where sugarcane is taken followed by one ratoon, little seed canary grass population goes down considerably (Bhan and Singh 1993). Replacing wheat with other crops like Egyptian clover (*Trifolium alexandrinum* L.), potato (*Solanum tuberosum* L.), sunflower (*Helianthus annuus* L.) and annual rape (*Brassica napus* L.) for 2–3 years in a rice–wheat cropping system significantly reduced the population of little seed canary grass (Brar 2002). A rice–wheat rotation suppressed the establishment and growth of wild oat in wheat, while a maize–wheat rotation resulted in a gradual build-up of wild oat. Integration of red clover in continuous maize resulted in a higher weed seed bank or emergence of several summer annual weeds compared to maize alone. In contrast, integration of red clover in the sweet corn–pea–wheat rotation led to a 96 % reduction in the seed bank density of winter annuals (Brainard et al. 2008). The inclusion of sesame in several cropping sequences reduced the aerial growth of nutsedge (Varshney 2000).

Parasitic weeds can be successfully managed by rotating the host crop with trap crops, as they induce germination of weed seeds but are themselves not parasitized. The added advantage of the crop rotation is that it also allows growers to use new herbicides that may control problematic weeds.

3.3.2.7 Cultivar Competitiveness

Crop species and cultivars differ in their competitiveness with weeds. The expression of competitive advantage of crop genotypes against weeds is strongly influenced by environmental conditions. The competitive ability of a crop variety is reflected either by its ability to reduce weed growth and seed production or to tolerate weed interference and maintain higher levels of grain yield. Different genotypes of the same crop may differ in their competitive ability against weeds due to varying morphological traits (Table 3.4). Although there is conflicting evidence as to which crop characteristics contribute most to competitiveness, several studies have highlighted the role of rapid germination and emergence, vigorous seedling growth, rapid leaf expansion, rapid canopy development, extensive root systems (Frick 2000; Rasmussen and Rasmussen 2000), and also production of allelopathic compounds by the crop (Baghestani et al. 1999). However, mostly the crop competitiveness is enhanced by vigorous growth that reduces light quality and quantity beneath the crop canopy (Buhler 2002).

A quick-growing and early canopy-producing crop is a better competitor against weeds than crops lacking these characters. Seed size within a species also influences competition through vigorous growth of plants from larger seeds. Use of weed-suppressing genotypes may therefore reduce the need for direct weed control measures. However, not all traits that give a crop-competitive advantage against weeds can be exploited. For example, plant height is usually correlated with weed suppression but it is often negatively correlated with crop yield and positively correlated with sensitivity to lodging. Competitive ability can also be related to the production and release of allelochemicals. There is considerable allelopathic potential in some rice varieties against weeds, which indicates potential for using crop genotype choice as a cultural method for weed management (Olofsdotter 2001).

Table 3.4 Dominant crop characteristics for weed competitiveness

Crop	Weed-competitive cultivar	Crop characteristics accounted for competitiveness	Weeds suppressed	References
Rice	PR 108	Leaf area index (LAI)	Mixed flora	Ghuman et al. (2008)
Rice	PI 312777	Allelopathic compound	Barnyard grass	Gealy et al. (2014)
Wheat	Sonalika, Sujata, HD 2285, PBW 343	LAI; biomass production	Wild oat	Mishra and Singh (2008)
Wheat	Saleem−2000 Ghaznavi−98	Biomass production	Wild oat	Khan et al. (2008)
Wheat	PBW 154, WH 435, PBW 343	LAI	Mixed flora	Chauhan et al. (2001), Walia (2002)
Corn	AG 1051	LAI; shoot and root biomass	Mixed flora	Silva et al. (2011)
Oat	Blaze	Biomass production; allopathic compound	Lamb's quarters	Grimmer and Masiunas (2005)
Barley	Aura 6	Plant height	Field pansy, chickweed	Auskalniene et al. (2010)
Canola and mustard	Yellow mustard	Quick emergence; biomass accumulation; plant height	Mixed flora	Beckie et al. (2008)
Canola	F1 hybrids	Plant height; vigorous canopy growth	Wild oat	Zand and Beckie (2002)
Sugarcane	B41227	Sprawling type	Mix flora	Yirefu et al. (2012)

Negligible emphasis has been given on breeding cultivars for competitive ability with weeds. Major focus given so far on breeding for yield and quality may have inadvertently eliminated competitive traits in crops (Hall et al. 2000; Lemerle et al. 2001). Therefore, development of weed-competitive cultivars without sacrificing yield potential is essential for integrated weed management. Future breeding and variety-testing programs should take such factors of crop-competitive ability with weeds into consideration.

3.3.2.8 Planting Geometry

Planting density and pattern modify the crop canopy structure, and in turn influence weed smothering ability. Narrow row spacing brings variation in microclimate, viz. light intensity, evaporation and temperature at soil surface. The establishment of a crop with a more uniform and dense plant distribution results in better use of light and water, and leads to greater crop-competitive ability. Crops grown in narrow rows start competing with weeds at an earlier stage than those in wide rows because of more rapid canopy closure and better root distribution. Narrow row widths and a higher seeding density will reduce the biomass of late-emerging weeds by reducing the amount of light available for weeds located below the crop canopy. Reduced growth of weeds was reported due to increased population and decreased spacing in rice (Ghuman et al. 2008). The leaf area index (LAI) of closely planted rice increased but photosynthetically active radiation (PAR) decreased, and grain yield was significantly higher than the widely spaced crop. Similarly, bidirectional sowing and closer row spacing (15 cm) were quite effective in suppressing the growth of little seed canary grass in wheat (Azad et al. 1988).

3.3.2.9 Allelopathy

There has long been observed an inhibitive response by plant species to certain neighbouring plants. The Greek philosopher and botanist, Theophrastus, noted this effect from cabbage as early as 300 BC (Willis 1985). In 1937, Austrian botanist, Hans Molisch, described this phenomenon as allelopathy, which he determined to be the result of biochemical interactions between plants (Putnam and Duke 1978). For instance, rapeseed, mustard and radish contain a number of compounds called glucosinolates that break down into powerful volatile allelochemicals called isothiocyanates during residue decomposition (Boydston and Hang 1995; Al-Khatib 1997; Uremis et al. 2009). These chemicals may suppress weed growth for several weeks or months. Several *Brassica* spp. could be useful allelopathic cover crops because these are winter hardy and can be grown almost anywhere. Rye residue contains good amounts of allelopathic chemicals, viz. isothiocyanate benzyl and isothiocyanate allyl. When left undisturbed on the soil surface, these chemicals leach out and prevent germination of small-seeded weeds. The magnitude of allelopathic influence depends on allelopathic crops as well as on target weeds in a crop–weed environment.

Crop allelopathy against weeds may be exploited as a useful tool to manage weeds under CA. Several crops are able to strongly suppress weeds, such as alfalfa, barley, black mustard, buckwheat, rice, sorghum, sunflower and wheat, by exuding allelochemical compounds either from living plant parts or from decomposing residues (Tesio and Ferrero 2010). The growing need for sustainable agricultural systems has necessitated increased cover crop research to better utilize these covers for effective weed control. Thus, it is necessary to understand the role of allelopathy for weed suppression within various cover crops (Burgos and Talbert 2000; Khanh et al. 2005; Price et al. 2008; Walters and Young 2008). Allelopathic interference on weeds is generally higher when grasses or crucifers are used as cover crops than when legumes are used (Blum et al. 1997). The use of allelopathic traits from crops or cultivars with important weed inhibition qualities, together with common weed control strategies, can play an important role in the establishment of sustainable CA systems, for instance, significant inhibitory effects of sunflower residues incorporated into field soil on the total number and biomass of weeds growing in a wheat field (Alsaadawi et al. 2012). Similarly, mulching of allelopathic plant residues, inclusion of certain allelopathic crops in cropping rotation or as intercrop or as cover crop may be practiced for weed management in CA (Table 3.5). These multiple

Table 3.5 Weed control through allelopathic mulches, crop residues incorporation, cover crops and intercropping

Allelopathic source	Application mode	Crop	Weed species	Reduction in weeds dry matter (%)	Yield increase (%)	Reference
Sorghum	Soil incorporation	Wheat	Little seed canary grass, lamb's quarter	48–56	16–17	Cheema and Khaliq (2000)
	Surface mulch	Cotton	Desert horse purslane (*Trianthema portulacastrum* L.), field bind weed (*Convolvulus arvensis*), bermuda grass	5–97	69–119	Cheema et al. (2000)
	Allelopathic extract	Cotton	Desert horse purslane	29	45	Cheema et al. (2000)
		Wheat	Little seed canary grass, Indian fumitory (*Fumaria indica* L.), lamb's quarter, toothed dock, nutsedge	35–49	11–20	Cheema and Khaliq (2000)
Sunflower + rice + *Brassica*	Soil incorporation	Maize	Desert horse purslane	60	41	Khaliq et al. (2010)
Cotton + sorghum	Intercropping	–	Desert horse purslane, field bind weed	92	24	Iqbal et al. (2007)
	Allelopathic extract	Wheat	Little seed canary grass, wild oat	2–16	2–6	Cheema et al. (2000)
Rye	Cover crop	–	Common purslane (*Portulaca oleracea* L.), pigweed	–	–	Nagabhushana et al. (2001)

approaches of allelopathic application have potential to act as natural weed-controlling agents with varying degree of success depending upon environmental and managerial factors (Farooq et al. 2013). Allelopathy thus offers a viable option for weed management in CA (Farooq et al. 2011b).

3.3.2.10 Sowing Time

Planting time influences the occurrence and manifestation of weed species. Thus, sowing time should be manipulated in such a way that ecological conditions for the germination of weed seeds are not met. In the north-western part of the Indo-Gangetic Plains, farmers advance wheat seeding by 2 weeks to get a head start over the noxious weed little seed canary grass and provide higher yield (Singh et al. 1999). Malik et al. (1988) reported more weed infestation in early-/timely-sown chickpea than when sowing was delayed. Similarly, delayed sowing of lentil and chickpea reduced the infestation of *Orobanche* (Linke and Saxena 1989). However, this is not a viable approach in all cases as delayed sowing may also result in reduced yield. Sinha et al. (1988) reported that early sowing and closer row spacing not only reduced weed growth and increased dry matter accumulation but also resulted in lower seed yield of pigeonpea. Lenssen (2008) reported that early planting of barley resulted in a small accumulation of weed biomass, and no weed seed production, while delayed planting resulted in decreased forage yield with high amounts of weed biomass and seed production, especially in ZT.

3.3.2.11 Nutrient and Water Management

The competitive interactions between crops and weeds get altered with increasing levels of soil fertility as both crops and weeds compete for the same nutrient pool. With added nutrients, resource use by weeds often increases more rapidly than by crops, resulting in a greater ability of weeds to compete for other resources. Nitrogen, the major nutrient for which the plants compete, should be banded close to the crop row, thus enhancing crop accessibility to the nutrient. Increasing rates of fertilizer application encourage more weed growth than crop growth if no weed control measure is followed (Sharma 1997). Under this situation, it is better to apply fertilizers at a lower rate than needed to maximize yields. Pre-sowing N fertilization can increase the competitive ability of the crop plant against weeds, particularly in crops with high growth rates at early stages. However, this effect is modulated by the type of weeds prevailing in a field. For example, in sunflower grown in Mediterranean conditions, a pre-sowing application of synthetic N fertilizer increased the suppression of late-emerging weeds such as lamb's quarter, black nightshade (*Solanum nigrum* L.) and common cocklebur (*Xanthium strumarium* L.) compared to a split application, i.e. 50% each at pre-sowing and top dressing (Paolini et al. 1998). In contrast, the same technique resulted in a competitive advantage for early-emerging weeds like wild mustard. Anticipation or delay of top-dressing N application in sugar beet increased crop-competitive ability with dominance of late- or early-emerging weeds respectively (Paolini et al. 1999). Das and Yaduraju (2007) observed that an increasing N level decreased the infestation of little seed canary grass but had no effect on wild oat in wheat. Inclusion of green manures not only adds nutrients and organic matter to the soil but also suppresses weed growth due to its dense foliage cover on the ground surface and the incorporation of existing weeds in the soil. In order to offset the likely initial setback to the ZT crop due to poor crop stand and vigour, it is advocated to use a 25% higher dose of nutrients, especially in crops like wheat (Sharma et al. 2012). Further, a greater proportion of N (up to 75%) can be applied as basal because top dressing of N may not be as beneficial especially under residue-retained and rainfed conditions.

In addition to fertilization, irrigation has a significant role in crop–weed competition. It offers selective stimulation to germination, growth and establishment of one plant over the others, and results in varying weed dynamics and competition in crops (Das and Yaduraju 1999). Dry weight of little seed canary grass was higher when wheat was irrigated at CRI and CRI + flowering stage than at other stages.

3.3.3 Mechanical Measures

Farm mechanization plays a vital role for the success of CA in different agro-ecologies and socio-economic farming groups. It ensures timeliness, precision and quality of field operations; reduces production costs; saves labour; reduces weather risk under the changing climatic scenario; improves productivity, environmental quality and sustainability and generates rural employment on on-farm and off-farm activities (Ladha et al. 2009, Saharawat et al. 2011). Reduced labour and machinery costs are economic considerations that are frequently given as additional reasons to use CA practices. Compared to intensive tilled conventional rice–wheat system, ZT systems require much lesser energy and give higher energy output to input ratio as well as system productivity (Gangwar et al. 2006; Mishra and Singh 2012a; Kumar et al. 2012). Mishra and Singh (2012a) reported lower cost of cultivation as well as higher net returns and benefit: cost ratio in ZT rice–wheat systems. Similarly, in ZT maize–wheat cropping system, low cost of cultivation, minimum energy usage, higher water productivity, higher net returns and enhanced energy input to output ratio were reported by Ram et al. (2010).

3.3.3.1 Farm Machinery

CA is essentially machine driven and suitable farm machinery is required for land levelling, sowing, fertilization, weeding, irrigation, harvesting and other operations. Hence, the availability of suitable farm machineries is of paramount importance for adoption of this technology by farmers. For example, Farooq et al. (2007) noticed that access to ZT drills contributed towards the adoption pattern of the ZT wheat technology in Pakistan’s Punjab province. ‘NT’ seed drill invented by Morton C. Swanson in 1975 was a great milestone in the history of modern day CA. It has allowed the farmers to sow seeds without tilling the land. Direct drilling with ZT drill is a practice that addresses the issues of labour, energy, water, soil health, etc. (Gathala et al. 2011a; Jat et al. 2013a). However, this machine faces difficulties if crop stubbles are in high quantity, a situation that commonly occurs in CA systems. ‘Happy Seeder’ technology—an improved version of the NT seed drill and initially developed for direct drilling of wheat into rice residues (typically 5–9 t ha^{-1} of anchored and loose straw) in north-west India—is a recent novel approach which combines stubble mulching and seed-cum-fertilizer drilling functions. The stubble is cut and picked up in front of the sowing tynes, which engage almost bare soil, and is deposited behind the seed drill as surface mulch. In addition to the benefits of direct drilling and retaining organic matter, the mulch also assists in moisture conservation and weed control. Observations from farmers’ fields across Indian

Punjab showed that the Happy Seeder (ZT) and rotavator (reduced tillage) are efficient methods for control of weeds as well as for in situ management of paddy straw (ACIAR 2013; Kang 2013). The average reduction in the weed population in the Happy Seeder-sown wheat crop over the rotavator and farmer's practice was 26.5 and 47.7 %, respectively. However, the reduction in weed population in the rotavator-sown crop was 29.3 % over the farmer's practice (Singh et al. 2013). Advanced versions of the Happy Seeder, viz. turbo seeder, post-consumer recycled (PCR) planter and easy seeder are also being developed for more efficient sowing and fertilizer placement. These machines could be used under CA systems for both seeding as well as managing weeds.

3.3.3.2 Land Levelling

Laser land levelling, an integral component of CA, provides uniform moisture distribution to the entire field and ensures a proper crop stand and growth with reduced weed infestation. Unlevelled fields frequently exhibit patchy crop growth with higher weed infestation. Compared to an unlevelled field, weed management in a laser-levelled field is relatively easy, and requires less labour for manual weeding operations due to less weed infestation. Weed populations in wheat were recorded under precisely levelled fields (200 no. m^{-2}) compared to traditional levelled fields (350 no. m^{-2}; Jat et al. 2003). Precision land levelling may reduce up to 75 % of the labour requirement needed for weeding operations (Rickman 2002).

3.3.4 Chemical Weed Management

Herbicides are an integral part of weed management in CA. The use of herbicides for managing weeds is becoming popular because they are cheaper than traditional weeding methods, require less labour, tackle difficult-to-control weeds and allow flexibility in weed management. However, to sustain CA systems, herbicide rotation and/or integration of weed management practices is preferred as continuous use of a single herbicide over a long period of time may result in the development of resistant biotypes, shifts in weed flora and negative effects on the succeeding crop and environment. In CA, the diverse weed flora that emerges in the field after harvesting the preceding crop must be killed using non-selective herbicides like glyphosate, paraquat and ammonium glufosinate. Non-selective burn-down herbicides can be applied before or after crop planting but prior to crop emergence in order to minimize further weed emergence.

Unlike in a conventional system, crop residues present at the time of herbicide application in CA systems may decrease the herbicide's effectiveness as the residues intercept herbicide droplets and reduce the amount of herbicide that reaches the soil surface. Proper selection of herbicide formulations for application under CA is necessary to increase their efficacy. For example, preemergence herbicides applied as granules may provide better weed control than liquid forms in NT systems. Some herbicides intercepted by crop residues in CA systems are prone to volatilization, photodegradation and other losses. The extent of loss, however, varies depending upon chemical properties and formulations. Herbicides with high vapour pressure, e.g. dinitroanilines are susceptible to volatilization from the soil surface. Climatic conditions and herbicide application methods significantly affect herbicide persistence under CA systems (Curran et al. 1992). Crop residues can intercept 15–80 % of the applied herbicides which may result in reduced efficacy of herbicides in CA systems (Chauhan et al. 2012). Weed control by herbicide application was better in the CT system (80–96 %) than in the ZT system (50–61 %; Chauhan and Opena 2012). Choosing an appropriate herbicide and timing of its application is critical in CA systems as weed control under NT systems varies with weed species and herbicides used.

Preemergence herbicides may not be as efficient in controlling weeds in CA systems due to the presence of crop residues which can bind to soil-applied herbicides and favour the weed seedlings to escape the applied herbicides. For example, barnyard grass was fully controlled by pendimethalin and oxadiazon when applied on bare soil (without residue cover); however, some seedlings survived when these herbicides were applied in the presence of residue cover (Chauhan and Abugho 2012).

Several selective postemergence herbicides, some of which are low dose and high-potency molecules, are now available to effectively manage weeds in major field crops like rice, wheat, soybean etc. under CA (Table 3.6). The effectiveness of postemergence herbicides may be reduced by the presence of crop residues. Wolf et al. (2000) observed that the quantity of spray lodged on smooth pigweed (*Amaranthus hybridus* L.) was reduced by 38–52 % by standing wheat stubble depending upon the spray travel speed. Hartzler and Owen (1997) suggested that postemergence herbicides should be applied once the weeds become established, since the timing of weed emergence is less uniform in CA systems than in CT systems.

3.3.5 Integrated Weed Management

Considering the diversity of weed problems in CA systems, no single method of weed control, viz. cultural, mechanical or chemical, provides the desired level of weed control. Therefore, a combination of different weed management strategies should be evaluated to widen the weed control spectrum and efficacy for sustainable crop production. The integrated weed management (IWM) system is not meant to replace selective, safe and efficient herbicides but is a sound strategy to encourage judicious use of herbicides along with other safe, effective, economical and eco-friendly control measures. The use of clean crop seeds and seeders and field sanitation (weed-free irrigation canals and bunds) should be integrated for effective weed management. Weed control efficiency of applied herbicides and crop competitiveness against weeds could be improved by combining good agronomic practices,

Table 3.6 Promising herbicides for weed control in different field crops under conservation agriculture (CA)

Herbicide	Dose (g ha^{-1})	Time of application	Remarks
a. Rice			
Azimsulfuron	35	20 DAS/DAT*	Annual grasses and some broad-leaved weeds
Bispyribac-sodium	25	15–25 DAS/DAT	Annual grasses and some broad-leaved weeds
Chlorimuron + metsulfuron	4	15–20 DAS/DAT	Annual broad-leaved weeds and sedges
2,4-D	500–750	20–25 DAS/DAT	Annual broad-leaved weeds and sedges
Pendimethalin	1000–1250	6–7 DAS/DAT	Annual grasses and some broad-leaved weeds. Ensure sufficient moisture at the time of application
Pyrazosulfuron	25–30	20–25 DAS/DAT	Annual grasses and some broad-leaved weeds
Fenoxaprop-p-ethyl	60–70	30–35 DAS/DAT	Annual grasses especially Echinochloa spp.
Fenoxaprop-p-ethyl + 2,4-D	60–70 + 500	20–25 DAS/DAT	Annual grasses and broad-leaved weeds
Fenoxaprop-p-ethyl + almix	60–70 + 20	20–25 DAS/DAT	Annual grasses, broad-leaved weeds and sedges
Bensulfuron + pretilachlor (londex power)	10,000	0–3 DAS/DAT	Annual grasses and broad-leaved weeds
b. Wheat			
Clodinafop propargyl	60	25–30 DAS	Annual grasses specially wild oat
2,4-D	500–750	20–25 DAS	Annual broad-leaved weeds and sedges
Metribuzin	175–200	30–35 DAS	Annual grasses and broad-leaved weeds
Sufosulfuron	25	25–30 DAS	Annual broad-leaved weeds and grasses
Pendimethalin	1000–1250	0–3 DAS	Annual grasses and some broad-leaved weeds. Ensure sufficient moisture at the time of application
Sufosulfuron + metsulfuron	30 + 2	25–30 DAS	Annual grasses, broad-leaved weeds and sedges
Mesosulfuron + idosulfuron	12 + 2.4	20–25 DAS	Annual grasses, broad-leaved weeds and sedges
Isoproturon + metsulfuron	1000 + 4	20–25 DAS	Annual grasses and broad-leaved weeds
c. Soybean			
Chlorimuron ethyl	6–9	15–20 DAS	Annual grasses, broad-leaved weeds and sedges
Fenoxaprop	80–100	20–25 DAS	Annual grasses
Fenoxaprop + chlorimuron	80 + 6	20–25 DAS	Annual grasses and broad-leaved weeds
Imazethapyr	100	20–25 DAS	Annual grasses and broad-leaved weeds
Metribuzin	35–525	0–3 DAS	Annual grasses and broad-leaved weeds

* *DAS* Days after sowing; *DAT* Days after transplanting

timeliness of operations, fertilizer and water management and retaining crop residues on the soil surface. For example, effective ryegrass control (up to 97 %) has been observed in a NT stubble-retained system by using soluble herbicides and minimal disturbance seeders (Crabtree 1999). Similarly, integrating superior genotypes with a high seeding rate and early weed control led to a 40 % yield increase compared with the combination of weaker genotype, low seeding rate and delayed weed control (Harker et al. 2003). Approaches such as stale seedbed practice, uniform and dense crop establishment, use of cover crops and crop residues such as mulch, crop rotations and practices for enhanced crop competitiveness with a combination of pre- and postemergence herbicides should be integrated to develop sustainable and effective weed management strategies under CA systems.

3.4 Herbicide-Tolerant Crops

Biotech crops have become the fastest adopted crop technology in the history of modern agriculture. Since commercialization in 1996, the biotech crop area has progressively grown for the past 17 years. Weeds of different types emerge in the field; therefore, farmers have to use several types of narrow-spectrum herbicides to control them. This weed control method can be very costly. Weed management, however, could be simplified by spraying a single broad-spectrum herbicide over the field anytime during the growing season. The important contribution of biotechnology has been the development of herbicide-tolerant crops (HTCs) for effective weed management. Several crops have been genetically modified for resistance to non-selective herbicides. These transgenic crops contain genes that enable them to degrade the active ingredient in an herbicide and render it harmless. They give farmers the flexibility to apply herbicides only when needed, to control total input of herbicides and to use herbicides with preferred environmental characteristics. Farmers can therefore easily control weeds during the entire growing season and have more flexibility in choosing times for spraying. HTCs offer farmers a vital tool in fighting weeds and are compatible with CA systems. HTCs of soybean, corn, canola and cotton are being grown on a large scale. In 2012, herbicide-tolerant soybean alone occupied 80.7 m ha, which is nearly half of the global biotech area.

CA systems have been adopted on a large scale worldwide; and the expansion in the area under CA was accelerated due to the introduction of HTCs (Cerdeira and Duke 2006). For instance, introduction of HT soybeans encouraged rapid adoption of CA practices in the USA (Ammann 2005). In fact, these two technologies have registered a double-digit growth in area with one complementing the other. Weed management in ZT-sown HTCs is much easier and post-emergence application of non-selective herbicides like glyphosate provides a weed-free environment without harming the crop plant. This results in considerably less costs for different operations such as ploughing, sowing, fertilization as well as weed control. Farmers in developing countries can benefit from relatively higher yields with reduced costs by adopting such technologies. There is a need to address some of the technologies and apprehension about GM crops in general and HTCs in particular, for practicing CA-based technologies.

Compared to selective herbicides, the use of non-selective herbicides in HTCs offers several potential advantages:

- Application of fewer herbicides to a crop.
- Reduced number of sprays in a season.
- Flexibility—possible to control weeds later in the plant's growth.
- Saving labour and fuel because of less spraying.
- Reduced soil compaction because of less spraying by tractors.
- Ability to control weeds that previously could not be controlled in a particular crop because of the absence of a suitable selective herbicide.
- Use of low-toxicity compounds which do not remain active in the soil. This may help farmers to manage weeds without the need for environmentally suspect herbicides.
- Ability to use NT or conservation-till systems, with consequent benefits to soil structure and organisms.
- Excellent weed control and hence higher crop yields.

The potential for weed resistance to a specific herbicide is always a concern with herbicide programs, and this concern increases with HTCs in CA systems. For instance, many farmers in the USA have adopted CA with repeated use of glyphosate on glyphosate-resistant crops (Givens et al. 2009). Some HTCs are becoming volunteer weeds and causing segregation and introgression of herbicide-resistant traits in weed populations (Owen and Zelaya 2004). Beckie and Warwick (2010) reported that oilseed rape transgenes can survive for several years even if all cultivars with the conferred trait are removed from the area. There are also other apprehensions that HTCs can lead to:

- Increased herbicide use,
- Adverse effects on biodiversity on the farm,
- Promotion of development of herbicide-resistant weeds due to overreliance on a single herbicide or a group of closely related herbicides. Horseweed (*Conyza Canadensis* (L.) Cronquist) has reportedly developed resistance to glyphosate in ZT roundup-ready corn–soybean rotations in the USA (Mueller et al. 2003),
- Gene drift from HTCs to similar species may confer resistance to their wild relatives which can become a serious weed in the crop, constituting a new phenomenon of intensification, the 'transgenic treadmill' (Binimelis et al. 2009),
- Poor application of herbicides can cause serious damage to non-HTC crop cultivars in adjoining areas.

Therefore, HTCs should not be considered as a stand-alone component of weed management. An integrated weed management strategy should be used to ensure that this important weed management tool remains profitable and environmentally sound over a long period of time.

Table 3.7 Two sides of the conservation agriculture (CA) system. (Source: Adopted from Huggins and Reganold 2008; Sharma et al. 2012)

Payoffs	Trade-offs
Timeliness of operations	Mindset: transition from conventional farming to no-till farming is difficult
Reduced soil erosion	Relatively knowledge intensive
Water conservation	CA equipment not available locally and adds to cost for transport
Improved soil health	Reliance on herbicides and their efficacy
Reduced fuel and labour costs	Prevalence of weeds, disease and other pests may shift in unexpected ways
Reduced sediment and fertilizer pollution in lakes and streams	Reduced crop yield in initial year if not properly practiced
Carbon sequestration	Need to refine nutrient and water management practices
Climate smart production practices	

3.5 Constraints in Adopting CA Systems

CA is not a panacea to solve all agricultural production constraints but offers potential solutions to break productivity barriers and sustain natural resources and environmental health. Despite several benefits, the adoption of CA systems by farmers in developing countries is still in its infancy as they require a total paradigm shift from conventional agriculture with regard to crop management. CA technologies are essentially herbicide driven, machine driven and knowledge driven, and therefore require vastly improved expertise and resources for adoption in large areas. For wider adoption of CA, there is an urgent need for researchers and farmers to change their mindset and explore these opportunities in a site- and situation-specific manner for local adaptation. The current major barriers to the spread of CA systems are: (i) lack of trained human resources, (ii) lack of suitable machinery and no quality control mechanism in place for CA machinery, (iii) competing use of crop residues in rainfed areas, (iv) weed management strategies, particularly for perennial species, (v) localized insect and disease infestation and (vi) likelihood of lower crop productivity if site-specific component technologies are not adopted. Several factors including biophysical, socio-economic and cultural limit the adoption of this promising innovation of the twentieth century by resource-poor, small land farmers in south and south-east Asia (Lal 2007). Despite several payoffs, there are also many trade-offs to the adoption of CA systems (Table 3.7).

3.6 Future Outlook

Development of integrated weed, disease or pest control strategies is paramount under CA systems. Weed management research is lacking under conditions of CA. Effort is needed to understand weed, disease and insect responses to NT soil and microclimate conditions on a long-term basis. Research should be conducted on soil biological aspects and the rhizosphere environment under contrasting soils and crops with particular emphasis on optimizing fertilizer management under CA. Other areas of research include machinery development for local farming systems, sowing into crop residues, understanding herbicide performance in crop residues with reduced tillage, changes in nutrient cycling and nitrogen demand, leaf and root diseases, etc. More focus on the influence of residue and weed management components in CA is required.

Since herbicides cannot be eliminated from NT, crop management, degradation pathways, adsorption–desorption and transport processes of herbicides remain important research areas. Further, overreliance on herbicides in a CA system is concerning from an environmental point of view. A major research effort in this area should be towards developing economically viable strategies to prevent and manage herbicide resistance. Inclusion of allelopathic crop cultivars for managing weeds in the CA systems could be a strategy to avoid development of herbicide resistance. Crop cultivars differ significantly in their ability to inhibit the growth of certain weed species. To date, progress has been made in understanding the genetics of crop allelopathic activity. However, more research is needed to thoroughly understand the genetic control of allelopathic activity. Several genes might be involved in regulating the production and exudation of allelochemicals. Concerted efforts using advances in plant biotechnology will help to unveil the genetics of this trait. A breeding program to transfer the allelopathic genes into modern cultivars to enhance their allelopathic activity for weed suppression may help to reduce overreliance on herbicides.

There is a need for analysis of factors affecting adoption and acceptance of NT agriculture among farmers. A lack of information on the effects and interactions of minimal soil disturbance, permanent residue cover, planned crop rotations and integrated weed management, which are key CA components, can hinder CA adoption (Farooq et al. 2011a). This is because these interactions can have positive and negative effects depending on regional conditions. The positive impacts should be exploited through systems research to enhance CA crop yields. Information has mostly been generated on the basis of research trials, but more on-farm-level research and development is needed. Farmers' involvement in participatory research and demonstration trials can accelerate adoption of CA, especially in areas where CA is a new technology.

3.7 Conclusions

CA is a complex suite of 'new' resource-efficient technologies. It is possible to achieve the same or even higher yields with CA compared with CT. Altering tillage practices changes the depth of weed seeds in the soil, which play a role in weed species shifts and affect the efficacy of control practices. ZT systems cause a shift in weed flora, and may result in the emergence of perennial weeds like purple nut sedge, Bermuda grass and Johnson grass in most crops; and others like cheeseweed mallow and toothed dock in wheat. Restricting tillage also reduces weed control options and increases reliance on herbicides; consequently, evolvement of weed resistance to herbicides has become a serious and escalating problem for many CA farmers worldwide. The use of HT crops further aggravates the situation. ZT along with residue has beneficial effects on soil moisture, temperature moderation and weed control. CA is a machine-, herbicide- and management-driven agriculture for its successful adoption. Integrated weed management involving chemical and non-chemical methods (residue, cover crops, varieties, etc.) is essential for the success of CA systems in the long term.

References

Abraham CT, Singh SP (1984) Weed management in sorghum-legume intercropping systems. J Agric Sci Camb 103:103–115

ACIAR (2013) Fine-tuning the Happy Seeder technology for adoption in northwest India. http://www.aciar.gov.au/project/cse/2006/124dt. Accessed 2 Dec 2013

Ali M (1988) Weed suppressing ability and productivity of short duration legumes intercropped with pigeonpea under rainfed conditions. Tropical Pest Manage 34:384–387

Al-Khatib K, Libbye C, Boydston R (1997) Weed suppression with *Brassica* green manure crops in green pea. Weed Sci 45:439–445

Alsaadawi IS, Sarbout AK, Al-Shamma LM (2012) Differential allelopathic potential of sunflower (*Helianthus annuus* L.) genotypes on weeds and wheat (*Triticum aestivum* L.) crop. Arch Agron Soil Sci 58:1139–1148

Ammann K (2005) Effects of biotechnology on biodiversity: herbicide-tolerant and insect-resistant GM crops. Trends Biotechnol 23:388–394

Anderson W (2005) Cited in Department of Agriculture and Food WA 2009. http:/www.agric.wa.gov.au/objwr/imported/assets/content/pw/weed/iwm/tactic%203.4.pdf

Auskalniene O, Psibisauskiene G, Auskalnis A, Kadzys A (2010) Cultivar and plant density influence on weediness in spring barley crops. Zemdirb Agric 97:53–60

Azad BS, Singh H, Dubey AN (1988) Control of *Phalaris minor* in wheat by cultural and chemical methods. Pesticides 22:41–42

Baghestani A, Lemieux C, Leroux GD, Baziramakenga R, Simard RR (1999) Determination of allelochemicals in spring cereal cultivars of different competitiveness. Weed Sci 47:498–504

Ballard CL, Scopel AL, Sanchez RA, Radosevich SR (1992) Photo-morphogenic processes in the agricultural environment. Photochem Photobiol 56:777–788

Baraibar B, Westerman PR, Carrion E, Recasens J (2009) Effects of tillage and irrigation in cereal fields on weed seed removal by seed predators. J Appl Ecol 46: 380–387

Bàrberi P, Lo Cascio B (2001) Long-term tillage and crop rotation effects on weed seed bank size and composition. Weed Res 41:325–340

Beckie HJ, Warwick SI (2010) Persistence of an oil seed rape transgene in the environment. Crop Prot 29:509–512

Beckie HJ, Johnson EN, Blackshaw RE, Gan Y (2008) Weed suppression by canola and mustard cultivars. Weed Technol 22:182–185

Bhan VM, Kumar S (1997) Integrated management of *Phalaris minor* in rice–wheat ecosystems in India. In: Proceedings of international conference on ecological agriculture: towards sustainable development, Chandigarh, India, pp 400–415

Bhan VM, Singh VP (1993) Integrated weed management (IWM)-an approach. In: Proceedings of the international symposium of the Indian society of weed science, Hisar, Nov 1993, vol 1, pp 287–297

Bhattacharyya R, Prakash V, Kundu S, Srivastva AK, Gupta HS (2009) Soil aggregation and organic matter in a sandy clay loam soil of the Indian Himalayas under different tillage and crop regimes. Agric Ecosyst Environ 132:126–134

Bilalis D, Sidiras N, Economuu G, Vakali C (2003) Effect of different levels of wheat straw soil surface coverage on weed flora in *Vicia faba* crops. J Agron Crop Sci 189:233–241

Binimelis R, Pengue W, Monterroso I (2009) Transgenic treadmill: responses to the emergence and spread of glyphosate-resistant johnsongrass in Argentina. Geo Forum 40:623–633

Blanco-Canqui H, Lal R (2009) Crop residue removal impacts on soil productivity and environmental quality. Crit Rev Plant Sci 28:139–163

Blum U, King LD, Gerig TM, Lehman ME, Worsham AD (1997) Effects of clover and small grain cover crops and tillage techniques on seedling emergence of some dicotyledonous weed species. Am J Altern Agric 4:146–161

Boydston RA, Hang A (1995) Rapeseed (*Brassica napus*) green manure suppresses weeds in potato (*Solanum tuberosum*). Weed Tech 9:669–675

Brainard DC, Bellinde RR, Hahn RR, Shah DA (2008) Crop rotation, cover crop, and weed management effects on weed seed banks and yields in snap bean, sweet corn, and cabbage. Weed Sci 56:434–441

Brar LS (2002) Current status of herbicide resistance in Punjab and its management strategies. In: Proceedings of international workshop on herbicide resistance and zero-tillage in rice–wheat cropping system, March 4–6, CCS HAU, Hisar, India, pp 6–10

Brar AS, Walia US (2007) Studies on composition of weed flora of wheat (*Triticum aestivum* L.) in relation to different tillage practices under rice–wheat cropping system. Indian J Weed Sci 39:190–196

Buhler DD (2002) Challenges and opportunities for integrated weed management. Weed Sci 50:273–280

Buhler DD, Mester TC, Kohler KA (1996) The effect of maize residues and tillage on emergence of *Setaria faberi, Abutilon theophrasti, Amaranthus retroflexus* and *Chenopodium album*. Weed Res 36:153–165

Buhler DD, Hartzler RG, Forcella F (1997) Implications of weed seed bank dynamics to weed management. Weed Sci 45:329–336

Bullied WJ, Marginet AM, Van Acker RC (2003) Conventional- and conservation-tillage systems influence emergence periodicity of annual weed species in canola. Weed Sci 51:886–897

Burgos NR, Talbert RE (2000) Differential activity of allelochemicals from *Secale cereale* in seedling bioassays. Weed Sci 48:302–310

Cerdeira AL, Duke SO (2006) The current status and environmental impacts of glyphosate-resistant crops: a review. J Environ Qual 35:1633–1658

Cardina J, Regnier E, Harrison K (1991) Long-term tillage effects on seed banks in three Ohio soils. Weed Sci 39:186–194

Chauhan BS, Abugho SB (2012) Interaction of rice residue and pre herbicides on emergence and biomass of four weed species. Weed Technol 26:627–632

Chauhan BS, Johnson DE (2009) Influence of tillage systems on weed seedling emergence pattern in rainfed rice. Soil Tillage Res 106:15–21

Chauhan BS, Johnson DE (2010) Implications of narrow crop row spacing and delayed *Echinochloa colona* and *Echinochloa crusgalli* emergence for weed growth and crop yield loss in aerobic rice. Field Crops Res 117:177–182

Chauhan BS, Opena J (2012) Effect of tillage systems and herbicides on weed emergence, weed growth, and grain yield in dry-seeded rice systems. Field Crops Res 137:56–69

Chauhan DS, Sharma RK, Verma OS, Singh G, Tyagi, BS (1998) Wheat: research needs beyond 2000 AD. In: Proceeding of international conference, 12–14 Aug 1997, Karnal, India, pp 263–273

Chauhan BS, Yadav A, Malik RK (2001) Competitive wheat genotypes under zero tillage-an important tool to manage resistant *Phalaris minor*. Indian J Weed Sci 33:75–76

Chauhan BS, Gill G, Preston C (2006) Tillage system effects on weed ecology, herbicide activity and persistence: a review. Aust J Exp Agric 46:1557–1570

Chauhan BS, Gill GS, Preston C (2007a) Factors affecting seed germination of linle mallow (*Malva parvifora*) in southern Australia. Weed Sci 54:1045–1050

Chauhan BS, Gill GS, Preston C (2007b) Effect of seeding systems and dinitroaniline herbicides on emergence and control of rigid ryegrass (*Lolium rigidum*) in wheat. Weed Technol 21:53–58

Chauhan BS, Migo T, Westerman PR, Johnson DE (2010) Post-dispersal predation of weed seeds in rice fields. Weed Res 50:553–560

Chauhan BS, Singh RG, Mahajan G (2012) Ecology and management of weeds under conservation agriculture: a review. Crop Prot 38:57–65

Cheema ZA, Khaliq A (2000) Use of sorghum allelopathic properties to control weeds in irrigated wheat in semi arid region of Punjab. Agric Ecosyst Environ 79:105–112

Cheema ZA, Asim M, Khaliq A (2000) Sorghum allelopathy for weed control in cotton (*Gossypium arboreum* L.). Int J Agric Biol 2:37–41

Chhokar RS, Malik RK (2002) Isoproturon-resistant little seed canary grass (*P. minor*) and its response to alternate herbicides. Weed Technol 16:116–123

Chhokar RS, Sharma RK, Jat GR, Pundir AK, Gathala MK (2007) Effect of tillage and herbicides on weeds and productivity of wheat under rice–wheat growing system. Crop Prot 26:1689–1696

Chhokar RS, Singh S, Sharma RK, Singh M (2009) Influence of straw management on *Phalaris minor* control. Indian J Weed Sci 41:150–156

Childs DT, Jordan T, Ross M, Bauman T (2001) Weed control in no-tillage systems. Purdue University Cooperative Extension Service. Conservational Tillage Series CT-2. Purdue University, West Lafayette

Chopra P, Angiras NN (2008a) Influence of tillage and weed control methods on weeds, yield and yield attributes of Maize (*Zea mays* L.). Indian J Weed Sci 40:47–50

Chopra NK, Angiras NN (2008b) Effect of tillage and weed management on productivity and nutrient uptake of maize (*Zea mays*). Indian J Agron 53:66–69

Chopra NK, Chopra N (2010) Evaluation of tillage system and herbicides on wheat (*Triticum aestivum*) performance under rice (*Oryza sativa*)–wheat (*Triticum aestivum*) cropping system. Indian J Agron 55:304–307

Crabtree W (1999) Stubble, harrows, ryegrass, soil residual herbicides and no-till sowing. In: Stewart V (ed) Western Australian GRDC crop updates-weed update. Department of Agriculture and Food, Government of Western Australia, Perth, pp 35–37

Cromar HE, Murphy SD, Swanton CJ (1999) Influence of tillage and crop residue on postdispersal predation of weed seeds. Weed Sci 47:184–194

Curran WS, Liebl RA, Simmons FW (1992) Effects of tillage and application method on clomazone, imazaquin, and imazethapyr persistence. Weed Sci 40:482–489

Curran WS, Lingenfelter DD, Garling L (1996) An introduction to weed management for conservation tillage systems. Conservation Tillage Series No. 2, College of Agricultural Sciences, Cooperative Extension. The Pennsylvania State University, University Park, p 6

D'Emden FH, Llewellyn RS, Flower K (2009) Is the no-till revolution complete in WA? In: Conference proceedings for Perth agribusiness crop updates, Feb, pp 304–307

Dale JE, Chandler JM (1979) Herbicide crop rotation for Johnson grass (*Sorghum halepense*) control. Weed Sci 27:479–485

Das TK (2014) Weeds and their control methods. (In) Weed management, pp 9–14. http://www.nsdl.niscair.res.in/bitstream/123456789/568/1/Weeds+and+their+control+methods+-+Formatted.pdf. Accessed 6 March 2014

Das TK, Yaduraju NT (1999) Effect of weed competition on growth, nutrient uptake and yield of wheat as affected by irrigation and fertilizers. J Agric Sci (Camb) 133:45–51

Das TK, Yaduraju NT (2007) Effect of irrigation and nitrogen level on grassy weed competition in wheat and comparative eco-physiology of *Phalaris minor* Retz and *Avena sterilis* ssp. *ludoviciana* Dur. in wheat. Indian J Weed Sci 39:178–184

Derksen DA, Lafond GP, Thomas AG, Loeppky HA, Swanton CJ (1993) Impact of agronomic practices on weed communities: tillage systems. Weed Sci 41: 409–417

Dick WA, McCoy EL, Edwards WM, Lal R (1991) Continuous application of no-tillage to Ohio soils. Agron J 83:65–73

Dubey RP (2008) Effect of weed control and nitrogen application rates on weed infestation and productivity in maize–cowpea intercropping system. Indian J Weed Sci 40:155–158

Erenstein O (2003) Smallholder conservation farming in the tropics and sub-tropics: a guide to the development and dissemination of mulching with crop residues and cover crops. Agric Ecosyst Environ 100:17–37

FAO (2014) CA adoption worldwide. http://www.fao.org/ag/ca/6c.html. Accessed 9 Oct 2014

Farooq U, Sharif M, Erenstein O (2007) Adoption and impacts of zero-tillage in the rice–wheat zone of irrigated Punjab, Pakistan. CIMMYT and the rice-wheat consortium for the Indo-Gangetic Plains, New Delhi, pp 9–18

Farooq M, Flower KC, Jabran K, Wahid A, Siddique KHM (2011a) Crop yield and weed management in rainfed conservation agriculture. Soil Tillage Res 117:172–183

Farooq M, Jabran K, Cheema ZA, Wahid A, Siddique KHM (2011b) Role of allelopathy in agricultural pest management. Pest Manage Sci 67:494–506

Farooq M, Bajwa AA, Cheema SA, Cheema ZA (2013) Application of allelopathy in crop production. Int J Agric Biol 15:1367–1378

Fillery IRP (2001) The fate of biologically fixed nitrogen in legume-based dryland farming systems: a review. Aust J Exp Agric 41:361–381

Fischer AJ (1996) Integrated red rice management in Latin American rice fields. In: Proceedings of the second international weed control congress. Copenhagen, Denmark, vol 2, pp 53–66

Forcella F, Lindstorm MJ (1998) Movement and germination of weed seeds in ridge-till crop production systems. Weed Sci 36:56–59

Franke AC, Singh S, Mcroberts N, Nehra AS, Godara S, Malik RK, Marshall G (2007) *Phalaris minor* seedbank studies: longevity, seedling emergence and seed production as affected by tillage regime. Weed Res 47:73–83

Frick B (2000) Weed management. Back to the basics: a manual for weed management on organic farms. Organic Producers Association of Manitoba, Virden, pp 3–30

Froud-Williams RJ (1988) Changes in weed flora with different tillage and agronomic management systems. In: Altieri MA, Liebman M (eds) Weed management in agroecosystems: ecological approaches. CRC Press, Boca Raton, pp 213–236

Gangwar KS, Singh KK, Sharma SK, Tomar OK (2006) Alternative tillage and crop residue management in wheat after rice in sandy loam soils of Indo-Gangetic Plains. Soil Tillage Res 88:242–252

Gathala MK, Ladha JK, Kumar V, Saharawat YS, Kumar V, Sharma PK, Sharma S, Pathak H (2011a) Tillage and crop establishment affects sustainability of south asian rice–wheat system. Agron J 103:961–971

Gathala MK, Ladha JK, Saharawat YS, Kumar V, Kumar V, Sharma PK (2011b) Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice–wheat rotation. Soil Sci Soc Am J 75:1851–1862

Gealy DR, Anders M, Watkins B, Duke S (2014) Crop performance and weed suppression by weed-suppressive rice cultivars in furrow- and flood-irrigated systems under reduced herbicide inputs. Weed Sci 62:303–320

Ghuman RS, Brar LS, Walia US (2008) Role of variety and plant geometry on weed management in transplanted rice (*Oryza sativa* L.). Indian J Weed Sci 40:137–141

Gill KS, Arshad MA (1995) Weed flora in the early growth period of spring crops under conventional, reduced, and zero tillage systems on a clay soil in northern Alberta, Canada. Soil Tillage Res 33:65–79

Gill GS, Holmes JE (1997) Efficacy of cultural control methods for combating herbicide resistant *Lolium rigidum*. Pestic Sci 51:352–358

Gill KS, Arshad MA, Chivundu BK, Phiri B, Gumbo M (1992) Influence of residue mulch, tillage and cultural practices on weed mass and corn yield from three field experiments. Soil Tillage Res 24:211–223

Giller KE, Witter E, Corbeels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crops Res 114:23–34

Givens WA, Shaw DR, Kruger GR, Johnson WG, Weller SC, Young BG, Wilson RG, Owen MDK, Jordan D (2009) Survey of tillage trends following the adoption of glyphosate-resistant crops. Weed Technol 23:150–155

Govaerts B, Sayre K.D, Deckers J (2005) Stable high yields with zero tillage and permanent bed planting. Field Crops Res 94:33–42

Govaerts B, Sayre KD, Goudeseune B, Corte PD, Lichter K., Dendooven L, Deckers J (2009). Conservation agriculture as a sustainable option for the central Mexican highlands. Soil Tillage Res 103:222–230

Grimmer OP, Masiunas JB (2005) The weed control potential of oat cultivars. Hort Technol 15:140–144

Gupta R, Seth A (2007) A review of resource conserving technologies for sustainable management of the rice–wheat cropping systems of the Indo-Gangetic Plains (IGP). Crop Prot 26:436–447

Hall JC, Van Eerd LL, Miller SD, Owen MDK, Prather TS, Shaner DL, Singh M, Vaughn KC, Weller SC (2000) Future research directions for weed science. Weed Technol 14:647–658

Harker KN, Clayton GW, Blackshaw RE, O'Donovan JT, Stevenson FC (2003) Seeding rate, herbicide timing and competitive hybrids contribute to integrated weed management in canola (*Brassica napus*). Can J Plant Sci 83:433–440

Hartzler RG, Owen MD (1997) Weed management in conservation tillage system. Iowa state university, Ames. http://www.extension.edu/Publications/PM1176.pdf

Hobbs PR, Gupta RK (2013) Resource-conserving technologies for wheat in rice–wheat system. In: Ladha JK et al (eds) Improving the productivity and sustainability of rice–wheat systems: issues and impacts. ASA Special Publication No. 65. America Society of Agronomy–Crop Science Society of America–Soil Science Society of America, Madison, Wisconsin, pp 149–172

Hobbs PR, Sayre K, Gupta R (2008) The role of conservation agriculture in sustainable agriculture. Philos Trans R Soc Lond Biol 363:543–555

Hoyle FC, Murphy DV (2006) Seasonal changes in microbial function and diversity associated with stubble retention versus burning. Aust J Soil Res 44:407–423

Huggins DR, Reganold JP (2008) No-till: the quiet revolution. Sci Am 299:70–77

Hulme PE (1994) Post-dispersal seed predation in grassland: its magnitude and sources of variation. J Ecol 81:645–652

Iqbal J, Cheema ZA, An M (2007) Intercropping of field crops in cotton for the management of purple nutsedge (*Cyperus rotundus* L.). Plant Soil 300:163–171

Janiya JD, Moody K (1984) Use of *Azolla* to suppress weeds in transplanted rice. Trop Pest Manage 30:1–6

Jat ML, Pal SS, Subba Rao AVM, Sharma SK (2003) Improving resource use efficiency in wheat through laser land leveling in an ustochrept of Indo-Gangetic plain. In: National seminar on developments in soil science, 68th annual convention of the India Society of Soil Science, Nov 4–8, CSAUAT, Kanpur (UP)

Jat ML, Singh S, Rai HK, Chhokar RS, Sharma SK, Gupta RK (2005) Furrow irrigated raised bed planting technique for diversification of rice–wheat system of Indo-Gangetic plains. J Jpn Assoc Int Coop Agric For 28:25–42

Jat ML, Gathala MK, Ladha JK, Saharawat YS, Jat AS, Kumar Vipin, Sharma SK, Kumar V, Gupta Raj (2009a) Evaluation of precision land leveling and double zero-till systems in rice–wheat rotation: water use, productivity, profitability and soil physical properties. Soil Tillage Res 105:112–121

Jat ML, Singh RG, Saharawat YS, Gathala MK, Kumar V, Sidhu HS, Gupta Raj (2009b) Innovations through conservation agriculture: progress and prospects of participatory approach in the

Indo-Gangetic Plains. In: Proceedings of the lead papers, 4th world congress on conservation agriculture, 4–7 Feb 2009, New Delhi, India, pp 60–64

Jat ML, Malik RK, Saharawat YS, Gupta R, Mal B, Paroda R (2012) In: Proceedings of regional dialogue on conservation agricultural in South Asia, New Delhi, India, 1–2 Nov, 2011. APAARI, CIMMYT, ICAR, p 32

Jat ML, Gathala MK, Saharawat YS, Tetarwal JP, Gupta R, Singh Y (2013a) Double no-till and permanent raised beds in maize–wheat rotation of north-western Indo-Gangetic Plains of India: effects on crop yields, water productivity, profitability and soil physical properties. Field Crops Res 149:291–299

Jat RK, Banga RS, Yadav A (2013b) Resource conservation techniques and pendimethalin for control of weeds in *durum* wheat cultivars. Indian J Weed Sci 45:93–98

Kang MS (2013) Happy Seeder technology is well received by punjab farmers. http://www.bharatsandesh.com/bharat/index.php?option=com_content&task=view & id=16957 & Itemid=27 dt. Accessed 2 Dec 2013

Kaschuk G, Alberton O, Hungria M (2010) Three decades of soil microbial biomass studies in Brazilian ecosystems: lessons learned about soil quality and indications for improving sustainability. Soil Biol Biochem 42:1–13

Khaliq A, Matloob A, Irshad MS, Tanveer A, Zamir MSI (2010) Organic weed management in maize through integration of allelopathic crop residues. Pak J Weed Sci Res 16:409–420

Khan IA, Hassan G, Daur I, Abdullah (2008) Competition of wild oats (*Avena fatua* L.) with different wheat cultivars. Sarhad J Agric 24:113–116

Khanh TD, Chung MI, Xuan TD, Tawata S (2005) The exploitation of crop allelopathy in sustainable agricultural productions. J Agron Crop Sci 191:172–184

Kumar V, Ladha JK (2011) Direct-seeding of rice: recent developments and future research needs. Adv Agron 111:297–413

Kumar R, Gopal R, Jat ML, Gupta RK (2010) Conservation agriculture based strategies for sustainable weed management in maize (*Zea mays*). (In): Training manual, maize for freshers. Directorate of Maize Research, New Delhi

Kumar V, Singh S, Chokar RS, Malik RK, Brainard DC, Singh M, Sharma PC, Kamboj BR, Mcdonald A, Ladha JK (2012) Conservation agriculture and weed management: experiences from rice–wheat cropping systems of the Indo-Gangetic Plains. Lead papers, 3rd international agronomy congress, 26–30 Nov 2012, New Delhi, India, vol 1, pp 82–83

Ladha JK, Dawe D, Ventura TS, Singh U, Ventura W, Watanabe I (2000) Long-term effects of urea and green manure on rice yields and nitrogen balance. Soil Sci Soc Am J 64:1993–2001

Ladha JK, Kumar V, Alam MM, Sharma S, Gathala M, Chandna P, Saharawat YS, Balasubramanian V (2009) Integrating crop and resource management technologies for enhanced productivity, profitability, and sustainability of the rice–wheat system in South Asia. In: Ladha JK, Singh Y, Erenstein O, Hardy B (eds) Integrated crop and resource management in the rice–wheat system of south Asia. IRRI, Los Banos, pp 69–108

Lafond GP, McConkey BG, Stumborg M (2009) Conservation tillage models for small-scale farming: linking the Canadian experience to the small farms of inner Mongolia autonomous region in China. Soil Tillage Res 104:150–155

Lai C, Chan C, Halbrendt J, Shariq L, Roul P, Idol T, Ray C, Evensen C (2012) Comparative economic and gender, labor analysis of conservation agriculture practices in tribal villages in India. Int Food Agribus Manage Rev 15:73–86

Lal R (2007) Constraints to adopting no-till farming in developing countries. Soil Tillage Res 94:1–3

Lal R, Regnier E, Eckert DJ, Edwards WM, Hammond R (1991) Expectations of cover crops for sustainable agriculture. In: Hargrove WL (ed) Cover crops for clean water. Soil and Water Conservation Society Publication, Ankey, pp 1–11

Lanini WT, Orloff SB, Marble RN, Vargas J, Orr VL, Grattan SR (1991) Oat companion crop seeding rate effect on alfalfa establishment yield and weed control. Agron J 83:330–333

Lathwal OP, Malik RK (2005) Effect of zero till seed-cum-fertilizer drill in economizing the cost of cultivation in wheat. Haryana J Agron 21:62–64

Lazzeri L, Manici LM (2000) The glucosinolate-myrosinase system: a natural and practical tool for biofumigation. Acta Horticul 532:89–95

Lemerle D, Gill GS, Murphy CE, Walker SR, Cousens RD, Mokhtari S, Peltzer SJ, Coleman R, Luckett DJ (2001) Genetic improvement and agronomy for enhanced wheat competitiveness with weeds. Aust J Agric Res 52:527–548

Lenssen AW (2008) Planting date and preplant weed management influence yield, water use, and weed seed production in herbicide-free forage barley. Weed Technol 22:486–492

Linke KH, Saxena MC (1989) Proceedings of international workshop on Orobanche, Oberrenchal, Germany, Aug 1989, pp 19–22

Locke MA, CT Bryson (1997) Herbicide-soil interactions in reduced tillage and plant residue management systems. Weed Sci 45:307–320

Mahajan G, Brar LS, Sardana V (1999) Effect of tillage and time of sowing on the efficacy of herbicides against Phalaris minor in wheat. In: Proceeding of 17th Asian pacific weed science society conference, Bangkok, Thailand, pp 193–198

Mahajan G, Brar LS, Walia US (2002) *Phalaris minor* response in wheat in relation to planting dates, tillage and herbicides. Indian J Weed Sci 34:213–215

Mahapatra BS, Mishra A, Kumar A (2004) Green manuring: a basic concept and its role in weed control. In: Training manual: advances in weed management. G.B. Pant University of Agriculture and Technology, Pantnagar, India

Malhi SS, Lemke R (2007) Tillage, crop residue and N fertilizer effects on crop yield, nutrient uptake, soil quality and nitrous oxide gas emissions in a second 4-year rotation cycle. Soil Tillage Res 96:269–283

Malik RK, Balyan RS, Bhan VM (1988) Effect of herbicides and planting dates of weeds in chickpea. Indian J Weed Sci 20:75–81

Malik RK, Yadav A, Singh S, Malik RS, Balyan RS, Banga RS, Sardana PK, Jaipal S, Hobbs PR, Gill G, Singh S, Gupta RK, Bellinder R (2002) Herbicide resistance management and evolution of zero-tillage—a success story. CCS Haryana Agricultural University Research Bulletin, Hisar, p 43

Malik RK, Gupta RK, Singh CM, Yadav A, Brar SS, Thakur TC, Singh SS, Singh AK, Singh R, Sinha RK (2005) Accelerating the adoption of resource conservation technologies in rice wheat system of the Indo-Gangetic Plains. Proceedings of project workshop, Directorate of Extension Education, Chaudhary Charan Singh Haryana Agricultural University (CCSHAU), 1–2 June 2005, Hisar, India

Mishra JS, Singh VP (2008) Competitive ability of wheat (*Triticum aestivum*) cultivars against wild oat (*Avena ludoviciana*) infestation under zero tillage. Indian J Agric Sci 78:838–841

Mishra JS, Singh VP (2009) Weed dynamics and productivity of soybean (*Glycine max*)—based cropping systems as influenced by tillage and weed management. Indian J Agron 54:29–35

Mishra JS, Singh VP (2012a) Tillage and weed control effects on productivity of a dry seeded rice–wheat system on a vertisol in central India. Soil Tillage Res 123:11–20

Mishra JS, Singh VP (2012b) Effect of tillage sequence and weed management on weed dynamics and productivity of dry-seeded rice (*Oryza sativa*)—wheat (*Triticum aestivum*) system. Indian J Agron 57:14–19

Mishra JS, Singh VP, Yaduraju NT (2005) Effect of tillage practices and herbicides on weed dynamics and yield of wheat (*Triticum aestivum*) under transplanted rice (*Oryza sativa*)– wheat system in vertisols. Indian J Agron 50:106–109

Mishra JS, Singh VP, Chandra Bhanu, Subrahmanyam D (2012) Crop establishment, tillage and weed management techniques on weed dynamics and productivity of rice (*Oryza sativa*) chickpea (*Cicer arietinum*) cropping system. Indian J Agric Sci 82:15–20

Mohler CL (1991) Effects of tillage and mulch on weed biomass and sweet corn yield. Weed Technol 5:545–552

Mohler CL, Calloway MB (1992) Effects of tillage and mulch on the emergence and survival of weeds in sweet corn. J Appl Ecol 29:21–34

Mohler CL, Teasdale JR (1993) Response of weed emergence to rate of *Vicia villosa* Roth and *Secale cereale* L. residue. Weed Res 33:487–499

Moyer JR (1985) Effect of weed control and a companion crop on alfalfa and sainfoin establishment, yields and nutrient composition. Can J Plant Sci 65:107–116

Mueller TC, Massey JH, Hayes RM, Main CL, Neal Stewart Jr. C (2003) Shikimate accumulates in both glyphosate-sensitive and glyphosate-resistant horseweed (*Conyza canadensis* L. Cronq.). J Agric Food Chem 51:680–684

Muliokela SW, Hoogmed WB, Steven P, Dibbits H (2001) Constraints and possibilities of conservation farming in Zambia. In: Garcia TL, Berutes J, Martinez VA (eds) Conservation agriculture: a world challenge. Volume II: offered contributions, environment, farmers' experiences, innovations, socio-economic policy. XUL Avda, Medina, pp 61–65

Mulugeta D, Stoltenberg DE (1997) Increased weed emergence and seed bank depletion by soil disturbance in a no-till system. Weed Sci 45:234–241

Nagabhushana GG, Worsham AD, Yenish JP (2001) Allelopathic cover crops to reduce herbicide use in sustainable agricultural systems. Allelopathy J 8:133–146

Nalewaja J (2001) Weeds and conservation agriculture. World congress on conservation agriculture. Madrid 1:191–200

Olofsdotter M (2001) Rice—a step toward use of allelopathy. Agron J 93:3–8

Owen MDK, Zelaya I (2004) Herbicide-resistant crops and weed resistance to herbicides. Pest Manage Sci 61:301–311

Palada MC, Ganser S, Hofstetter R, Volak B, Culik M (1983) Association of interseeded legume cover crops and annual row crops in year-round cropping systems. In: Lockeretz W (ed) Environmentally sound agriculture. Praeger, New York, pp 193–213

Paolini R, Principi M, Del Puglia S, Lazzeri L (1998) Competitive effects between sunflower and six broad-leaved weeds. In: Proceedings of the 6th EWRS mediterranean symposium, Montpellier, France, pp 81–88

Paolini R, Principi M, Froud-Williams RJ, Del Puglia S, Biancardi E (1999) Competition between sugarbeet and *Sinapis arvensis* and *Chenopodium album*, as affected by timing of nitrogen fertilization. Weed Res 39:425–440

Pathak H, Saharawat YS, Gathala M, Mohanty S, Handrasekharan S, Ladha JK (2011) Simulating the impact of resource conserving technologies in rice– wheat system on productivity, income and environment—part I. Green house gases. Sci Technol 1:1–17

Pittelkow CM, Fischer AJ, Moechnig MJ (2012) Agronomic productivity and nitrogen requirements of alternative tillage and crop establishment systems for improved weed control in direct-seeded rice. Field Crops Res 130: 128–137

Price AJ, Stoll ME, Bergtold JS, Arriaga FJ, Balkcom KS, Kornecki TS, Raper RL (2008) Effect of cover crop extracts on cotton and radish radicle elongation. Communi Biometry Crop Sci 3:60–66

Putnam AR, Duke WB (1978) Allelopathy in agroecosystems. Ann Rev Phytopathol 16:431–451

Ram H, Kler DS, Singh Y, Kumar K (2010) Productivity of maize (*Zea mays*)—wheat (*Triticum aestivum*) system under different tillage and crop establishment practices. Indian J Agron 55:185–190

Rao VS (2000) Principles of weed science, 2nd edn. Science Publishers Inc. Enfield, pp 37–39

Rao AN, Mortimer AM, Johnson DE, Sivaprasad B, Ladha JK (2007) Weed management in direct-seeded rice. Adv Agron 93:155–257

Rasmussen K, Rasmussen J (2000) Barley seed vigour and mechanical weed control. Weed Res 40:219–230

Rathi JPS, Rathi PK, Singh OP (2007) Studies on integrated weed management technique in chickpea with mustard intercropping system. Plant-Arch 7:909–912

Reicosky DC, Saxton KE (2007) The benefits of no-tillage. In: Baker CJ, Saxton KE, Ritchie WR, Chamen WCT, Reicosky DC, Ribeiro MFS, Justice SE, Hobbs PR (eds) No-tillage seeding in conservation agriculture, 2nd edn. FAO/CAB International, pp 11–20, CABI, Nosworthy Way, Wallingford, Oxfordshire OX10 8DE, UK

Rickman JF (2002) Manual for land leveling, rice–wheat consortium technical bulletin series 5. Rice–wheat consortium for the Indo-Gangetic Plains, New Delhi-12, India, p 24

Risch SJ, Carroll CR (1986) Effects of seed predation by a tropical ant on competition among weeds. Ecology 67:1319–1327

RWC-CIMMYT (2005) Agenda notes. 13th regional technical coordination committee meeting. RWC-CIMMYT, Dhaka, Bangladesh

Saharawat YS, Ladha JK, Pathak H, Gathala M, Chaudhary N, Jat ML (2011) Simulation of resource conserving technologies on productivity, income and green house gas (GHG) emission in rice–wheat system. J Soil Sci Environ Manage 3:9–22

Saharawat YS, Ladha JK, Pathak H, Gathala M, Chaudhary N, Jat ML (2012) Simulation of resource-conserving technologies on productivity, income and greenhouse gas emission in rice–wheat system. J Soil Sci Environ Manage 3:9–22

Samson R, Foulds C, Patriquin D (1990) Choice and management of cover species and varieties for use in row crop dominant rotations: final report. Resource Efficient Agricultural Production (REAP), Ste. Anne-de-Bellevue, Quebec, pp 83–90

Saturnino HM, Landers JN (2001) Introduction: what is zero tillage? In: Saturnino HM, Landers JN (eds) The environment and zero tillage. Associac¸a˜o de Plantio Direto no Cerrado. Federac¸a˜o Brasileira de Plantio Direto na Palha, Brasil, pp 13–24

Scursoni JA, Gigon R, Martin AN, Vigna M, Leguizamon ES, Istilart C, Lopez R (2014) Changes in weed communities of spring wheat crops of buenos aires province of Argentina. Weed Sci 62:51–62

Sharma AR (1997) Effect of integrated weed management and nitrogen fertilization on the performance of rice under flood-prone lowland conditions. J Agri Sci Camb 129:409–418

Sharma RK, Srinivasa Babu K, Chhokar RS, Sharma AK (2004) Effect of tillage on termites, weed incidence and productivity of spring wheat in rice–wheat system of North Western Indian plains. Crop Prot 23:1049–1054

Sharma AR, Singh R, Dhyani SK, Dube RK (2010) Effect of live mulching with annual legumes on performance of maize (*Zea mays*) and residual effect on following wheat (*Triticum aestivum*). Indian J Agron 55:177–184

Sharma AR, Jat ML, Saharawat YS, Singh VP, Singh, R (2012) Conservation agriculture for improving productivity and resource-use efficiency: prospects and research needs in Indian context. Indian J Agron 57 (3rd IAC Special Issue):131–140

Shrestha A, Knezevic SZ, Roy RC, Ball-Coelho BR, Swanton CJ (2002) Effect of tillage, cover crop and crop rotation on the composition of weed flora in a sandy soil. Weed Res 42:76–87

Shrestha AR, Mitchell VJ, Cordova D (2003) Initial experiences in transition from conventional to conservational tillage: a farming systems perspective. In: Proceedings of Conservation Tillage 2003: The California Experience. October 7–9, Tulare, Five Points, Davis, CA

Shrestha A, Lanini T, Wright S, Vargas R, Mitchell J (2006) Conservation tillage and weed management. ANR publication 8200. http://www.anrcatalog.ucdavis.edu. Accessed 5 March 2014

Sidhu HS, Singh M, Humphreys E, Singh Y, Singh B, Dhillon SS, Blackwell J, Bector VM, Singh S (2007) The Happy Seeder enables direct drilling of wheat into rice straw. Aust J Exp Agric 47:844–854

Silva PS, Silva PIB, Silva KMB, Oliveira VR, Pontes Filho FST (2011) Corn growth and yield in competition with weeds. Planta daninha Viçosa-MG 29(4):793–802

Singh S (2007) Role of management practices on control of isoproturon-resistant littleseed canarygrass (*Phalaris minor* Retze) in India. Weed Technol 21:339–346

Singh S, Kirkwood RC, Marshall G (1999) A review of the biology and control of *Phalaris minor* Retz (little seed canary grass) in cereals. Crop Prot 18:1–16

Singh RG, Singh VP, Singh G, Yadav SK (2001) Weed management studies in zero till wheat in rice–wheat cropping system. Indian J Weed Sci 33:95–99

Singh S, Ladha JK, Gupta RK, Bhushan L, Rao AN, Sivaprasad B, Singh PP (2007) Evaluation of mulching, intercropping with Sesbania and herbicide use for weed management in dry-seeded rice (*Oryza sativa* L.). Crop Prot 26:518–524

Singh RK, JS Bohra, VK Srivastava, RP Singh (2008) Effect of diversification of rice–wheat system on weed dynamics in rice. Indian J Weed Sci 40:128–131

Singh A, Kang JS, Kaur M, Goel A (2013) Farmer's participatory approach for the in-situ management of paddy straw with Happy Seeder and rotavator. Int J Agric Innovations Res 2:178–185

Sinha AC, Mandal BB, Jana PK (1988) Physiological analysis of yield variation in irrigated pigeonpea in relation to time of sowing, row spacing and weed control measures. Indian Agric 32:1777–1785

Spandl E, Durgan BR, Forcella F (1998) Tillage and planting date influence foxtail (*Setaria* spp.) emergence in continuous spring wheat (*Triticum aestivum*). Weed Technol 12:223–229

Spandl E, Durgan BR Forcella F (1999) Foxtail (*Setaria* spp.) seedling dynamics in spring wheat (*Triticum aestivum*) are influenced by seeding date and tillage regime. Weed Sci 47:156–160

Swanton CJ, Shrestha A, Chandler K, Deen W (2000) An economic assessment of weed control strategies in no-till glyphosate-resistant soybean (*Glycine max*). Weed Techn 14:755–763

Tahir MA, Younas M (2004) Feasibility of dry sowing technology of wheat in cotton growing districts and impact evaluation of zero tillage technology in rice growing districts. Publication No. 364. Punjab Economic Research Institute (PERI), Lahore

Teasdale JR (1993) Interaction of light, soil moisture, and temperature with weed suppression by hairy vetch residue. Weed Sci 41:46–51

Teasdale JR, Mohler CL (2000) The quantitative relationship between weed emergence and the physical properties of mulches. Weed Sci 48:385–392

Tesio F, Ferrero A (2010) Allelopathy, a chance for sustainable weed management. Int J Sustain Dev World Ecol 17:377–389

Torres RO, Pareek RP, Ladha JK, Garrity DP (1995) Stemnodulating legumes as relay-cropped or intercropped green manures for lowland rice. Field Crops Res 42:39–47

Tuesca D, Puricelli E, Papa JC (2001) A long-term study of weed flora shifts in different tillage systems. Weed Res 41:369–382

Tuti MD, Das TK (2011) Carry-over effect of metribuzin applied to soybean (*Glycine max*) on weeds and wheat (*Triticum aestivum*) under zero and conventional tillage. Indian J Agron 50:121–126

Unamma RPA, Ene LSO, Odurukwe SO, Enyinnia T (1986) Integrated weed management for cassava intercropped with maize. Weed Res 26:9–17

Uremis I, Arslan M, Uludag A, Sangun MK (2009) Allelopathic potentials of residues of 6 *Brassica* species on johnsongrass [*Sorghum Halepense* (L.) Pers.]. African J Biotech 8:3497–3501

Van Der Weide RY, Bleeker PO, Lotz LAP (2002) Simple innovations to improve the effect of the false seed bed technique. In: Proceedings of the 5th workshop of the EWRS working group on physical and cultural weed control, Pisa, Italy, pp 3–4

Varshney JG (2000) Final report of ICAR adhoc research scheme "Nutsedge management in field crops with particular emphasis on pulses", Indian Institute of Pulse Research, Kanpur, pp 163

Vogel H (1994) Weeds in single crop conservation farming in Zimbabwe. Soil Tillage Res 31:169–185

Walia US (2002) Competitive ability of wheat cultivars against Phalaris minor. In: Proceedings of international workshop on herbicide resistance and zero-tillage in rice–wheat cropping system, March 4–6, CCS HAU, Hisar, India, pp 47–49

Walters SA, Young BG (2008) Utility of winter rye living mulch for weed management in zucchini squash production. Weed Technol 22:724–728

Westerman PR, Hofman A, Vet LEM, Van Der Werf W (2003) Relative importance of vertebrates and invertebrates in epigaeic weed seed predation in organic cereal fields. Agric Eco and Environ 95:417–425

Willis RJ (1985) The historical bases of the concept of allelopathy. J Hist Biol 18:71–102

Wolf TM, Harrison SK, Hall FR, Cooper J (2000) Optimizing post-emergence herbicide deposition and efficacy through application variables in no-till systems. Weed Sci 48:761–68

Yadav DS, Shukla RP, Sushant, Kumar B (2005) Effect of zero tillage and nitrogen level on wheat (*Triticum aestivum*) after rice (*Oryza sativa*). Indian J Agron 50:52–53

Yirefu F, Tana T, Tafesse A, Zekarias Y (2012) Competitive ability of sugarcane (*Saccharum officinarum* L.) cultivars to weed interference in sugarcane plantations of Ethiopia. Crop Prot 32:138–143

Young KR, Cousens RD (1999) Factors affecting the germination and emergence of wild radish (*Raphanus raphanistrum*) and their effect on management options. In: Bishop AC et al (eds) Proceedings of 12th Australian weeds conference. Tasmanian Weed Society, Tasmania, pp 179–182

Zand E, Beckie HJ (2002) Competitive ability of hybrid and open-pollinated canola (*Brassica napus*) with wild oat (*Avena fatua*). Can J Plant Sci 82:473–480

Chapter 4
Nutrient Management Perspectives in Conservation Agriculture

Christos Dordas

Abstract Conservation agriculture (CA) has been promoted as a major way forward to make agriculture sustainable by protecting soils from degradation processes. The focus of this chapter is on nutrient management in CA. Special attention is given to crop management and its effect on nutrient management with particular emphasis on the three major principles of CA—tillage, crop rotation, and residue management. Nutrient management has received little attention in CA despite the fact that it has a direct effect not only on crop yield but also on the tolerance of crop plants to pests. Further research on nutrient management could increase the adoption of CA worldwide. In this chapter, nutrient management in CA is discussed and proposed as the fourth principle of CA. Breeding genotypes for better nutrient-use efficiency in CA is also important, as is the control of weeds, insect pests, and diseases. In addition, the appropriate use of fertilizer and nutrients is essential to increase crop productivity and to produce sufficient crop residues in the different climates that CA is practiced.

Keywords Nitrogen · Phosphorus · Potassium · Nutrient-use efficiency · Fertilizers · Mulch · Crop rotation · Tillage

4.1 Introduction

Sustainability is a term that has been used extensively in modern agriculture in recent years because of the effect that certain crop production methods have on the environment (Atkinson and McKinlay 1997; Hanson et al. 2007). Sustainable agriculture is the management and utilization of the agricultural ecosystem in a way that maintains its biological diversity, productivity, regeneration capacity, vitality, and ability to function, so that it can fulfill—today and in the future—significant

---

C. Dordas (✉)
Faculty of Agriculture, Forestry and Natural Environment, School of Agriculture,
Laboratory of Agronomy, Aristotle University of Thessaloniki,
University Campus, 54124 Thessaloniki, Greece
e-mail: chdordas@agro.auth.gr

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_4

ecological, economic, and social functions at local, national, and global levels that does not harm other ecosystems (Lewandowski et al. 1999).

The sustainability of agriculture has faced significant challenges in recent years (Oborn et al. 2003; Hanson et al. 2007) including: (1) increased food demand for the ever-increasing human population, (2) overdependence on fossil energy and the increased monetary and environmental costs of nonrenewable resources, (3) global climate change (Diamond 2005; Brown 2006), and (4) globalization (Hanson et al. 2007). These dominant issues are challenging agriculturists to develop more sustainable management systems. To meet the food and nutritional needs of a growing population, agriculture needs to move beyond the past emphasis on productivity to encompass improved public health, social well-being, and a sound environment (Hanson et al. 2007).

Conservation agriculture (CA) is an important aspect of agriculture that contributes to sustainability. CA is based on the integrated management of different agricultural resources such as soil, water, and other resources to create an economically, ecologically, and socially sustainable agricultural production system. It relies on three major principles:

a. Minimal soil disturbance by direct planting through the soil cover without seedbed preparation.
b. Maintenance of a permanent vegetative soil cover or mulch to protect the soil surface.
c. Diversified crop rotations in the case of annual crops or plant associations in the case of perennial crops.

Nutrient management has received little attention in CA despite its direct effect on crop yield. Further research on nutrient management should increase the adoption of CA worldwide. In this chapter, nutrient management in CA is discussed and proposed as the fourth principle of CA (Vanlauwe et al. 2014).

4.2 Nutrient Management Perspectives

Nutrient management is an important aspect of CA for crop productivity and for the adoption of CA by farmers (Vanlauwe et al. 2014). CA improves nutrient-use efficiency (NUE) as it reduces soil erosion and prevents nutrient loss from the field. Nutrient loss may be minimized due to reduced runoff and the appropriate use of deep-rooting cover crops that recycle nutrients leached from the topsoil (FAO 2001). This leads to the greater availability of both native and applied nutrients to crop plants which can have a significant effect on fertilizer efficiency. It was found that in a rice–wheat system, fertilizer efficiency increased by 10–15 % due to better placement of fertilizer with the seed drill compared with broadcasting in the traditional system (Hobbs and Gupta 2004). There are reports of lower N fertilizer efficiency when soil microorganisms immobilized mineral N in the crop residues (Verhulst et al. 2010). Nonetheless, long-term experiments have indicated an increased release of nutrients owing to microbial activity and nutrient recycling (Carpenter-Boggs et al. 2003). In addition, increased soil organic matter (SOM) at the soil surface may increase NUE and water-use efficiency (Franzluebbers 2002). Similarly, crop residues can increase plant availability of phosphorus and its efficiency in no-tillage systems (Iyamuremye and Dick 1996; Sanchez et al. 1997).

A few studies have evaluated the effects of cover crops combined with different tillage systems on N mineralization and release, as well as P sorption (Fontes et al. 1992; Afif et al. 1995; Bhatti et al. 1998). Adsorption sites of goethite can be blocked by organic matter (OM) components, e.g., humic acids, and other organic compounds, such as oxalate and malate, which decreases P sorption in the soil (Fontes et al. 1992; Afif et al. 1995; Bhatti et al. 1998). In addition, it is not clear whether this positive effect of organic compounds on decreasing P sorption by soils exists in the field as most studies have been conducted under controlled environments (Ziadi et al. 2013).

Legume-based crop rotations in CA significantly improve nutrient availability for crop plants (Burle et al. 1997; Govaerts et al. 2007b). Higher levels of exchangeable calcium (Ca), potassium (K), and magnesium (Mg) were found when pigeon pea (*Cajanus cajan* L.) and lablab (*Lablab purpureus* L.) were used compared with when white clover (*Trifolium repens* L.; Burle et al. 1997). In addition, others found higher C, N, K, and lower sodium (Na) concentration when the crop residue remained in the field compared to residue removal (Govaerts et al. 2007b). The effect of CA practices on nutrients can be due to decreased infiltration, which can decrease deep drainage and the leaching of mobile nutrients, and most of the applied N is retained in the topsoil (Erenstein 2002; Scopel et al. 2004).

4.2.1 Nutrient-Use Efficiency

Fertilizers and especially N fertilizers are an important input for many crops and account for approximately half of the energy inputs in cereal production worldwide (Raun and Johnson 1999). In addition, cereal crops are quite inefficient in using N and other nutrients as only 33 % of the applied N as fertilizer can be recovered in the grain (Raun and Johnson 1999). The term NUE has been used extensively to describe nutrient use by a crop and is defined as grain yield divided by the supply of available nutrient from the soil and added fertilizer (Moll et al. 1982; Fageria et al. 2008). NUE is an important index that can be used in CA in order to quantify the different nutrient management practices and to determine which is better for increasing the NUE. NUE has two components: (1) nutrient uptake efficiency (crop nutrient uptake per unit of nutrient available from the soil and fertilizer) and (2) nutrient utilization efficiency (which is grain dry matter (DM) yield per unit crop nutrient uptake at harvest; Moll et al. 1982; Fageria et al. 2008). However, “nutrient efficiency” has many different meanings in crop production and several definitions within the literature (Fageria et al. 2008). In short, there are two primary efficiencies to consider, one is fertilizer efficiency and the other is crop efficiency. Fertilizer efficiency is the fraction of freshly applied fertilizer that is recovered in the current crop.

Fertilizer efficiency can be measured in CA in several ways:

1. The fertilizer is labeled with a stable isotope, e.g., ^{15}N for nitrogen to differentiate fertilizer N from indigenous soil N. In winter wheat, the crop recovered 68 % of the N applied, of which 18 % was retained in the topsoil (as nitrate and ammonium ions in the soil solution, as exchangeable ammonium ions on clays, and as organic N incorporated into microbes), and 14 % was lost by leaching and denitrification (Powlson and Jenkinson 1981).
2. The "apparent fertilizer recovery efficiency" is less accurate but more easily measured. It is the total nutrient uptake (in aboveground parts of the crop at maturity) at a given fertilizer rate minus the uptake at zero fertilizer rate, divided by the amount of the nutrient applied. It is called "apparent" because part of the total uptake will be from mineralized soil organic nutrient and the amount that was mineralized varies with the amount of fertilizer that has been applied.
3. Fertilizer efficiency can be calculated by dividing the total nutrients removed in grain by the nutrients applied as fertilizer. Raun and Johnson (1999) calculated that only 33 % of the fertilizer applied to cereals is removed by the harvested grain, resulting in 67 % either lost from the soil or remaining in the soil.

4.2.2 *Strategies for Improving NUE*

An important target of modern crop production is to improve NUE as this will increase profitability through increased yields or reduced fertilizer costs, and environmental protection through reduced greenhouse gas emissions (Hirel et al. 2007).

NUE can be increased by adopting appropriate nutrient management strategies and through crop breeding. NUE is affected by soil conditions particularly leaching, denitrification, volatilization, and immobilization of nutrients in the soil; fertilizer rates; source, placement, and timing of fertilizer application; climatic conditions; plant type which can affect absorption, translocation, assimilation, and retranslocation of the nutrient; and plant characteristics such as tissue nutrient concentration, size, and number of reproductive sinks.

Management strategies involve manipulation of soil, plant, climatic, and fertilizer variables. These strategies involve soil sampling and analysis, crop monitoring and sampling, crop rotation, tillage practices, form of fertilizer and time of application, irrigation, and precision agriculture. Adopting these strategies could lead to increased crop yield and enhanced NUE. Ways to increase NUE include:

1. Crop rotations, especially when legumes are used, can significantly improve NUE (Raun and Johnson 1999).
2. Forage production systems which have lower plant gaseous losses due to leaf senescence and higher NUEs as they tend not to flower (when N losses are

greater) and the biomass is harvested and removed from the field, e.g., wheat forage has N-use efficiency of 77 % compared with grain at 33 % and corn forage has N-use efficiency at 70 % (Raun and Johnson 1999).

3. Improved cultivars with higher NUE. Wheat cultivars were produced by genetic selection under low nutrient inputs to increase NUE. These wheat cultivars have high harvest index, low nutrient loss, and increased NUE. In addition, high NUE has also been observed in rice varieties with high harvest index (Raun and Johnson 1999).
4. Conservation tillage can improve NUE. In addition, erosion control and subsurface placement of fertilizers such as N has the potential to significantly improve N availability and NUE (Raun and Johnson 1999).
5. Fertilizer form. In many cases, the form of fertilizer can affect NUE, e.g., N as NH_4-N is more efficient as plants require more energy to assimilate NO_3 compared with NH_4 form. N uptake is higher at 35 % (NH_4), assimilation of N (NO_3 20 mol ATP/mol NO_3^-, NH_4 5 mol ATP/mol NH_4^+; Raun and Johnson 1999)
6. Fertilizer application should be in season; foliar application is more effective (pre-plant N reduces NUE, late-season N increases grain protein and NUE, foliar applied N (at flowering) and increases protein content and NUE; Raun and Johnson 1999).
7. Irrigation can increase NUE as maximum NUE obtained with low N rates, which were applied in season together with irrigation (Raun and Johnson 1999).
8. Precision agriculture practices can improve NUE. These practices include timely and precise application to meet plant needs; exact implementation of all management operations uniformly applied to a single field; site-specific management within a field to account for spatial variation in soil and pests; crop management: variety/hybrid selection, tillage, planting date, density and row spacing, nutrient amount, formulation, and placement; integrated pest management; and amount of irrigation and timing (Raun and Johnson 1999).

4.2.3 Management of N, P, and K in CA

CA practices, especially tillage, residue management, and crop rotation have a significant impact on nutrient distribution and transformation in soils (Etana et al. 1999; Galantini et al. 2000), and the effects of these practices are related to soil organic matter content (SOC). The distribution of nutrients in a soil under zero tillage differs from that in tilled soil as enhanced conservation increases the stratification of nutrients and their availability near the soil surface compared to conventional tillage (Follett and Peterson 1988; Franzluebbers and Hons 1996; Duiker and Beegle 2006; Table 4.1). The altered nutrient availability under zero tillage is probably due to the surface placement of crop residues as opposed to the incorporation of crop residues with conventional tillage (Blevins et al. 1977; Unger 1991; Ismail et al. 1994). Slower decomposition of crop residues left on the soil surface (Kushwaha et al. 2000; Balota et al. 2004) can prevent rapid

Table 4.1 Soil organic carbon, total nitrogen and phosphorus content under conventional and zero tillage from different studies

Organic C (g kg^{-1})		Total N (g kg^{-1})		P (mg g^{-1})		Reference
CT	ZT	CT	ZT	CT	ZT	
49.00	50.00	3.60	3.80	6	12.2	Astier et al. (2006)
27.4	33.40	–	–	11.13	19.6	Lal et al. (1990)
9.80	8.80	1.18	0.99	–	–	Kushwaha et al. (2000)
22.60	28.20	–	–	0.031	0.058	Duiker and Beegle (2006)
10.75	11.30	–	–	12.00	11.5	Roldan et al. (2007)
50.00	67.60	4.40	5.80	21.9	23.8	Borie et al. (2006)
27.10	29.20	2.85	3.03	–	–	Larney et al. (1997)

CT conventional tillage, *ZT* zero tillage

leaching of nutrients through the soil profile, which is more likely when residues are incorporated into the soil. However, the possible development of continuous pores between the surface and subsurface under zero tillage (Kay 1990) may lead to more rapid passage of soluble nutrients deeper into the soil profile than when soil is tilled (Franzluebbers and Hons 1996). Furthermore, the response of soil chemical properties to tillage practices in site-specific management depends on soil type, cropping systems, climate, fertilizer application, and management practices (Rahman et al. 2008). The density of crop roots is usually greater near the soil surface under zero tillage compared to conventional tillage (Qin et al. 2004), as more nutrients are taken up from near the soil surface as illustrated by a significantly higher P uptake by corn from the 0–7.5 cm soil layer under zero tillage than under conventional tillage (Mackay et al. 1987).

4.2.3.1 Nitrogen

Nitrogen is the most important nutrient for plant growth, yield, quality and the environment, with extensive literature on the effect of N on crop yields (Marschner 1995; Fageria et al. 2008). The efficient use of N fertilizer is important for crop yield, the environment, and the adoption of CA and depends on the level of available N in the rooting zone. Applied N fertilizer rates should consider the available N in soils and other factors that affect crop response to N fertilization. Despite the importance of soil tests for N application, the adjustment of fertilizer rates as a result of soil tests is rare, together with calculations for N agronomic efficiency and the profit that can be gained by N fertilization. This is because these studies require trials on farmers' fields for several years. In addition, apart from inorganic N, organic soil N mineralized during crop growth can provide N for the crop (Mengel et al. 2001). A number of different extraction methods have been proposed to determine soil N levels (Sparks et al. 1996; Mengel et al. 2001).

In addition to soil N status measurements, several other diagnostic tools have been developed to determine N deficiency, which is used to improve N management and decrease the risk of N loss to ground and surface waters (Fageria and Baligar 2005; Lemaire et al. 2008). The plant-based diagnostic methods such as chlorophyll meters provide a valuable estimation of the N status of the crop (Piekielek and Fox 1992; Dordas and Sioulas 2008; Dordas et al. 2008; Lemaire et al. 2008; Ziadi et al. 2008; Lemaire and Gastal 2009; Ziadi et al. 2010). Other diagnostic tools such as the nitrogen nutrition index (NNI) may be used to determine the level of plant N nutrition (Debaeke et al. 2006; Prost and Jeuffroy 2007; Dordas 2011) and is calculated by dividing the actual N concentration by the critical N concentration (N_c). N_c is defined as the minimum N concentration in shoot biomass required for maximum growth. The NNI is considered as a reference tool for assessing plant N status, but has limitations at the farm level as the actual crop biomass and its N concentration need to be determined at different growth stages which can be difficult. A more simplified method to evaluate crop N status and estimate NNI is needed.

During the first few years of CA, N is mainly found in organic forms (immobilized) and is not available for plants (Verhulst et al. 2010) because the mineralization process in the first years is quite slow and there is a need for application of N fertilizer which can speed up the mineralization process. In the years following the adoption of CA, soil microorganisms will significantly increase and essential plant nutrients will be efficiently recycled leading to less need for fertilizers. Therefore, N needs to be managed carefully to avoid N deficiency due to slow mineralization, immobilization, and volatilization, and to avoid excess N fertilization. There are several options that allow sufficient time for SOM to decompose before sowing the crop. Application of N fertilizer (25–70 kg ha^{-1}) before sowing will speed up mineralization. During sowing, N can be applied in bands to prevent immobilization and provide young seedlings with adequate N. The use of nitrate fertilizers is preferred over ammonium fertilizers as nitrate dissolves easier and is more mobile in soil.

Soil mineral N available for plant uptake depends on the rate of C mineralization. There is no clear trend on the effect of reduced tillage on residue retention and N mineralization as zero tillage is generally associated with lower N availability due to increased immobilization by residues left on the soil surface (Rice and Smith 1984; Bradford and Peterson 2000; Table 4.1). The net immobilization phase, when zero tillage is adopted, is transitory and immobilization of N under zero tillage systems in the longer term reduces the opportunity for leaching and denitrification losses of soil mineral N (Rice et al. 1986; Follet and Schimel 1989). Higher immobilization in CA systems can increase the conservation of soil and fertilizer N in the long run, and the higher initial N fertilizer requirements decrease over time because of reduced losses by erosion and the buildup of a larger pool of readily mineralizable organic N (Schoenau and Campbell 1996). In addition, the efficiency of chemical fertilizers can be increased by applying them to mulch rather than to soil (Verhulst et al. 2010).

CA affects total N content, which is closely related to total SOC, as the N cycle is closely linked to the C cycle (Bradford and Peterson 2000; Table 4.1). A higher total N content under both zero tillage and permanent raised beds compared to conventional tillage has been reported (Borie et al. 2006; Astier et al. 2006; Govaerts et al. 2007b). However, no influence of tillage or cropping system on SOC and total N contents has been observed in some experiments (Sainju et al. 2008). Zero tillage affects mineralizable N and the light fraction of soil N more than total N

(Larney et al. 1997). Significant increases in total N have been measured with increasing additions of crop residue (Graham et al. 2002) and the amount of straw retained under permanent raised beds (Govaerts et al. 2007b).

Tillage practices also affect N mineralization as tillage increases aggregate disruption, and the SOC is more accessible to soil microorganisms (Beare et al. 1994; Six et al. 2002); thereby increasing mineral N released from active and physically protected N pools (Kristensen et al. 2000). In permanent raised beds, residue retention caused more stable macroaggregates and increased the protection of C and N in the microaggregates within the macroaggregates compared to conventionally tilled raised beds (Lichter et al. 2008). In addition, there is increased susceptibility to leaching or denitrification if the growing crop does not take advantage of these nutrients at the time of their release (Doran 1980; Christensen et al. 1994; Randall and Iragavarapu 1995). In corn, NO_3-N losses were about 5 % higher with conventional tillage compared to zero tillage (Randall and Iragavarapu 1995). In the initial years after switching to zero tillage, there was no effect on N availability (Jowkin and Schoenau 1998). However, the N mineralization rate increased as tillage decreased (Larney et al. 1997). Similarly, Wienhold and Halvorson (1999) reported that N mineralization generally increased in the 0–5 cm soil layer as the intensity of tillage decreased. Govaerts et al. (2006) observed that after 26 cropping seasons in a high-yielding, high-input irrigated production system, the N mineralization rate was higher in permanent raised beds with residue retention than in conventionally tilled raised beds with all residues incorporated, and that it increased with increasing rate of inorganic N fertilizer application. The tillage system determines the placement of residues. In a conventional tillage system, crop residues are incorporated, while in the case of zero tillage, residues are left on the soil surface. These placement differences contribute to the effect of tillage on N dynamics. Incorporated crop residues decomposed 1.5 times faster than surface-placed residues (Kushwaha et al. 2000; Balota et al. 2004). However, the type of residues and the interactions with N management practices may also affect C and N mineralization (Verachtert et al. 2009).

The composition of crop residues left on the field can affect their decomposition (Trinsoutrot et al. 2000). The C/N ratio of crop residues is used as a criterion for residue quality (Vanlauwe et al. 1996; Nicolardot et al. 2001; Hadas et al. 2004) together with initial residue N, lignin, polyphenols, and soluble C concentrations (Thomas and Asakawa 1993; Trinsoutrot et al. 2000; Moretto et al. 2001). Inorganic N can be immobilized during decomposition of SOM especially when organic material with a large C/N ratio is added to the soil (Zagal and Persson 1994). Total soil N mineralization has been significantly correlated with the C/N ratio of crop residues (Kumar and Goh 2002). Some plant species used as cover crops (such as *Tithonia diversifolia*) have relatively high N and P contents, while their crop residues have very low N (ca. 1 %) and P contents (ca. 0.1 %; Palm et al. 2001). However, these residues are more important in contributing to SOM buildup than as inorganic nutrient sources for plant growth because of their lignin and polyphenol contents (Palm et al. 2001). N immobilization can be significant when cereal residues are incorporated during the first years of implementation (Erenstein 2002). Kandeler et al. (1999) found that after a 4-year period, N mineralization in a conventionally tilled treatment was significantly higher than that in minimum and reduced tillage plots due to buried organic materials. In contrast, others observed that in soil with retention of maize residues, N immobilization still occurred after 13 years in an irrigated maize–wheat rotation system (Govaerts et al. 2006).

In conclusion, CA affects N soil levels especially during the first years of application as mineralization is quite slow which can lead to N deficiency. However, this can be corrected with N application to speed up the N mineralization process and with careful N management to ensure the availability of N for the crop plants. In addition, in the following years after adoption of CA, soil microorganisms increase and the essential nutrients are efficiently recycled leading to lower need for chemical fertilizers.

4.2.3.2 Phosphorus

Phosphorus (P) is the second most common nutrient applied to crops, is a part of many organic molecules of the cell (deoxyribonucleic acid (DNA), ribonucleic acid (RNA), adenosine triphosphate (ATP), and phospholipids) and is involved in many metabolic processes making it an important plant nutrient. Conservation tillage in most cases improves the availability of surface phosphorus by converting it into organic phosphorus. Plants take up P from below, "mining" and depositing it on the surface. In conventional tillage systems, P is remixed into the soil profile, whereas in conservation tillage P accumulates at the soil surface (Robbins and Voss 1991; Zibilske et al. 2002). Therefore, conservation of P may be a potential benefit of conservation tillage, improving P availability.

Several studies found higher extractable P levels in zero tillage compared with tilled soil (e.g., Follett and Peterson 1988; Franzluebbers and Hons 1996; Du Preez et al. 2001; Duiker and Beegle 2006; Table 4.1). This is because reduced mixing of fertilizer P with the soil leads to lower P-fixation. This is an important benefit when P is limiting, but may be a threat when there is excess P due to the possibility of soluble P losses in runoff water (Duiker and Beegle 2006). After 20 years of zero tillage, extractable P was 42 % greater at 0–5 cm, but 8–18 % lower at 5–30 cm depth compared with conventional tillage treatments in a silt loam soil (Ismail et al. 1994). Others found higher extractable P levels in zero tillage compared to tilled soil in the topsoil (Unger 1991). Therefore, accumulation of P at the soil surface under continuous zero tillage is commonly observed (e.g., Eckert and Johnson 1985; Follett and Peterson 1988; Franzluebbers and Hons 1996; Table 4.1). Concentrations of P are higher in the surface layers of all tillage systems compared to deeper layers, but are most striking in zero tillage (Duiker and Beegle 2006). When P fertilizers are used on the soil surface, a part of P will be directly fixed by soil particles making it unavailable for the crop plants. However, when P was banded as a starter application below the soil surface, there was P stratification which was taken up by the crop plants (Eckert and Johnson 1985; Duiker and Beegle 2006). This suggests that there may be less need for P starter fertilizer in long-term zero tillage because of high available P levels in the topsoil where the seed is placed (Duiker and Beegle 2006). Placement of P in zero tillage deeper in the soil may be beneficial if the surface soil dries out frequently during the growing season. However, if mulch is present on the soil surface in zero tillage, the surface soil is likely to be moister than conventionally tilled soils and the need for deep P placement is unlikely, especially in humid areas. Extractable P is redistributed in zero tillage compared with conventional tillage which is likely a direct result of surface placement of crop residues leading to accumulation of SOM and microbial biomass near the surface (Duiker and Beegle 2006). However, others found higher extractable P levels below the tillage zone, probably due to accumulation of P in senescent roots and the higher SOC content of the soil (Franzluebbers and Hons 1996). In contrast, in other studies available P was not affected by tillage system, soil depth, and crop type (Roldan et al. 2007).

4.2.3.3 Potassium

After nitrogen and phosphorus, potassium (K) is the nutrient most likely to limit plant production. In conservation tillage systems, K stays at the surface because it is not remixed by tillage (Robbins and Voss 1991). This redistribution of K can limit its availability to deeper-rooting crops or increase salinity problems. Cover cropping and conservation tillage may conserve K by taking up and redistributing it to the soil surface. Zero tillage conserves and increases the availability of K and other nutrients near the soil surface where crop roots proliferate (Franzluebbers and Hons 1996). Govaerts et al. (2007b) reported 1.65 and 1.43 times higher K concentrations in the 0–5 cm and 5–20 cm layers, respectively, on permanent raised beds than conventionally tilled raised beds, both with crop residue retention. A higher extractable K levels at the soil surface with decreased tillage intensity has also been reported (Lal et al. 1990; Unger 1991; Ismail et al. 1994). Du Preez et al. (2001) found higher levels of K in zero tillage compared to conventional tillage, and this effect declined with depth. However, others found surface accumulation of available K irrespective of tillage practice (Hulugalle and Entwistle 1997; Duiker and Beegle 2006). There is no clear trend with regard to soil extractable K as some authors reported either higher or similar extractable K levels in zero tillage compared to mouldboard tillage (Follett and Peterson 1988), while others reported no effect of tillage or depth on available K concentrations (Roldan et al. 2007). In contrast, Standley et al. (1990) observed higher exchangeable K in the topsoil (0–2 cm) when sorghum stubble was retained rather than removed. The increased K concentration was more pronounced for wheat than for maize because wheat takes up large amounts of K, and most of this remains in harvest residues (Du Preez et al. 2001). K accumulated in the rows of the previous crop, probably because it leached from the crop residue that accumulated there (Duiker and Beegle 2006). Higher concentrations of K were observed in crop rows of the zero tillage treatment but not the mouldboard tillage (Mackay et al. 1987).

4.3 Crop Management and its Effect on Nutrient Management

Sustainable agriculture approaches provide balanced plant nutrition and help to increase the availability of certain elements (Oborn et al. 2003). Approaches such as crop rotation, green manuring, manure application, residue retention, and tillage can affect nutrient availability and also plant growth and crop yield.

4.3.1 Soil Organic Matter

SOM content and quality affects many soil functions which are related to soil health such as moisture retention, infiltration, release, and plant health. Field-applied organic residues (crop residues, cover crops, and organic wastes) can affect soil microorganisms and thus the availability of nutrients (Stone et al. 2004). Practices such as addition of sphagnum peat, green manures, and animal manures have produced suppressive soils on which plant pathogens do not establish or persist and do not affect crop plants. Suggested mechanisms involved in biological and organic material-mediated disease suppression include microbiostasis, microbial colonization of pathogen propagulates, destruction of pathogen propagulates, antibiosis, competition for substrate colonization, competition for root infection sites, and induced system resistance (or systemic acquired resistance (SAR); Dordas 2008; Huber and Graham 1999). SOM quantity and quality can affect plant nutrient status and impact not only total soil nutrient content but also nutrient availability through the activity of soil microorganisms (Dordas 2008; Huber and Graham 1999).

4.3.2 Crop Rotations and Residue Management

Crop rotation is the practice of growing a sequence of different crops on the same field. Long-term experiments (more than 100 years) have shown that crop rotation together with other fertility management practices is fundamental to long-term agricultural productivity and sustainability (Reid et al. 2001; Stone et al. 2004). The most straightforward principle underlying crop rotation is disease and pest control as plant pathogen propagules have a lifetime in soils and by rotating with nonhost crops, starves them (Reid et al. 2001). Crop rotation can increase N levels and affect the availability of other nutrients which can then affect growth and yield of crop plants (Huber and Graham 1999; Reid et al. 2001). Crop rotation also affects the survival of pathogens and has been used extensively to reduce the severity of many diseases, pest and weed infestations.

Soil cover and residue management can change soil chemical, physical, and biological properties including the composition of the soil microbial community, and can affect the availability of nutrients (Dordas 2008). The extent of the effect depends on the plant species and cultivars. Cover crops can increase the active OM content in the soil, microbial biomass, and microbial activity and contribute to the suppression of pathogens and better crop growth. Cover crops affect the rhizosphere and indirectly can affect plant nutrient status (Huber and Graham 1999).

Green manure can affect the availability of N and other nutrients such as P and K. Most green manure species can fix N with N-fixing bacteria and increase soil N levels by 459 kg N ha^{-1} (Cherr et al. 2006). This can have a significant effect on disease and pest development. Green manures can also affect the availability of other nutrients such as P, Mn, Zn, which can affect disease and pest tolerance and crop growth and yield (Graham and Webb 1991; Huber and Graham 1999).

4.3.3 Tillage, Pest and Nutrient Management

Reduced-tillage systems or zero tillage can increase SOM content in many agricultural systems. Reduced tillage has the advantage that it conserves SOM and reduces erosion, energy consumption, and production costs (Carter 1994; Fernandez et al. 1998). It can also alter the soil environment and these changes can result in an increase, decrease, or no change in disease and pest incidence or severity depending on the cropping system and disease/pest (Dordas 2008; Ziadi et al. 2013). Minimum tillage concentrates residues at the soil surface and therefore concentrates pathogen propagule numbers at the soil surface; this may or may not impact disease incidence. Minimum and zero tillage do not disrupt plant residues on the soil surface as much as conventional tillage (i.e., since they tend not to bury them), thereby leaving more stubble on the soil surface. The adoption of conservation tillage by farmers has led to an increase in the incidence and severity of many stubble-borne diseases. Stand residues or residues lying on the soil surface are colonized by soil organisms much more slowly, and pathogen survival and growth in undisturbed residues is favored in these systems. Residue-colonizing pathogens are therefore favored over the reduced-tillage system and can generate significant yield reductions (Bockus and Shroyer 1998). Conservation tillage systems concentrate plant residues in the surface soil layer and microbial biomass and activity are higher in that layer (Dick 1992).

4.3.4 Impact of CA on Soil Microorganisms

Several microorganisms such as *Actinomycetes*, bacteria, fungi, protozoa, and algae exist in the rhizosphere. *Actinomycetes* play an important role in the soil especially in the decomposition of plant material as they produce bioactive metabolites that can be used to produce antibiotics and synthesize enzymes such as cellulase or lignin-degrading enzymes (McCarthy 1987; Wellington and Toth 1994). Filamentous fungi are decomposing OM such as lignin and play an important role in nutrient cycling (Parkinson 1994; van Elsas et al. 1997). Arbuscular mycorrhizal fungi are important for agriculture and are ubiquitous symbionts of most of the higher plants, including crops. Arbuscular mycorrhizal fungi act as an extension of host plant roots and absorb nutrients from the soil, especially those with low mobility such as P, Cu, and Zn (Li et al. 1991; Burkert and Robson 1994). In addition, arbuscular mycorrhizae interact with pathogens and other rhizosphere inhabitants affecting plant health and nutrition. Fungi are also important in soil conservation as they are involved in soil aggregation (Roldán et al. 2007).

Crop residues can serve as a continuous energy source for soil microorganisms when retained in the soil. Crop residues can increase microbial abundance as conditions are ideal for reproduction (Carter and Mele 1992; Salinas-Garcia et al. 2002). Govaerts et al. (2008) found increased populations of *Actinomycetes*, total bacteria, and fluorescent *Pseudomonas* under both zero and conventional tillage when crop residue was retained which indicates a clear interaction between tillage and residue management on microflora populations. Others found that reduced tillage stimulated rhizosphere bacteria, particularly *Agrobacterium* spp. and *Pseudomonas* spp., in different soil layers in different crop species, e.g., winter wheat, winter barley, winter rye, and maize (Höflich et al. 1999). The combination of zero tillage and residue retention seems to increase microflora and not zero tillage per se.

Crop residues that remain at the soil surface under no-tillage conditions have increased populations of fungi (Hendrix et al. 1986). Under zero tillage, parameters which indicate the size of the mycorrhizal population such as arbuscular mycorrhizal spore number, active hyphal length, and glomalin concentration are higher in the topsoil (0–10 cm) compared with those in the tillage treatments (Borie et al. 2006; Roldan et al. 2007). Under zero tillage systems, fungi generally dominate while under conventional tillage systems the bacterial population increases depending on whether the measurements are made near the soil surface or deeper in the soil profile (Kladivko 2001).

Under conventional tillage, root colonization by arbuscular mycorrhiza may decrease due to disruption of the mycorrhizal hyphae network. In addition, tillage transports hyphae and colonized root fragments to the upper soil layer, reducing and diluting their activity as viable propagules for the following crops (Borie et al. 2006). The differences in fungal populations between zero and conventional tillage systems are due to the ability of an ecosystem to withstand disturbance, where bacterial-dominated systems are more resilient than fungal-dominated systems due to the different energy pathways (Bardgett and Cook 1998; Simmons and Coleman 2008). Fungi are characterized as slow energy microorganisms while bacteria breakdown quicker via a "fast" energy channel (Coleman et al. 1983; Hendrix et al. 1986; de Ruiter et al. 1998). An increased population of fungal feeding nematodes in the 0–5 cm layer under zero tillage, reportedly showed decomposition processes occurring predominantly through the slower, fungal-based channel instead of the bacterial-based energy channel (Bell et al. 2006).

CA can affect soil microorganisms and especially biological N fixation (N_2) by legumes, an important biological phenomenon that adds N to agricultural systems reducing the need for chemical fertilizers. Crop rotation with legumes can maintain productivity of the land for many years (Papastylianou 1999; Cherr et al. 2006). More than 60% of the N inputs to natural plant communities have a biological origin (Postgate and Hills 1979). The amount of N fixed by legumes depends on the soil–plant environment and can be around 70 kg N year^{-1} ha^{-1} (Larue and Patterson 1981). Better crop management can increase N fixation in cropping systems, e.g., in the case of acid soils where N_2 fixation is low and increasing the pH of soil through liming improves N_2 fixation significantly (Correa et al. 2001). Organisms living free in the soil and not directly associated with higher plants are capable of nonsymbiotic N fixation. Many bacteria were studied for N fixation including *Beijerinckia, Azotobacter,* and *Clostridium* (Davis et al. 2003). *Azospirillum* is a bacterium that lives in the rhizosphere of tropical grass roots. There are photosynthetic bacteria and cyanobacteria (blue-green algae) that live near the soil surface which can fix N nonsymbiotically (Davis et al. 2003). The contribution of nonsymbiotic N_2 fixation from microorganisms to arable soils is quite small and can be around 5 kg N ha^{-1} year^{-1} (Steyn and Delwiche 1970).

4.4 Breeding for Better NUE in CA

Plant breeding may contribute to increasing productivity of CA by investigating and exploiting genetic variability under CA conditions. Studies have shown significant differences among cultivar performance when evaluated under different agronomic systems (O'Leary and Smith 1999). Thus, in order to identify suitable genotypes for CA, it may not be enough to merely evaluate genetic material developed for CA under high inputs with conventional tillage and without crop rotation, and with no residue retention. Selection for system yield under CA revealed adaptation to the CA environment that was not matched by selection for crop yield in conventional agriculture (O'Leary and Smith 2004). This suggests the need for further research on the value of separate breeding programs to develop varieties adapted to CA conditions and cultural methods.

As previously mentioned, for a CA system to be biologically advantageous, the genotypes need to be chosen with care. Unfortunately, the interactions among plants, animals, and microorganisms in a crop are so subtle and specific to particular locations that present knowledge only provides a rough guide as to what crops and varieties should be tried. Consequently, if the advantages of CA are to be exploited, then local experimentation will be needed using different crop species and cultivars over several seasons. However, in reality, it is not usually the biological but the economic advantage which decides which cropping systems are actually used.

Breeding and selection for nutrient-efficient species or genotypes within a species is important to reduce fertilizer input costs and contamination of soil, air, and water resources (Fageria et al. 2008). Significant efforts improved the yield potential in wheat, maize, soybean, and peanuts (Gifford et al. 1984; Ho 1988). In addition, several studies found genetic variability for macro- and micronutrient use or requirement in several species (Clark and Duncan 1991; Baligar and Fageria 1999;

Baligar et al. 2001; Fageria and Baligar 2005; Hillel and Rosenzweig 2005). Since micronutrients are required in small amounts by crop plants, the use of efficient genotypes can meet their requirements. In addition, important research has identified crop species and genotypes within a species which are efficient in nutrient use and tolerate elemental toxicity (Graham 1983; Foy 1984, 1992; Maas 1986; Clark and Duncan 1991; Marschner 1995; Baligar et al. 2001; Blamey 2001; Okada and Fischer 2001; Fageria et al. 2003; Yang et al. 2004; Epstein and Bloom 2005; Fageria and Baligar 2005; Fageria et al. 2006). Despite the published studies on breeding for nutrient efficiency, the release of new crop cultivars with improved nutrient efficiency is limited. Iron deficiency selection for iron-efficient genotypes in maize, sorghum, rice, and soybean lead to increased yields in calcareous soils (Graham 1983). Iron deficiency is widespread and a major problem for crop plants grown on calcareous or alkaline soils; the use of efficient genotypes is the best solution for correcting this problem (Welch et al. 1991; Marschner 1995; Fageria et al. 2003). Iron efficiency ranges from monogenic to polygenic control and the gene action can be additive or dominant (Duncan 1994; Duncan and Carrow 1999). Efforts to find efficient genotypes for major nutrients, e.g., N, P, and K concluded that under nutrient deficiency, grain yield is very low, so efficient genotypes need an appropriate amount of fertilizer. The genetic basis for the plant responses to N, P, and K are not well understood and appear complex (Clark and Duncan 1991). The heritability of some N-efficiency traits was relatively high, however, the heritability of other traits was low (Clark and Duncan 1991). In addition, P efficiency is heritable and can be used to improve germplasm (Clark and Duncan 1991). Yield of crop plants is a quantitative trait affected by many gene and yield improvements; nutrient efficiency deserves special attention in relation to identifying physiological components causing differences among cultivars. Soil P uptake can be increased by increasing the area of the root system (Lynch 1995). Biotechnology offers the opportunity to manipulate the structure and function of plant roots for improved acquisition of soil P (Richardson 2001). Technologies developed by molecular biology can help to isolate, identify, localize, and characterize gene(s) carrying desirable nutrient efficiency traits (Clark and Duncan 1991). Genetic engineering techniques have not been used in nutrient efficiency studies. There is potential to improve nutrient efficiency in crop plants by transferring the identified genes into other species or using them as molecular markers in breeding programs for CA.

There are several traits that can affect NUE (Fig. 4.1) such as demand at a cellular level (compartmentation, binding form), utilization within the shoot (e.g., retranslocation) and from seed reserves. In addition, the transport of nutrients a short distance (within the root) or long distance (root–shoot transport), and the compartmentation/binding form within the root can affect plant nutrient use (Marschner 1995). It is also important that the acquisition of nutrients by plants, is affected by root geometry/morphology (such as decreasing root radius, increasing mean root density, increasing root length and depth, increasing lateral spreading, branching, and number of root hairs). In addition, root physiology and biochemistry can affect nutrient uptake through the higher affinity of the uptake system (K_m), the threshold concentration (C_{min}), and modification of the rhizosphere (pH, oxidation

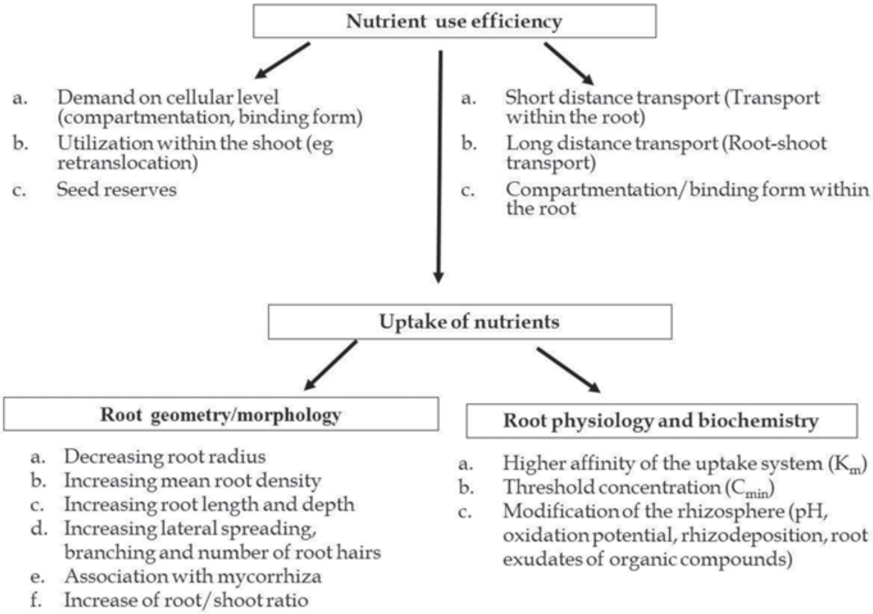


Fig. 4.1 Mechanisms of nutrient efficiency in plants. (Marschner 1995; Fageria et al. 2008)

potential, rhizodeposition, root exudates of organic compounds; Marschner 1995; Fageria et al. 2008).

Genetic variation in NUE and its components is important for improving NUE under low and high nutrient levels. Improvements in NUE (especially N) in wheat under low N supply occurred by improving N uptake efficiency (NUpE; Ortiz-Monasterio et al. 1997; Muurinen et al. 2006; LeGouis et al. 2000) or N utilization efficiency (NUtE; Foulkes et al. 1998; Barraclough et al. 2010). Under high N supply, improved NUE was explained approximately equally by NUpE and NUtE (Foulkes et al. 1998; Ortiz-Monasterio et al. 1997; Muurinen et al. 2006). In contrast, others reported that NUpE was the most important component of NUE under both low and high N supply (Dhugga and Waines 1989). From these studies, it is clear that there is an interaction between N supply and genotype which affects NUE and its components. In addition, grain yield was closely correlated with either NUpE or NUtE at low N supply depending on location, whereas at high N supply grain yield was correlated more with NUtE than with NUpE (Ortiz-Monasterio et al. 1997; LeGouis et al. 2000).

4.5 Effect of Nutrient Management on Weed Dynamics in CA

CA can affect the weed population. Certain practices can control weeds, such as crop rotation, mulching, nutrient management, and the efficient and reduced use of herbicides (Mousques and Friedrich 2007). These practices significantly affect nutrient levels, so it is possible that better weed control can be due to the nutrient effect. Use of CA for a long time can reduce weed infestations and weed pressure even after 1 year. Mulching can have positive effects on reducing the number and weight of weeds (Mousques and Friedrich 2007). Crop residues inhibit weed seed germination, and growth leads to reduced weed seed viability and therefore reduced weed numbers (Nurbekov 2008). Seed germination of weeds was lower under CA in rice–wheat systems due to less soil disturbance as was found for littleseed canary grass (*Phalaris minor* L.; Hobbs 2007). The residues from certain crop species such as cereals can have an allelopathic effect on inhibiting weed seed germination (Steinsiek et al. 1982; Lodhi and Malik 1987; Jung et al. 2004). Certain crop management techniques can affect weeds, such as when the cover crop is cut, rolled flat or killed by herbicides. Zero tillage increases the perennial weed population more than conservation tillage because tillage destroys the weeds and prevents them from setting seeds (Carter et al. 2002).

The use of mulch residue can reduce the weed population due to light exclusion (Ross and Lembi 1985). Under zero tillage systems, germination of some weeds such as littleseed canary grass decreased as a result of less soil disturbance in the wheat crop (Hobbs and Gupta 2003). The use of herbicide-tolerant crops (soybeans, maize, cotton, canola) reduced weed problems associated with zero tillage in many countries where CA is used. Moreover, crop rotation is important in CA and leads to diversification of cropping practices which can significantly affect the weed population (Hobbs and Govaerts 2010). In addition, soil microorganisms and microbial activity increases under CA which can suppress the weed population (Kennedy 1999). However, the net effect of crop residues maintained in CA on weed control is sometimes contradictory. In some cases, the maintenance of crop residue reduced herbicide efficacy (Erbach and Lovely 1975; Forcella et al. 1994) while in other cases, rainfall washed intercepted herbicides into the soil and efficacy remained high (Johnson et al. 1989) or the crop residue suppressed weed seed germination and/or seedling growth, thereby complementing the effects of herbicides (Crutchfield et al. 1986). All these CA practices have a direct effect on nutrient availability, yet there are no studies on the effect of nutrient availability under CA conditions on the weed population and dynamics. Therefore, research is needed on the interaction between CA, nutrient management, and weed population and infection.

4.6 Effect of Nutrient Management on Insect Pests and Disease Infestation in CA

Nutrients are important for growth and development of plants. They are also important factors in insect pest and disease control (Agrios 2005; Dordas 2008). The essential nutrients can affect the infestation of crop plants by pests and the disease severity (Huber and Graham 1999). There is no general rule of thumb as one nutrient can decrease the severity of a pest and at the same time increase the severity of other pests, and could have the opposite effect in a different environment (Huber 1980; Graham and Webb 1991; Marschner 1995). Despite the importance of nutrients on pest and disease control, nutrient management to control pests and diseases in CA has received little attention (Huber and Graham 1999; Dordas 2008).

Nutrients can affect pest and disease resistance or tolerance (Graham and Webb 1991). Resistance of the host is its ability to limit the penetration, development, and reproduction of attacking pests (Graham and Webb 1991). Tolerance of the host is measured in terms of its ability to maintain its own growth or yield in spite of the infection. Resistance depends on the genotype of the two organisms, plant age, and with changes in the environment. Although plant pest and disease resistance and tolerance are genetically controlled (Agrios 2005), they are affected by the environment, particularly by nutrient deficiencies and toxicities (Marschner 1995; Krauss 1999). The physiological functions of plant nutrients are generally well understood, but there are still unanswered questions regarding the dynamic interaction between nutrients and the plant–pathogen system. A number of studies have shown the importance of the correct nutrient management to control diseases in order to obtain higher yield (Marschner 1995; Huber and Graham 1999; Graham and Webb 1991; Dordas 2008 and references therein). However, there is no enough information regarding appropriate crop management practices in CA to reduce yield losses from pests and diseases. Many factors can affect the severity of plant disease, such as seeding date, crop rotation, mulching and mineral nutrients, organic amendments (manures and green manures), liming for pH adjustment, tillage and seedbed preparation, and irrigation (Huber and Graham 1999). Many of these practices are used in CA and can affect the level of nutrients available for both plant and pathogen which affects disease severity.

It is important to manage nutrient availability through fertilizer or change the soil environment to influence nutrient availability; in that way, plant disease is controlled in an integrated pest management system (Huber and Graham 1999; Graham and Webb 1991). The use of fertilizers produces a more direct means of using nutrients to reduce the severity of many diseases and, together with cultural practices, can affect the control of diseases (Marschner 1995; Atkinson and McKinlay 1997; Oborn et al. 2003).

Nutrients can affect the development of a pest or disease by affecting plant physiology or by affecting the pest, the pathogen, or both. The level of nutrients can influence plant growth which can affect the microclimate and therefore the infection, growth, and development of the pathogen (Marschner 1995). The level of nutrients can affect the physiology and biochemistry of crop plants, especially the integrity of cell walls, the membrane leakage, and the chemical composition of the host, e.g., the concentration of phenolics can be affected by B deficiency and therefore the infection by fungi (Graham and Webb 1991). Nutrients can affect the growth rate of the host which enables seedlings to escape/avoid infection at the most susceptible stages. In addition, fertilizers and especially organic fertilizers can influence the soil environment by altering the microorganism population and species and the development of pathogens and pests.

Fertilizer application affects the development of pests under field conditions directly through the nutritional status of the plant and indirectly by affecting the conditions which influence the development of pests, such as dense stands and changes in light interception and humidity within the crop stand. It is important to provide balanced nutrition at the critical time when the nutrient is most effective for pest control and higher crop yields. It is not only fertilizer application that affects disease development but other factors also affect the soil environment, such as pH modification through lime application, tillage, seedbed firmness, moisture control (irrigation or drainage), crop rotation, cover crops, green manures, manures, and mulch.

There are several studies on insect-pest dynamics under CA with different results. Reduced tillage generally increases the number of insect pests (Musick and Beasley 1978) and increases the diversity of predators and parasites of crop-damaging insects (Stinner and House 1990). Crop rotations used in CA can reduce the insect pest population by breaking the cycles of insect pests, diseases, and weeds. During the transition from conventional agriculture to CA, there may be more crop loss due to insect pests when the population of predators/parasites is low. It is possible that a diversified double-cropping system can be effective in solving the problems associated with insect pests, diseases, weeds, and herbicide resistance (Mousques and Friedrich 2007). Reduced soil tillage and soil cover can protect the biological components of the soil and keep pests and diseases under control while increasing biological diversity (Hobbs and Govaerts 2010). When the diversity of microorganisms has increased, it is possible to have integrated pest control under CA and, together with better nutrient management, the effects will be better. Moreover, conservation practices which enhance biological activity and diversity and predators/competitors can improve pest management. In addition, nematodes can increase as SOM increases which stimulates the action of several fungi-attacking nematodes and their eggs (Forcella et al. 1994). Reduced tillage can affect the various pathogens differently depending on their survival strategies and life cycle (Bockus and Shroyer 1998) and soil moisture and temperature (Krupinsky et al. 2002).

Crop rotation is important under zero tillage as it decreases pathogen numbers and reduces pathogen carryover from one season to another (Reid et al. 2001; Stone et al. 2004). This environment can be more antagonistic to pathogens due to competition (Cook 1990) and to cooler temperatures (Knudsen et al. 1995). Residue management can affect the balance of beneficial and detrimental microorganisms in the soil (Cook 1990). Zero tillage over the long term creates favorable conditions for the development of predators, by creating a new ecological stability. In addition, some crop residues reduce the damage to crops which can be due to inhibitory chemicals, stimulatory chemicals that promote beneficial microbial control agents, high C/N ratios which increase the populations of competitive pathogenic species, and higher soil water contents that increase crop vigor making them less susceptible to diseases (Huber and Graham 1999; Graham and Webb 1991). Crop residues are sources of food for bacteria, fungi, nematodes, earthworms, and arthropods which can cause major changes in disease pressure in CA (Hobbs and Govaerts 2010). Increased soil microbial biomass suppresses pathogens as increased numbers of microorganisms compete for resources or cause inhibition through antagonism or the release of antibiotic (Cook 1990; Sturz et al. 1997; Weller et al. 2002). Better disease control occurred in zero tillage and conservation tillage compared with conventional tillage (Govaerts et al. 2007a).

4.7 Challenges and Future Outlook

More research is needed to find the effect of different CA practices on crop yield and nutrient dynamics especially in long-term experiments. Best integrated management approaches should be optimized with new varieties which can be combined with specific cultural management techniques and CA. The influence of different management practices on nutrient dynamics should also be explored. Despite the fact that each nutrient has several functions, mild deficiency can usually be linked to one or more sensitive processes which are linked to secondary metabolism and not immediately necessary for the survival of the organism. Secondary metabolism is involved in the defense against pests and weeds; some of the roles are well understood while others remain to be determined.

The reduction in crop production costs, conservation of beneficial biological enemies of pests, preservation of environmental quality, and slowing the rate of development of pesticide-resistant strains are some of the benefits that fertilizer use can have on integrated pest management and sustainable agriculture. Increases in NUE under CA should be studied, especially the use of more efficient genotypes. Breeding programs should be developed under CA conditions in different environments.

4.8 Conclusions

CA is a sustainable and eco-friendly crop production technique which is practiced in many countries of the world. Although slight yield reductions have been reported during the initial years of adoption, the reduction in cultivation costs due to reduced tillage and higher input-use efficiency has resulted in minimal effects on economic returns for farmers. In addition, CA has important benefits such as soil conservation with improved soil health, higher rain-water-use efficiency, climate change mitigation and adaptation, improved biodiversity, resilience to climate shocks, higher economic returns, and more leisure time for farmers. It is important that medium to long-term studies on CA and nutrient management are conducted in different environments to better guide farmers to successful adoption. In sustainable agriculture, balanced nutrition is an essential component of any integrative crop protection program because in most cases it is more cost-effective and environmental friendly to control plant disease with adequate amounts of nutrients and no pesticides. Nutrients can reduce disease to an acceptable level or at least to a level where further control by other cultural practices or conventional organic biocides are more successful and less expensive.

Many CA practices affect soil processes such as increased SOM content and soil porosity, increased biological nitrogen fixation by legumes in rotation, or exploitation of deeper soil layers by crops with deep and dense root systems, all of which have a significant bearing on nutrient management. In addition, the nutrient requirements of CA systems are lower than conventional agriculture, as nutrient efficiencies are higher and the risk of polluting water systems with mineral nutrients is lower. Moreover, nutrients are a necessary production input but not a sufficient condition for sustainable production intensification. In CA systems, the emphasis is on managing soil health and productive capacity simultaneously, which depends on many complex cropping system relationships in space and time, and biodiversity and OM within soil systems when enlisted for agricultural production. The management of nutrient input–output relationships in CA systems must balance the nutrient accounts. The output levels of biological products will dictate the levels of inputs, and ongoing nutrient balances must remain positive. The major difference with CA systems is the management of multiple sources of nutrients and the processes by which they are acquired, stored, and made available to crops are more biologically mediated. More research is needed on different aspects of soil health and nutrient management in CA systems, as more countries begin to adopt and integrate CA concepts and practices into commercial production activities at both small and large scales for future sustainable production. In many countries, there is a growing interest in applying CA technologies and practices, and as attempts are made to move farming towards CA, policy and institutional support must be provided to accelerate the transformation of these agricultural practices. This transformation must be backed up by new scientific thinking and research, including in the area of nutrient management, to fill the knowledge gap that currently exists about CA in different environments and countries.

Acknowledgments The author wishes to thank Professor A. Gagianas, Faculty of Agriculture, Forestry and Natural Environment Aristotle University of Thessaloniki, and also the editors of the book for their critical review and constructive comments of this book chapter.

References

Afif E, Barrón V, Torrent J (1995) Organic matter delays but does not prevent phosphate sorption by cerrado soils from Brazil. Soil Sci 159:207–211

Agrios NG (2005) Plant pathology, 5th edn. Elsevier Academic, San Diego, p 635

Astier M, Maass JM, Etchevers-Barra JD, Pena JJ, Gonzalez FD (2006) Short-term green manure and tillage management effects on maize yield and soil quality in an Andisol. Soil Till Res 88:153–159

Atkinson D, McKinlay RG (1997) Crop protection and its integration within sustainable farming systems. Agric Ecosyst Environ 64:87–93

Baligar VC, Fageria NK (1999) Plant nutrient use efficiency: towards the second paradigm. In: Siqueira JO, Moreira FMS, Lopes AS, Guilherme LRG, Farquin V, Furtini Neto AE, Carvalho JG (eds) Soil fertility, soil biology and plant nutrition interrelationships. Brazilian Soil Science Society/ Federal University of Lavras, Lavras, pp 183–204

Baligar VC, Fageria NK, He ZL (2001) Nutrient use efficiency in plants. Comm Soil Sci Plant Anal 32:921–950

Balota EL, Colozzi A, Andrade DS, Dick RP (2004) Long-term tillage and crop rotation effects on microbial biomass and C and N mineralization in a Brazilian Oxisol. Soil Till Res 77:137–145

Bardgett RD, Cook R (1998) Functional aspects of soil animal diversity in agricultural grasslands. Appl Soil Ecol 10:263–276

Barraclough PB, Howarth JR, Jones J, Lopez-Bellido R, Parmar S, Shepherd CE, Hawkesford MJ (2010) Nitrogen efficiency of wheat: genotypic and environmental variation and prospects for improvement. Europ J Agron 33:1–11

Beare MH, Hendrix PF, Coleman DC (1994) Water-stable aggregates and organic-matter fractions in conventional-tillage and no-tillage soils. Soil Sci Soc Am J 58:777–786

Bell M, Seymour N, Stirling GR, Stirling AM, Van Zwieten L, Vancov T, Sutton G, Moody P (2006) Impacts of management on soil biota in Vertosols supporting the broadacre grains industry in northern Australia. Aust J Soil Res 44:433–451

Bhatti JS, Comerford NB, Johnston CT (1998) Influence of oxalate and soil organic matter on sorption and desorption of phosphate onto a Spodic horizon. Soil Sci Soc Am J 62:1089–1095

Blamey FPC (2001) The role of root cell wall in aluminum toxicity. In: Ae N, Arihara J, Okada K, Srinivasan A (eds) Plant nutrient acquisition: new perspectives. Springer, Tokyo, pp 201–226

Blevins RL, Thomas GW, Cornelius PL (1977) Influence of no-tillage and nitrogen-fertilization on certain soil properties after 5 years of continuous corn. Agr J 69:383–386

Bockus WW, Shroyer JP (1998) The impact of reduced tillage on soil-borne plant pathogens. Annu Rev Phytopathol 36:485–500

Borie F, Rubio R, Rouanet JL, Morales A, Borie G, Rojas C (2006) Effects of tillage systems on soil characteristics, glomalin and mycorrhizal propagules in a Chilean Ultisol. Soil Till Res 88:253–261

Bradford JM, Peterson GA (2000) Conservation tillage. In: Sumner ME (ed) Handbook of soil science. CRC, Boca Raton, pp G247–G269

Brown LR (2006) Plan B 2.0: rescuing a planet under stress and a civilization in trouble. W.W. Norton & Company, New York

Burkert B, Robson A (1994) Zn-65 uptake in subterranean clover (*Trifolium-Subterraneum* L) by 3 vesicular-arbuscular Mycorrhizal fungi in a root-free sandy soil. Soil Biol Biochem 26:1117–1124

Burle B, Mielniczuk J, Focchi S (1997) Effect of cropping systems on soil chemical characteristics, with emphasis on soil acidiification. Plant Soil 190:309–316

Carpenter-Boggs L, Stahl PD, Lindstrom MJ, Schumacher TE (2003) Soil microbial properties under permanent grass, conventional tillage, and no-till management in south Dakota. Soil Till Res 71:15–23

Carter MR (1994) Strategies to overcome impediments to adoption of conservation tillage. In: Carter MR (ed) Conservation tillage in temperate agroecosystems. Lewis Publishers, Boca Raton, pp 1–22

Carter MR, Mele PM (1992) Changes in microbial biomass and structural stability at the surface of a duplex soil under direct drilling and stubble retention in North-Eastern victoria. Aust J Soil Res 30:493–503

Carter MR, Sanderson JB, Ivany JA, White RP (2002) Influence of rotation and tillage on forage maize productivity, weed species and soil quality of a fine sandy loam in the cool-humid climate of Atlantic Canada. Soil Till Res 67:85–98

Cherr CM, Scholberg JMS, McSorley R (2006) Green manure approaches to crop production: a synthesis. Agron J 98:302–319

Christensen NB, Lindemann WC, Salazarsosa E, Gill LR (1994) Nitrogen and carbon dynamics in no-till and stubble mulch tillage systems. Agr J 86:298–303

Clark RB, Duncan RR (1991) Improvement of plant mineral nutrition through breeding. Field Crops Res 27:219–240

Coleman DC, Reid CPP, Cole CV (1983) Biological strategies of nutrient cycling in soil systems. Adv Ecol Res 13:1–55

Cook RJ (1990) Twenty-five years of progress towards biological control. In: Hornby D (ed) Biological control of soil borne pathogens. CAB International, Wallingford pp 1–14

Correa OS, Aranda A, Barneix AJ (2001) Effects of pH on growth and nodulation of two forage legumes. J Plant Nutr 24:1367–1375

Crutchfield DA, Wicks GA, Burnside OC (1986) Effect of winter wheat (*Triticum aestivum*) straw mulch level on weed control. Weed Sci 34:110–114

Davis RL, Patton JJ, Teal RK, Tang Y, Humphreys MT, Mosali J, Girman J, Lawles JM, Moges SM, Malapati A, Si J, Zhang H, Deng S, Johnson GV, Mullen RW, Raun WR (2003) Nitrogen balance in the magruder plots following 109 years in continuous winter wheat. J Plant Nutr 26:1561–1580

de Ruiter PC, Neutel AM, Moore JC (1998) Biodiversity in soil ecosystems: the role of energy flow and community stability. Appl Soil Ecol 10:217–228

Debaeke P, Rouet P, Justes E (2006) Relationship between the normalized SPAD index and the nitrogen nutrition index: application to durum wheat. J Plant Nutr 29:75–92

Dhugga KS, Waines JG (1989) Analysis of nitrogen accumulation and use in bread and durum wheat. Crop Sci 29:132–139

Diamond J (2005) Collapse: how societies choose to fail or succeed. Penguin Books, New York

Dick RP (1992) A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. Agric Ecosyst Environ 40:25–36

Doran JW (1980) Soil microbial and biochemical-changes associated with reduced tillage. Soil Sci Soc Am J 44:765–771

Dordas C (2008) Role of nutrients in controlling plant diseases in sustainable agriculture: a review. Agron Sustain Develop 28:33–46

Dordas CA (2011) Nitrogen nutrition index and its relationship to N use efficiency in linseed. Europ J Agron 34:124–132

Dordas C, Sioulas C (2008) Safflower yield, chlorophyll content, photosynthesis, and water use efficiency response to nitrogen fertilization under rainfed conditions. Industrial Crop Prod 27:75–85

Dordas CA, Lithourgidis AS, Matsi Th, Barbayiannis N (2008) Application of liquid cattle manure and inorganic fertilizers affect dry matter, nitrogen accumulation, and partitioning in maize. Nutr Cycl Agroecosystems 80:283–296

Du Preez CC, Steyn JT, Kotze E (2001) Long-term effects of wheat residue management on some fertility indicators of a semi-arid Plinthosol. Soil Till Res 63:25–33

Duiker SW, Beegle DB (2006) Soil fertility distributions in long-term no-till, chisel/disk and moldboard plow/disk systems. Soil Till Res 88:30–41

Duncan RR (1994) Genetic manipulation. In: Wilkinson RE (ed) Plant environment interactions, Marcel Dekker, New York, pp 1–38

Duncan RR. Carrow RN (1999) Turfgrass molecular genetic improvement for abiotic/edaphi stress resistance. Adv Agron 67:233–306

Eckert DJ, Johnson JW (1985) Phosphorus fertilization in no-tillage corn production. Agron J 77:789–792

Epstein E, Bloom AJ (2005) Mineral nutrition of plants: principles and perspectives, 2nd edn. Sinauer Associations, Inc, Sunderland

Erbach DC, Lovely WG (1975) Effect of plant residue on herbicide performance in no-tillage corn Weed Sci 23:512–515

Erenstein O (2002) Crop residue mulching in tropical and semi-tropical countries: an evaluation of residue availability and other technological implications. Soil Till Res 67:115–133

Etana A, Hakansson I, Zagal E, Bucas S (1999) Effects of tillage depth on organic carbon content and physical properties in five Swedish soils. Soil Till Res 52:129–139

Fageria NK, Baligar VC (2005) Enhancing nitrogen use efficiency in crop plants. Adv Agron 88: 97–185

Fageria NK, Slaton NA, Baligar VC (2003) Nutrient management for improving lowland rice productivity and sustainability. Adv Agron 80:63–152

Fageria NK, Baligar VC, Clark RB (2006) Physiology of crop production. The Haworth Press, New York

Fageria NK, Baligar VC, Li YC (2008) The role of nutrient efficient plants in improving crop yields in the twenty first century. J Plant Nutr 31:1121–1157

FAO (2001) Conservation agriculture case studies in Latin America and Africa. Introduction. FAO Soils Bulletin No. 78. FAO, Rome

Fernandez MR, Zentner RP, McConkey BG, Campbell CA (1998) Effects of crop rotations and fertilizer management on leaf spotting diseases of spring wheat in southwestern Saskatchewan. Can J Plant Sci 78: 489–496

Follett RF, Peterson GA (1988) Surface soil nutrient distribution as affected by wheat-fallow tillage systems. Soil Sci Soc Am J 52:141–147

Follett RF, Schimel DS (1989) Effect of tillage on microbial biomass dynamics. Soil Sci Soc Am J 53:1091–1096

Fontes MR, Weed SB, Bowen LH (1992) Association of microcrystalline goethite and humic acid in some Oxisols from Brazil. Soil Sci Soc Am J 56:982–990

Forcella F, Buhler DD, McGiffen ME (1994) Pest management and crop residues. In: Hatfield JL, Stewart BA (eds) Crop residue management, Adv Soil Sci CRC, N W Boca Raton, pp 173–189

Foulkes MJ, Sylvester-Bradley R, Scott RK (1998) Evidence for differences between winter wheat cultivars in acquisition of soil mineral nitrogen and uptake and utilization of applied fertiliser nitrogen. J Agric Sci Camb 130: 29–44

Foy CD (1984) Physiological effects of hydrogen aluminum and manganese toxicities in acid soils In: Adams F (ed) Soil acidity and liming, 2nd edn. SSSA ASA and CSSA, Madison, pp 57–97

Foy CD (1992) Soil chemical factors limiting plant root growth. Adv Soil Sciences 19:97–149

Franzluebbers AJ (2002) Water infiltration and soil structure related to organic matter and its stratification with depth. Soil Till Res 66:197–205

Franzluebbers AJ, Hons FM (1996) Soil-profile distribution of primary and secondary plant available nutrients under conventional and no tillage. Soil Till Res 39:229–239

Galantini JA, Landriscini MR, Iglesias JO, Miglierina AM, Rosell RA (2000) The effects of crop rotation and fertilization on wheat productivity in the Pampean semiarid region of Argentina. Nutrient balance, yield and grain quality. Soil Till Res 53:137–144

Gifford RMJ, Thorne H, Hitz W, Giaquinta RT (1984) Crop productivity and photoassimilate partitioning. Science 225:801–808

Govaerts B, Sayre KD, Ceballos-Ramirez JM, Luna-Guido ML, Limon-Ortega A, Deckers J, Dendooven L (2006) Conventionally tilled and permanent raised beds with different crop residue management: effects on soil C and N dynamics. Plant Soil 280:143–155

Govaerts B, Mezzalama M, Unno Y, Sayre KD, Luna-Guido M, Vanherck K, Dendooven L, Deckers J (2007a) Influence of tillage residue management, and crop rotation on soil microbial biomass and catabolic diversity. App Soil Ecol 37:18–30

Govaerts B, Sayre KD, Lichter K, Dendooven L, Deckers J (2007b) Influence of permanent raised bed planting and residue management on physical and chemical soil quality in rainfed maize/wheat systems. Plant Soil 291:39–54

Govaerts B, Mezzalama M, Sayre KD, Crossa J, Lichter K, Troch V, Vanherck K, De Corte P, Deckers J (2008) Long-term consequences of tillage, residue management, and crop rotation on selected soil micro-flora groups in the subtropical highlands. Appl Soil Ecol 38:197–210

Graham DR (1983) Effects of nutrients stress on susceptibility of plants to disease with particular reference to the trace elements. Adv Bot Res 10:221–276

Graham DR, Webb MJ (1991). Micronutrients and disease resistance and tolerance in plants. In: Mortvedt JJ, Cox FR, Shuman LM, Welch RM (eds) Micronutrients in agriculture, 2nd edn. Soil Science Society of America Inc, Madison, pp 329–370

Graham MH, Haynes RJ, Meyer JH (2002) Soil organic matter content and quality: effects of fertilizer applications, burning and trash retention on a long-term sugarcane experiment in South Africa. Soil Biol Biochem 34:93–102

Hadas A, Kautsky L, Goek M, Kara EE (2004) Rates of decomposition of plant residues and available nitrogen in soil, related to residue composition through simulation of carbon and nitrogen turnover. Soil Biol Biochem 36:255–266

Hanson JD, Liebig MA, Merrill SD, Tanaka DL, Krupinsky JM, Stott DE (2007) Dynamic cropping systems: increasing adaptability amid an uncertain future. Agron J 99:939–943

Hendrix PF, Parmelee RW, Crossley DA, Coleman DC, Odum EP, Groffman PM (1986) detritus food webs in conventional and no-tillage agroecosystems. Bioscience 36:374–380

Hillel D, Rosenzweig C (2005) The role of biodiversity in agronomy. Adv Agron 88:1–34

Hirel B, LeGouis J, Ney B, Gallais A (2007) The challenge of improving nitrogen use efficiency in crop plants: towards a more central role for genetic variability and quantitative genetics within integrated approaches. J Exp Bot 58:2369–2387

Ho LC (1988) Metabolism and compartmentation of imported sugars in sink organs in relation to sink strength. Ann Rev Plant Phys Plant Mol Biol 39:355–378

Hobbs PR (2007) Conservation agriculture: what is it and why is it important for future sustainable food production? J Agric Sci 145:127–137

Hobbs PR, Govaerts B (2010) How conservation agriculture can contribute to buffering climate change. In: Reynolds MP (ed) Climate change and crop production. CAB International, Cambridge, USA, pp 177–199

Hobbs PR, Gupta RK (2003) Resource conserving technologies for wheat in the rice–wheat system. In: Ladha JK, Hill J, Gupta RK, Duxbury JM, Buresh RJ (eds) Improving the productivity and sustainability of rice–wheat systems: issues and impact. American Society of Agronomy (ASA), Madison, pp 149–171

Hobbs PR, Gupta RK (2004) Problems and challenges of no-till farming for the rice-wheat systems of the Indo–Gangetic Plains in South Asia. In: Lal R, Hobbs P, Uphoff N, Hansen DO (eds) Sustainable agriculture and the rice–wheat system. Ohio State University and Marcel Dekker, Inc, Ohio, pp 101–119

Höflich G, Tauschke M, Kuhn G, Werner K, Frielinghaus M, Hohn W (1999) Influence of long-term conservation tillage on soil and rhizosphere microorganisms. Biol Fert Soils 29:81–86

Huber DM (1980) The role of mineral nutrition in defense. In: Horsfall JG, Cowling EB (eds) Plant disease an advanced treatise volume 5 how plants defend themselves. Academic, New York, pp 381–406

Huber DM, Graham RD (1999) The role of nutrition in crop resistance and tolerance to disease In: Rengel Z (ed) Mineral nutrition of crops fundamental mechanisms and implications. Food Product, New York, pp 205–226

Hulugalle NR, Entwistle P (1997) Soil properties, nutrient uptake and crop growth in an irrigated Vertisol after nine years of minimum tillage. Soil Till Res 42:15–32

Ismail I, Blevins RL, Frye WW (1994) Long-term no-tillage effects on soil properties and continuous corn yields. Soil Sci Soc Am J 58:193–198

Iyamuremye F, Dick RP (1996) Organic ammendments and phosphorus sorption by soils Adv Agron 56:139–185

Johnson MD, Wyse DL, Lueschen WE (1989) The influence of herbicide formulation on weed control in four tillage systems. Weed Sci 37:239–249

Jowkin V, Schoenau JJ (1998) Impact of tillage and landscape position on nitrogen availability and yield of spring wheat in the Brown soil zone in southwestern Saskatchewan. Can J Soil Sci 78:563–572

Jung WS, Kim KH, Ahn JK, Hahn SJ, Chung IM (2004) Allelopathic potential of rice (*Oryza sativa* L.) residues against *Echinochloa crusgalli*. Crop Protect 23:211–218

Kandeler E, Tscherko D, Spiegel H (1999) Long-term monitoring of microbial biomass, N mineralisation and enzyme activities of a Chernozem under different tillage management. Biol Fert Soils 28:343–351

Kay BD (1990) Rates of change of soil structure under different cropping systems. Adv Soil Sci 12:1–52

Kennedy AC (1999) Soil microorganisms for weed management J Crop Prod 2:123–138

Kladivko EJ (2001) Tillage systems and soil ecology. Soil Till Res 61:61–76

Knudsen IMB, Hockenhull J, Jensen DF (1995) Biocontrol of seedling diseases of barley and wheat caused by Fusarium culmorum and Bipolaris sorokiniana: effects of selected fungal antagonists on growth and yield components. Plant Pathol 44:467–477

Krauss A (29 June–2 July 1999) Balanced nutrition and biotic stress. IFA Agricultural Conference on Managing Plant Nutrition, Spain

Kristensen HL, McCarty GW, Meisinger JJ (2000) Effects of soil structure disturbance on mineralization of organic soil nitrogen. Soil Sci Soc Am J 64:371–378

Krupinsky JM, Bailey KL, McMullen MP, Gossen BD, Turkington TK (2002) Managing plant disease risk in diversified cropping systems Agron J 94:198–209

Kumar K, Goh KM (2002) Management practices of antecedent leguminous and non-leguminous crop residues in relation to winter wheat yields, nitrogen uptake, soil nitrogen mineralization and simple nitrogen balance. Eur J Agr 16:295–308

Kushwaha CP, Tripathi SK, Singh KP (2000) Variations in soil microbial biomass and N availability due to residue and tillage management in a dryland rice agroecosystem. Soil Till Res 56:153–166

Lal R, Logan TJ, Fausey NR (1990) Long-term tillage effects on a mollic ochraqualf in NorthWest Ohio. 3. Soil Nutrient Profile. Soil Till Res 15:371–382

Larney FJ, Bremer E, Janzen HH, Johnston AM, Lindwall CW (1997) Changes in total, mineralizable and light fraction soil organic matter with cropping and tillage intensities in semiarid southern Alberta, Canada. Soil Till Res 42:229–240

Larue TA, Patterson TG (1981) How much nitrogen does legume fix? Adv Agron 34:15–38

LeGouis J, Beghin D, Heumez E, Pluchard P (2000) Genetic differences for nitrogen uptake and nitrogen utilisation efficiencies in winter wheat. Eur J Agron 12:163–173

Lemaire G, Gastal F (2009) Quantifying crop response to nitrogen deficiency and avenues to improve nitrogen use efficiency. In: Sadras V, Calderini D (eds) Crop physiology: applications for genetic improvements and agronomy. Elsevier Academic, California, pp 171–211

Lemaire G, Jeuffroy MH, Gastal F (2008) Diagnosis tool for plant and crop N status in vegetative stage theory and practices for crop N management. Eur J Agron 28:614–624

Lewandowski I, Hardtlein M, Kaltschmitt M (1999) Sustainable crop production: Definition and methodological approach for assessing and implementing sustainability. Crop Science 39:184–193

Li XL, Marschner H, George E (1991) Acquisition of phosphorus and copper by va-Mycorrhizal Hyphae and root-to-shoot transport in white clover. Plant Soil 136:49–57

Lichter K, Govaerts B, Six J, Sayre KD, Deckers J, Dendooven L (2008) Aggregation and C and N contents of soil organic matter fractions in a permanent raised-bed planting system in the highlands of Central Mexico. Plant Soil 305:237–252

Lodhi MAK, Malik KA (1987) Allelopathy in agroecosystems: wheat phytotoxicity and its possible role in crop rotation. J Chem Ecol 13:1881–1891

Lynch J (1995) Root architecture and plant productivity. Plant Physiol 109: 7–13

Maas EV (1986) Salt tolerance of Plants. App Agric Res 1:12–26

Mackay AD, Kladivko EJ, Barber SA, Griffith DR (1987) Phosphorus and potassium uptake by corn in conservation tillage systems. Soil Sci Soc Am J 51:970–974

Marschner H (1995) Mineral nutrition of higher plants, 2nd edn. Academic, London, pp 889–1995

McCarthy AJ (1987) Lignocellulose-degrading Actinomycetes. Fems Microbiol Rev 46:145–163

Mengel KE, Kirkbay A, Kosegarten H, Appel T (2001) Principles of plant nutrition,5th edn. Kluwer Academic Publishers, Dordrecht the Netherlands

Moll RHE, Kamprath J, Jackson WA (1982) Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. Agron J 74: 562–564

Moretto AS, Distel RA, Didone NG (2001) Decomposition and nutrient dynamic of leaf litter and roots from palatable and unpalatable grasses in a semi-arid grassland. Appl Soil Ecol 18:31–37

Mousques C, Friedrich T (2007) Conservation agriculture in china and the democratic people's republic of Korea. FAO crop and grassland service working paper, Food and Agriculture Organization of the United Nations, Rome

Musick GJ, Beasley LE (1978) Effect of crop residue management system on pest problems in field corn (*Zea mays* L.) production. In: Oshwald WR (ed) Crop residue management systems. ASA Special Publication 31, Madison, pp 173–186

Muurinen S, Slafer GA, Peltonen-Sainio P (2006) Breeding effects on nitrogen use efficiency of spring cereals under Northern conditions. Crop Sci 46:561–568

Nicolardot B, Recous S, Mary B (2001) Simulation of C and N mineralisation during crop residue decomposition: A simple dynamic model based on the C: N ratio of the residues. Plant Soil 228:83–103

Nurbekov A (2008) Manual on Conservation agriculture practices in Uzbekistan. ABU Matbuot-Consult, Tashkent, pp 40

O'Leary N, Smith ME (1999) Breeding corn for adaptation to two diverse intercropping companions. Am J Altern Agric 14: 158–164

O'Leary N, Smith ME (2004) Uncovering corn adaptation to intercrop with bean by selecting for system yield in the intercrop environment. Am J Altern Agric 24:109–121

Oborn I, Edwards AC, Witter E, Oenema O, Ivarsson K, Withers PJA, Nilsson SI, Richert Stinzing A (2003) Element balances as a toll for sustainable nutrient management: a critical appraisal of their merits and limitations within an agronomic and environmental context. Europ J Agron 20: 211–225

Okada K, Fischer AJ (2001) Adaptation mechanisms of upland rice genotypes to highly weathered acid soils of South American Savannah's. In: N Ae, J Arihara, K Okada, A Srinivasan (eds) Plant nutrient acquisition: new perspectives. Springer, Tokyo, pp 185–200

Ortiz-Monasterio JI, Sayre RKD, Rajaram S, McMahon M (1997) Genetic progress in wheat yield and nitrogen use efficiency under four nitrogen rates. Crop Sci 37:898–904

Palm CA, Giller KE, Mafongoya PL, Swift MJ (2001) Management of organic matter in the tropics: translating theory into practice. Nutr Cycl Agroecosys 61:63–75

Papastylianou I (1999) Estimation of nitrogen fixed by legumes in long-term vs short-term cropping systems. Agron J 91:329–334

Parkinson D (1994) Filamentous fungi. In: Weaver RW, Angle JS, Bottomley P, Bezdicek D, Smith S, Tabatabai A, Wollum AG (eds) Methods of soil analysis: microbiological and biochemical properties. Soil Science Society of America, Madison, pp 329–350

Piekielek WL, Fox RH (1992) Use of chlorophyll meter to predict sidedress nitrogen requirements for maize. Agron J 84:59–65

Postgate JR, Hills S (1979) Microbial ecology. Blackwell, Oxford

Powlson DS, Jenkinson DS (1981) A comparison of the organic matter, biomass, adenosine triphosphate and mineralizable nitrogen contents of ploughed and direct drilled soils. J Agric Sci 97:713–721

Prost L, Jeuffroy MH (2007) Replacing the nitrogen nutrition index by the chlorophyll meter to assess wheat N status. Agron Sustain Develop 27:1–10

Qin RJ, Stamp P, Richner W (2004) Impact of tillage on root systems of winter wheat. Agr J 96:1523–1530

Rahman MH, Okubo A, Sugiyama S, Mayland HF (2008) Physical, chemical and microbiological properties of an Andisol as related to land use and tillage practice. Soil Till Res 101:10–19

Randall GW, Iragavarapu TK (1995) Impact of long-term tillage systems for continuous corn on nitrate leaching to tile drainage. J Environ Qual 24:360–366

Raun WR, Johnson GV (1999) Improving nitrogen use efficiency for cereal production. Agron J 91:357–363

Reid LM, Zhu X, Ma BL (2001) Crop rotation and nitrogen effects on maize susceptibility to gibberella (*Fusarium graminearum*) ear rot. Plant Soil 237:1–14

Rice CW, Smith MS (1984) Short-term immobilization of fertilizer nitrogen at the surface of no-till and plowed soils. Soil Sci Soc Am J 48:295–297

Rice CW, Smith MS, Blevins RL (1986) Soil nitrogen availability after long-term continuous no-tillage and conventional tillage corn production. Soil Sci Soc Am J 50:1206–1210

Richardson AE (2001) Prospects for using soil microorganisms to improve the acquisition of phosphorus by plants. Aust J Plant Phys 28:897–906

Robbins SG, Voss RD (1991) Phosphorus and potassium stratification in conservation tillage systems. J Soil Water Conserv 46:298–300

Roldan A, Salinas-Garcia JR, Alguacil MM, Caravaca F (2007) Soil sustainability indicators following conservation tillage practices under subtropical maize and bean crops. Soil Till Res 93:273–282

Ross MA, Lembi CA (1985) Applied weed science. Macmillan Publishing Company, New York

Sainju UM, Senwo ZN, Nyakatawa EZ, Tazisong IA, Reddy KC (2008) Soil carbon and nitrogen sequestration as affected by long-term tillage, cropping systems, and nitrogen fertilizer sources. Agr Ecosyst Environ 127:234–240

Salinas-García JR, Velázquez-García JD, Gallardo-Valdez A, Díaz-Mederos P, Caballero-Hernández F, Tapia-Vargas LM, Rosales-Robles E (2002) Tillage effects on microbial biomass and nutrient distribution in soils under rain-fed corn production in central-western Mexico. Soil Till Res 66:143–152

Sanchez PA, Shepherd KD, Soule MJ, Place FM, Buresh RJ, Izac AM, Mokwunye AU, Kwesiga FR, Ndiritu CG, Woomer PL (1997) Soil fertility replenishment in Africa: an investment in natural resource capital. In: Buresh RJ, Sanchez PA, Calhoun F (eds) Replenishing soil fertility in Africa. Soil Science Society of America, Madison, pp 1–46

Schoenau JJ, Campbell CA (1996) Impact of crop residues on nutrient availability in conservation tillage systems. Can J Plant Sci 76:621–626

Scopel E, Da Silva FA, Corbeels M, Affholder FO, Maraux F (2004) Modeling crop residue mulching effects on water use and production of maize under semi-arid and humid tropical conditions. Agronomie 24:383–395

Simmons BL, Coleman DC (2008) Microbial community response to transition from conventional to conservation tillage in cotton fields. Appl Soil Ecol 40:518–528

Six J, Conant RT, Paul EA, Paustian K (2002) Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241:155–176

Sparks DL, Page AL, Helmke PA, Loeppert RH, Soltanpour PN, Tabatabai MA, Johnson CT, Sumner ME (1996) Methods of soil analysis: part 3-chemical methods, 2nd edn. ASA and SSSA, Madison (Agron Monogr 9)

Standley J, Hunter HM, Thomas GA, Blight GW, Webb AA (1990) Tillage and crop residue management affect vertisol properties and grain-sorghum growth over 7 years in the semiarid subtropics. 2. Changes in soil properties. Soil Till Res 18:367–388

Steinsiek JW, Oliver LR, Collins F (1982) Allelopathic potential of wheat (*Triticum aestivum*) straw on selected weed species. Weed Sci 30:495–497

Steyn PL, Delwiche CC (1970) Nitrogen fixation by nonsymbiotic microorganisms in some California soils. Environ Sci Tech 4:1122–1128

Stinner BR, House GJ (1990) Arthropods and other invertebrates in conservationtillage agriculture. Annual Rev Entomol 35:299–318

Stone AG, Scheuerell SJ, Darby HD (2004) Suppression of soilborne diseases in field agricultural systems: organic matter management cover cropping and other cultural practices. In: Magdoff F, Weil RR (eds) Soil organic matter in sustainable agriculture. CRC, London

Sturz AV, Carter MR, Johnston HW (1997) A review of plant disease pathogen interactions and microbial antagonism under conservation tillage in temperate humid agriculture. Soil Till Res 41: 169–189

Thomas RJ, Asakawa NM (1993) Decomposition of leaf-litter from tropical forage grasses and legumes. Soil Biol Biochem 25:1351–1361

Trinsoutrot I, Recous S, Bentz B, Lineres M, Cheneby D, Nicolardot B (2000) Biochemical quality of crop residues and carbon and nitrogen mineralization kinetics under nonlimiting nitrogen conditions. Soil Sci Soc Am J 64:918–926

Unger PW (1991) Organic-matter, nutrient, and ph distribution in no-tillage and conventional-tillage semiarid soils. Agron J 83:186–189

van Elsas JD, Trevors JT, Wellington EMH (1997) Modern soil microbiology. Marcel Dekker Inc, New York

Vanlauwe B, Nwoke OC, Sanginga N, Merckx R (1996) Impact of residue quality on the C and N mineralization of leaf and root residues of three agroforestry species. Plant Soil 183:221–231

Vanlauwe BJ, Wendt KE, Giller M, Corbeels B, Gerard C, Noltega A (2014) A fourth principle is required to define conservation agriculture in sub-Saharan Africa: the appropriate use of fertilizer to enhance crop productivity. Field Crops Res 155:10–13

Verachtert E, Govaerts B, Lichter K, Sayre KD, Ceballos-Ramirez JM, Luna- Guido ML, Deckers J, Dendooven L (2009) Short term changes in dynamics of C and N in soil when crops are cultivated on permanent raised beds. Plant Soil 320:281–293

Verhulst N, Govaerts B, Verachtert E, Castellanos-Navarrete A, Mezzalama M, Wall P, Deckers J, Sayre KD (2010) Conservation agriculture, improving soil quality for sustainable production systems? In: Lal R, Stewart BA (eds) Advances in soil science: food security and soil quality. CRC Press, Boca Raton, FL, USA, pp 137–208

Welch RM, Alloway WH, House WA, Kubota J (1991) Geographic distribution of trace element problems. In: Mortvedt JJ, Cox FR, Shuman LM, Welch RM (ed) Micronutrients in agriculture, 2nd edn. SSSA, Madison, pp 31–35

Weller DM, Raaijmakers JM, Gardener BBM, Thomashow LS (2002) Microbial populations responsible for specific soil suppressiveness to plant pathogens. Ann Rev Phytopath 40:309–348

Wellington EMH, Toth IK (1994) Actinomycetes. In: Weaver RW, Angle JS, Bottomley P, Bezdicek D, Smith S, Tabatabai A, Wollum AG (eds) Methods of soil analysis: Microbiological and biochemical properties. WI: Soil Science Society of America, Madison, pp 269–290

Wienhold BJ, Halvorson AD (1999) Nitrogen mineralization responses to cropping, tillage, and nitrogen rate in the Northern Great Plains. Soil Sci Soc Am J 63:192–196

Yang X, Wang W, Ye Z, He Z, VC Baligar (2004) Physiological and genetic aspects of crop plant adaptation to elemental stresses in acid soils. In: Wilson Z He MJ, Yang X (eds) The red soils of China: their nature management and utilization. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp 171–218

Zagal E, Persson J (1994) Immobilization and remineralization of nitrate during glucose decomposition at 4 rates of nitrogen addition. Soil Biol Biochem 26:1313–1321

Ziadi N, Brassard M, Bélanger G, Claessens A, Tremblay N, Cambouris AN, Nolin MC, Parent LE (2008) Chlorophyll measurements and nitrogen nutrition index for the evaluation of corn nitrogen status. Agron J 100:1264–1273

Ziadi N, Bélanger G, Claessens A, Lefebvre L, Cambouris AN, Tremblay N, Nolin MC, Parent LE (2010) Determination of a critical nitrogen dilution curve for spring wheat. Agron J 102:241–250

Ziadi N, Whalen JK, Messiga AJ, Morel C (2013) Assessment and modeling of soil available phosphorus in sustainable cropping systems. Adv Agron 122:85–126

Zibilske LM, Bradford JM, Smart J-R (2002) Conservation tillage induced changes in organic carbon, total nitrogen and available phosphorus in a semi-arid alkaline subtropical soil. Soil Till Res 66:153–163

Chapter 5
Farm Machinery for Conservation Agriculture

S. Mkomwa, P. Kaumbutho and P. Makungu

Abstract Conservation agriculture (CA)—a farming strategy based on three principles of minimum soil disturbance (or direct seeding), permanent vegetative soil cover and crop rotation—is seen as the alternative to tillage, with multiple benefits with regard to productivity and sustainability. The first two core principles of CA call for specialised machinery for seeding on unploughed fields with residues, management of cover crops or crop residues and weed management. With two thirds of CA being about mechanisation and use of specialised machinery, it is not surprising that close to 97 % of the 155 million ha under CA worldwide is large-scale commercial farming. Direct seeding and management of soil cover are also the most difficult to implement without access to appropriate farm machinery and, in essence, are the weakest links in the CA adoption chain. Contrary to the farmer-ownership model, a farmer-to-farmer CA service provision model is a preferred approach to enable smallholders' access to farm machinery. This chapter provides an overview of the essential machinery requirements for the different farm operations involved in CA. Regional-specific issues with emphasis on developing countries are also discussed, and pragmatic solutions of vital interest to researchers, academia and policy makers globally are proposed.

Keywords Mechanisation · Farm machinery · Conservation agriculture · Residue management · Direct seeding

---

S. Mkomwa (✉)
African Conservation Tillage Network, KARI NARL Compound, Waiyaki Way, P. O. Box 10375, Nairobi, Kenya
e-mail: saidi.mkomwa@act-africa.org

P. Kaumbutho
Kenya Network for Dissemination of Agricultural Technologies, P. O. Box 2859, Nairobi, Kenya

P. Makungu
Sokoine University of Agriculture, P.O. Box 3000, Morogoro, Tanzania

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_5

5.1 Introduction

Historical events and trends have compelled farmers in the last five decades to reverse the culture of ploughing for food production in a bid to reduce the amount of fossil fuels used, soil and wind erosion, pollution of water bodies and air pollution. With close to 40 % of the global workforce, agriculture is the world's largest provider of jobs for more than 1.3 billion people. In developing countries, where the agricultural sector employs 60–70 % of the population with significant contributions to the growth domestic product, ploughing (synonymous to farming) needs to transform to increase productivity and override crop yield stagnation to feed the hungry and burgeoning population.

Farmers worldwide are faced with the challenges of rising production costs due to rising input costs including machinery, land degradation and the need to cope with climate change and variability. Climate-smart agriculture technologies are being promoted for greener production which leaves a smaller footprint. Conservation agriculture (CA), defined by Food and Agriculture Organization FAO (2014) as a farming strategy based on three principles namely minimum soil disturbance (or direct seeding), permanent vegetative soil cover and crop rotation is seen as the alternative to tillage, with multiple benefits for productivity and sustainability. Globally, CA is expanding at the rate of 6 million ha annually (Kassam et al. 2011).

Some elements of CA are said to have started with the early Egyptians who used dibble sticks to plant crops on unploughed land. This was gradually replaced with the animal-drawn ploughs perceived as the symbol of modernization in Mesopotamia as early as 600 BC. The trend continued to mouldboard ploughs made of iron in the Iron Age and resulting in food production booms. By the 1930s, ploughing had created the worst man-made ecological disaster in American history, dubbed 'dust-bowls' befitting the cloud-like dust storms in which the wheat boom was followed by a decade-long drought during the 1930s (Worster 2004). The need to reconsider how land preparation was made started right away and, by the 1950s, prototype no-till equipment was already in use. It was in 1972, in Brazil, where pioneer farmers such as Herbert Bartz started practicing no-till simultaneous to the other two CA principles of permanent soil cover and crop rotation (Casão et al. 2012).

The first two principles of CA are at the heart of CA and call for specialised machinery for the seeding operation on unploughed fields with residues, management of cover crops or crop residues and weed management. With two thirds of CA being about mechanisation and use of specialised machinery, it is not surprising that close to 97 % of the 155 million ha under CA worldwide is large-scale commercial farming. Direct seeding and management of soil cover are also the most difficult to implement without access to appropriate farm machinery and in essence are the weakest links in the CA adoption chain.

Improvising CA to suit smallholder farming in developing countries (e.g. the *basins* in Zambia and Zimbabwe) has proven beneficial even when the three principles are not fully adopted. It is, however, clear that hand-hoe-based and poorly mechanised CA is still labour intensive (a disincentive in the endeavour to replace the ageing population of farmers), and its sustainability over time is still questionable.

This chapter presents an overview of the essential machinery requirements for the different farm operations required in CA. It cites regional-specific issues with an emphasis on developing countries, where the problem is more severe, and recommends solutions which should be of vital interest to researchers, the academia and policy makers globally.

This chapter identifies and describes the preconditions that need to be addressed for the successful introduction of CA. Corrections for plough pans, soil salinity/sodicity, ridges and furrows are presented and discussed.

5.2 Mechanised Soil-Corrective Operations

De-compacting soils can be done mechanically using machinery or biologically using suitable deep-rooted plants such as pigeon peas (*Cajanus cajan* L.), dolichos lablab bean (*Lablab purpureus* L.), sunn hemp (*Crotalaria juncea* L.) or radish (*Raphanus sativus* L.). Biological tillage is the least expensive but may take longer, and its effectiveness depends on the degree of compaction.

While the use of farm machinery is indispensable for crop production, it can also be the source of some detrimental effects on sustainable production such as accelerated soil erosion on soil loosened by tillage (Lal 1998), formation of plough pans (Ley et al. 2003), soil compaction caused by traffic of tractors and other farm machines (Hakansson et al. 1998; Hakansson 2005). Selecting appropriate machinery is important to minimise detrimental effects or to correct existing anomalies. Some key issues to be considered with regard to farm machinery requirements include amelioration of plough pans and compacted soils, removal of ridges and furrows in fields where wheeled direct planters are used, construction of permanent broad bunds or other soil drainage structures, contour bunds and bench terraces in steep slopes and correction of soil acidity and sodicity (pH; Ristow et al. 2010; Chen and Dick 2011).

5.2.1 Treating Compacted Soils and Hardpans

5.2.1.1 Compacted Soils

Compacted soils have a dense layer near the surface which makes it difficult for water to penetrate and for the proper establishment of seedlings (Ley et al. 2003; Hakansson 2005). The reasons soil become compacted include:

- Animal hooves compact the top 5 cm of soil, which is more pronounced when soils are wet.
- Heavy rainfall compacts the surface on tilled, bare soils where the natural system of drainage pores and channels is broken. The soil surface may then form a crust which prevents emergence of planted seeds, reduces infiltration of rainwater and causes run-off and erosion.

- The wheels of tractors or carts compact the soil to a depth of 10–15 cm. The extent of the damage depends on the frequency of passage and is more pronounced on wet soils.

Compacted soils make it hard for crop roots to grow and reach water and nutrients. They prevent water and air from moving into the soil (Van and Hill 1995). This can lower yields and make crops more susceptible to drought. If the soil is compacted, it is harder to till.

5.2.1.2 Hardpans

Hardpans are formed when the soil is ploughed or hoed at the same depth repeatedly. They are the result of soil smearing due to the sliding action or mechanical impacts of tillage tools. The dense, hard soil layer, ranging from 0.5 to 2 cm, can effectively prevent water and plant roots from moving to deeper layers (Calegari et al. 1998), resulting in waterlogging or quicker withering of plants in times of dry spells. Hardpans need to be broken for CA to work properly and to obtain good yields.

It is necessary to validate the existence and extent of compacted soil layers in a field so that amelioration is made only when necessary. Soil penetrometers can be used to identify plough pans or compacted layers and determine the effectiveness of subsoiling operations to remedy the problem. The optimal time to test for compacted layers is when the soils are uniformly saturated with moisture. Penetrometers consist of a rod which is pushed into the ground and a probe which determines the amount of pressure required keeping the rod moving. A sudden increase in the required pressure at about ploughing depth would signal an encounter with a soil layer of higher bulk density (the plough pan). Penetrometers are not effective in rocky soils or soils with lots of roots since the effect of the penetrometer hitting a rock, root or a compacted layer cannot be distinguished.

Other, less quantitative approaches include observations for stunted or uneven crops in the field, rapid wilting during dry spells, waterlogging or distorted roots. Digging up a few plants and observing the root growth pattern can confirm the presence of a hardpan. For example, the presence of roots growing sideways at the tillage depth or its absence where the roots continue growing straight down is undisputed (Ley et al. 2003).

5.2.1.3 Equipment for Treating Compaction and Hardpans

The Animal-Drawn Subsoiler Animal-drawn subsoilers can penetrate to a depth of 30 cm while the tractor-drawn chisel plough will loosen soil to up to a depth of 50 cm (GART 2003, MARTI Uyole 2004). The tools are effective—depending on how and when they are used—in breaking hardpans and loosening the soil without inverting it (Fig. 5.1a). They do, however, have a high draft requirement, especially on clay soils.

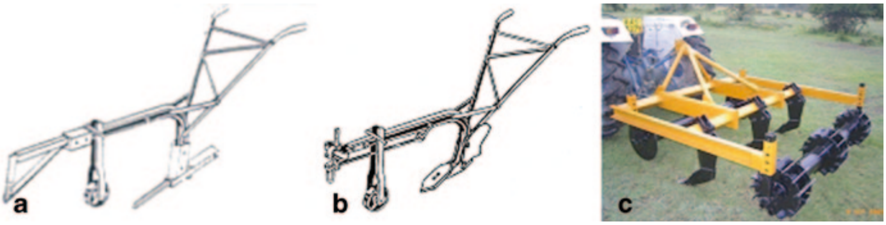


Fig. 5.1 **a** Animal-drawn subsoiler; **b** animal-drawn ripper; **c** tractor-mounted ripper

The Ripper The ripper is used to make planting furrows (called ripping) in unploughed fields (Fig. 5.1b). Ripping usually follows a subsoiling operation (if hardpans were present). Some rippers are designed to achieve greater depths and, therefore, may also be used for breaking hardpans.

The Subsoiler/Chisel Plough These tools have various shank designs (swept, straight or parabolic) which affect shank strength, effectiveness in bursting compacted layers, surface and residue disturbance and the power required to pull the implement (Fig. 5.1c). Shanks may be designed to handle rocks, large roots and highly compacted soils. Winged or conventionally straight tips are fitted at the end of the shank as per available pulling power and quality of work (GART 2003).

It is possible for compaction to be more of a soil surface problem where cattle are allowed to overgraze a CA plot, particularly after it has rained. Should this occur, chisel-tined implements can be employed to reverse the damage. Livestock should, however, not be seen as a threat to the adoption of CA. They are a necessary and complementary enterprise to a farming business, and successful models that have been developed to integrate crop–livestock zero-tillage systems with pasture, fodder and livestock production (e.g. from Brazil) should be considered.

Similarly, the removal of vehicle-induced compaction from cropped soils can ensure a better environment from crop root system development and crop nutrition (Bmssaard and van Faassen 1994). Controlled traffic farming is far from being relevant to most smallholder farmers; there is growing awareness that operations should only be carried out when the soil surface is in its most resistant condition (dry), and the passage of agricultural and transport equipment over CA soils should be kept to a minimum to avoid compaction.

Although rippers are relatively cheap, given that attachments only need to be purchased and adaptable to the ox-drawn plough beam, they cannot be used effectively where there are heavy loads of mulch because the residues get caught in the implement. The presence of heavy loads of residue suggests that ripping (to break plough pans and harvest rain) may not be needed. Otherwise, residue-cutting blades need to be attached in front of the ripper tine to cut through the residue and facilitate seed and fertiliser deposition.

5.3 Machinery for Correction of Soil Acidity and Sodicity

Soil salinity issues may be remedied with effective drainage to lower the water table and desalinize the root zone through leaching. This can be attained in areas under irrigation or with waterlogging problems by establishing permanent raised beds. Alternatively, lime can be used to correct soil acidity. Since lime requires 6 months to 3 years before it fully neutralises acidity and must be mixed with the soil, it has to be applied differently under CA than under conventional ploughing systems where it is broadcasted (Fig. 5.2a) and subsequently mixed with ploughing. Under CA, lime is banded at the planting depth with specialised equipment or added to the direct-seeding operation (Fig. 5.2b).

Improving sodic soils requires partial removal of the sodium and replacing it with calcium ions in the root zone. This can be accomplished—over the long term—by incorporating organic residues and/or farmyard manure. For quick results, cropping must be preceded by the application of soil amendments such as gypsum or calcium chloride followed by leaching to remove salts derived from the reaction of the amendment with the sodic soil. The type and quantity of chemical amendment to use, to replace the exchangeable sodium in soils, depends on the characteristics of the soil, including the extent of soil deterioration, desired level of soil improvement, including crops intended to be grown, and economic considerations. Given its limited solubility in water, gypsum ($CaSO_4.2H_2O$) is also applied in powder form through banding.

Mulch protects the soil surface from heavy rain and stops a crust from forming. It also helps reduce compaction by animals and equipment. By not ploughing, the pores and channels made by roots, earthworms and other soil life are preserved. They let water and air move into the soil which is good for crops.

Fig. 5.2 **a** Spreading lime prior to ploughing; **b** animal-drawn seeder fitted with lime hopper

5.3.1 Removing Ridges, Furrows and Making Permanent Beds

The use of machinery, particularly those with ground-driven wheels, requires a reasonably smooth field without ridges or furrows. Uneven ground causes ground wheels (and hence openers in seeders where the beams do not independently move vertically) to lose contact with the ground. As a consequence, seeding depth and metering of seeds and fertilisers is uneven. Even when the seeder uses vertically independent openers, field efficiency is severely hampered, and operator safety and productivity is compromised.

In areas where farming is rainfed and waterlogging is not an issue, ridges, furrows and stumps should be removed. This can be accomplished effectively by undertaking the last ploughing operation before commencing CA.

Where irrigation is used or waterlogging is an issue, permanent raised beds should be formed. The field should be ploughed to incorporate residues and break-up clods and enable bed formation 10–15 cm high. Formation of the beds requires specialised equipment such as a disc bedder (Fig. 5.3a) to create the furrows. The two units are sometimes combined as one machine (Fig. 5.3b, c). Bed width can range from 75 to 160 cm to accommodate two to six rows per bed for small grains or one to two rows for crops such as maize.

The versatile multi-crop planter (VMP) developed by the Bangladesh Agricultural Research Institute, is an innovation for smallholders which can simultaneously create permanent beds and sow seeds (Fig. 5.3d, e). Powered by a 9–12-kW two-wheel tractor (2WT), it can also apply seed and fertiliser in variable row spacings using single-pass shallow tillage, strip tillage or zero tillage (Haque et al. 2011).

Fig. 5.3 **a**, **b**, **c** Buckeye Tractors' disc bedder and shaper pan for making permanent broad beds. **d**, **e**—VMP. VMP versatile multi-crop planter

The management of permanent broad beds requires that bed tops are not tilled from year to year. Furrows are tilled at planting each year to maintain bed shape and clean out furrows to allow for drainage or irrigation water. Residue management and weed control are carried out as per CA requirements. The furrows provide a driving lane after crop establishment whereby fertilisers can be banded after crop establishment facilitating split applications and increased fertiliser use efficiency.

Permanent raised beds have several advantages, namely improved soil fertility and quality, reduced salinity problems, improved water management arising from better infiltration, storage and less evaporation, reduced wind/water erosion and reduced labour and fuel costs (Limon-Ortega 2011). Challenges include the lack of availability of specialised equipment for direct seeding in broad beds, the need to match available equipment with bed width depending on the agronomy of the crops grown and the need to consider subsequent crops in the rotation. Concern has also been voiced that not all seed varieties thrive on raised beds.

5.4 Mechanised Field Preparation Options in CA

Field preparation operations in order of occurrence from the beginning of the season are discussed below and include—managing residues, weed desiccation, planting–drilling, sowing of cover crops (in mixed cropping systems) and secondary weed management and harvesting. Fertiliser application is done using conventional technology and is therefore not discussed.

5.4.1 Implements for Mechanical Management of Cover Crops and Residues

The guiding rule for residue management is to ensure that crop residues are evenly distributed in the field after harvest in order to retain soil moisture, regulate soil temperatures for living organisms, suppress weeds and facilitate subsequent seeding operations (IIRR and ACT 2005).

In hand-tools-based CA systems, plants are cut about 20 cm above the ground, and the cut material is laid parallel to the rows. The formed residue lines slow down run-off or stop erosion, suppress weed growth and also function as compost strips to improve soil fertility. Where small machines such as 2WT reaper–binder attachments are used, threshing should preferably be done nearer to the fields so that straw is returned and spread thereafter. Combine harvesters should use a straw spreader or chopper to ensure this. Current combine harvesters have options for residue choppers or spreaders at the back, and these should be used to ensure the even spread of residues.

Variations exist in mixed cropping systems, e.g. maize and lablab bean or pigeon pea, where crops mature and are harvested at different times. In this case,

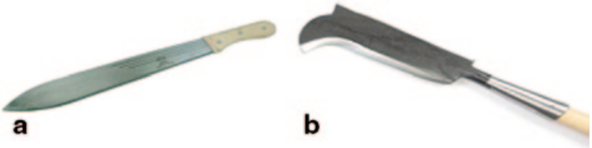


Fig. 5.4 **a** Machete and **b** billhook (with provision to fit longer handle)

manual harvesting is made of the mature crop (e.g. maize) allowing space for better establishment of the other, which will be harvested later, and its residues managed separately. In drier areas, with lower biomass production, termites can be a challenge to residue retention. It is, however, considered that termite damage is less detrimental than leaving soils bare (standing residues), and the plants should be cut and laid along the rows.

Hand tools for residue and cover crop management include machetes (Fig. 5.4), billhooks and slashers. A machete is long heavy broad-bladed knife, typically 50–60 cm long with a thin blade under 3 mm thick, used as a cutting tool and occasionally for digging shallow holes for planting seeds. There are many specialised designs for different regions to suit ergonomic requirements and suitability for the intended tasks to be performed. Depending on the growth stage and amount of crop residues, manual slashing can be highly labour intensive.

Knife rollers consist of a frame with a cylinder with sets of cutting knives mounted in various patterns on the roller. The function of the knives is to crush cover crops or standing crop residues. The rollers can be constructed from either wood (Fig. 5.5a) or steel (Fig. 5.5b). Steel rollers can be filled with sand or water to regulate the desired working weight.

Knife roller weight must be matched to the size and capacity of the animals or tractor being used. Typical parameters are a working weight of 200–350 kg when fully loaded with sand with a 35-cm cylinder diameter and 1.20-m working width. Field capacities vary greatly depending on field conditions and power source.

The effectiveness of knife rolling depends upon the weight of the roller, the number, mounting angle and shape of the knives and the moisture content of the plant (Araújo et al. 1993; MARTI Uyole 2004). Other factors limiting the performance of knife rolling are:

- Wet soils allowing cover crop stalks to sink instead of providing hard-bearing surfaces for the stalks to break/crush and desiccate.
- Uneven or irregular ground surface allowing the knife roller to simply roll over the cover crops without breaking up the stalks as required.

Baker et al. (2007) identified the different forms of residues: (i) short, root-anchored standing vegetation, (ii) tall, root-anchored standing vegetation or (iii) lying straw or stover. The direction of knife rolling and the different forms that residues take determine the subsequent direction of direct seeding. Knife rolling of short and tall root-anchored standing vegetation should cross the direction of future planting rows (Fig. 5.5c).

Fig. 5.5 **a** Knife roller from wood roller; **b** metallic roller—pulled by small tractor; **c** tractor knife roller; **d** stalk roller crusher (attachment to combine harvester)

A similar concept for large-scale farming where harvesting is done by hand is the Yetter Stalk Devastator. It is a stalk roller fitted to a large combine harvester (Fig. 5.5d) which crushes tough maize stalks as it rolls through the field, preventing premature tyre damage and allowing easier conditions for planting the next crop. Crimpled stalks are likely to decompose faster which is advantageous for higher rainfall areas but a problem for low rainfall and longer dry period areas. The concept presents an opportunity to adapt suitable equipment for small machines (such as 2WTs) for the developing world, where the bulk of the harvesting is by hand and residue management, and is challenging for effective direct seeding.

5.4.2 *Hand Tools for Planting Basins*

CA for smallholder African farmers introduced several modifications to the North American version which were largely driven by poor access to motorised and animal-traction-based mechanisation inputs. They tend to be based on the low-cost hand hoe and, to some extent, on the indigenous pitting system of the *Zai,* practised for generations in West Africa.

With this technique, carefully and uniformly spaced planting stations, about 15 cm deep, 30 cm long and 15 cm wide, are placed along a straight line running across the main slope with the aid of a string and pegs at each end of the string. Manure and/or fertiliser are precisely placed into each basin, rather than broadcast, saving on resources. The few farmers who use mulch, imported as grass from

Fig. 5.6 **a** Hoe; **b** pickaxe; **c** planting basins; **d** basins field covered with imported grass mulch

adjacent fields, encounter fewer weed incidences controllable by hand weeding. Most farmers manage weeds by weeding (two to three times) with a hand hoe or machete. Planting basins should be maintained for use in subsequent years to save on labour and improve fertility. Subsequent crops in the rotation should be planted in exactly the same basins ensuring more efficient utilization of residual fertility from previous crops. This method is popular because the basins may be made at any time before the growing season so the farmer is ready to plant on time. The tools used are a hoe (Fig. 5.6a) and a pickaxe (Fig. 5.6b). A typical layout soon after preparing the planting basins is shown in Fig. 5.6c.

Mazvimavi and Twomlow (2009) show that this system improves crop yields, particularly in drier years. However, in reality, farmers have to dig basins every year, particularly where communal livestock grazing is common or hard soil setting due to inadequate use of soil cover. This is an innovative entry point for CA for smallholder farmers who do not have access to alternative sources of power such as motorised or animal traction based. To sustain productivity of the system, the use of soil cover from mixed cover crops, legumes and ‘protecting’ crop residues from other uses will encourage biological tillage by roots, earthworms and other soil-living organisms resulting in soft soils and prevent re-digging basins every season.

5.5 Direct Seeding

The preferred method of planting a crop under CA is with a direct planter of some kind. This can be a device as simple as a sharpened stick (called a dibble stick) or a specially designed planter which can cut through surface residues and deposit the seed in its correct soil environment. Direct planters are classified by the following:

- The source of power namely manually operated, pulled by draught animals or tractors.
- The number of rows planted in one pass of the machine.
- The type of planting machine based on the resultant planting pattern, e.g. broadcast, drill, precision, dibble/punch or specialised (seedling trans-planters, tubers).

All direct seeders are designed to cut through mulch, place fertiliser, place seed to a controlled planting depth and close the planting slot with minimum impact on the soil in order to preserve its natural structure, thereby enhancing gaseous exchange and water infiltration.

5.5.1 Manually Operated Tools and Practices

Jab Planters The hand-jab planter is a simple and relatively low-cost implement for penetrating surface mulch and depositing seed and fertiliser at the required soil depth. Fig. 5.7 illustrates four types: (a) cylindrical metallic twin-hopper jabs, Krupp, (b) rectangular metallic twin hoppers on wooden frame jabs, Werner and Fitarelli and (c) Li seeder with seed and fertiliser provisions, hoeing acting, (d1 and d2) Oklahoma State University (OSU) dibbler. Jab planters consist of two shafts (metal or wood) connected to metal beaks with carrying handles and hoppers for seed and fertiliser. When the shafts are opened by hand, the beaks close and seed and fertiliser are metered into the space between them. In this position, the planter is pushed into the soil. Once in the soil, the handles are brought together to open the beaks to deposit the seed and fertiliser. In this position, the planter is withdrawn from the soil and the process is repeated.

Hand-jab planters are low cost, light and easy to operate. It is for these reasons that they are often used by women and youths. By jabbing seeds in individual spots, soil cover is undisturbed resulting in minimal soil disturbance and moisture loss. As a result, seed emergence is more efficient and weed-seed germination is minimised. Being light (1.5–4.5 kg) makes jab planters suitable for operation on hilly, stony and stumpy areas and for under-sowing cover crop seeds (e.g. sowing dolichos lablab between maize rows).

Operation of the Jab Planter A jab planter can be calibrated to plant different seed sizes and precisely meter the required number of seeds in a single location, or hill, with a defined space between hills. A plate or roller inside the hopper with different sizes of holes can be replaced with another to plant smaller or larger seeds.

The jab planter is easy to use but requires practice to master its operation which suggests that not every farmer will master the use of jab planters. Excessive force should not be used on the downward stroke to avoid placing seeds too deep in the soil. Some people prefer to use a marked line (string) to guide the planting stations on unploughed land. This may, however, slow down the planting operation. Experienced operators can achieve fairly straight lines and consistency in both row and inter-row spacings without using the guiding line. The stubble row of the previous crop can be a handy guide.

Common Problems when Using the Jab Planter Common problems when using the jab planter include clogging the beaks (hole openers), inconsistent seed numbers dropped per station and failure to drop any seeds in some stations (voids). Clogging the beaks is caused by opening the beaks on the downward stroke. The beaks should

Fig. 5.7 Jab planters. (**a**) cylindrical metallic twin hopper; (**b**) rectangular metallic twin-hopper jabs; (**c**) Li seeder and (**d**) dibbler. (1) Soil- and residue-cutting device; (2) furrow-opening device; (3) fertilizer- and seed-covering device (4) seed-firming device

be in a fully closed position on the downward stroke, which requires practice. Inconsistency in the number of seeds dropped and failure to drop seeds in some stations is a problem associated with the variation in seed sizes. Most seeds are not graded as they are meant for hand planting. Experienced operators can tell when seeds have not been dropped and repeat the particular station.

5.5.2 Animal Traction Direct-Seeding Equipment

Row-Type Animal-Drawn Planters No-tillage and direct seeding are terms which describe the sowing of seeds into soil that has not been tilled and usually has vegetative cover. No-tillage aims to minimise soil disturbance and maintain as much crop residue cover as possible in order to minimise disturbance of soil cover, reduce soil moisture loss, reduce germinating weed seeds, reduce fuel use for field operations and protect the soil from wind and water erosion.

No-tillage planters are designed to plant through surface mulch in untilled soil with ease by opening a furrow, metering the seed, delivering and appropriately placing the seed in the furrow, covering the seed in the furrow and firming the seedbed.

A variety of models exist, most being single-row types. They are typically pulled by a single animal (e.g. horse, mule) a pair of oxen or donkeys.

5.6 Soil-Engaging Parts

The full range of soil-engaging components available for use on planting equipment has been classified by Murray et al. (2010) under seven functional groups:

- Group 1: Soil- and residue-cutting devices
- Group 2: Row-preparation devices
- Group 3: Furrow-opening devices
- Group 4: Seed-firming devices
- Group 5: Seed-covering devices
- Group 6: Row-specific seedbed firming devices
- Group 7: Non-row-specific seedbed firming/levelling devices

Not all direct seeders will have the components identified above. The relative position or location of the most common soil-engaging component groups, in relation to the direction of travel of a planter, is shown in Fig. 5.8.

Other seeders are designed in such a way that one component addresses several group functions. Residue cutting, furrow opening, seed/fertiliser covering/firming devices are discussed below, along with other non-soil-engaging devices such as seed metering, fertiliser metering, power requirements, adjustment and maintenance.

Residue and Soil-Cutting Devices These devices lead all other soil-engaging parts and handle residues in different ways depending on their design and the amount and type of residues. When the cutting devices are powered, as is the case with strip tillage by 2WTs, the residues are chopped and incorporated into the soil (Haque et al. 2011). Some value of no-tillage is therefore lost. One advantage is that blockage is unlikely to occur. Openers mounted on straight or parabolic shanks will push soil and some of the surface residues aside as they move forward. Depending on the amount of residues, they are likely to cause device blockages. Farmers improvise

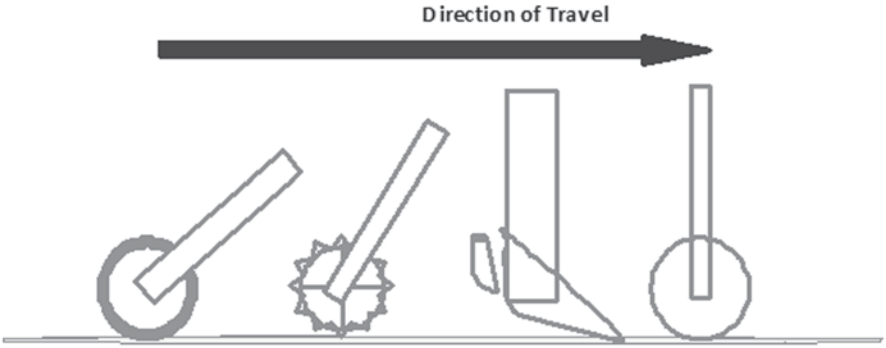


Fig. 5.8 Planter soil-engaging component groups

shank shape by inserting a piece of plastic pipe to facilitate ‘sliding-off’ residues and reduce blockage. Cutting devices made up of discs tend to push down some uncut residues into the opened slot. The extent of this effect depends on several other factors, but the lesser the amount is what is desired. Cutting discs are the most commonly used option. Finger wheels or ‘rotary rakes’ are sometimes used to remove residues prior to the furrow-opening devices (Morrison et al. 2014). Their effectiveness is low, particularly when not powered.

Furrow-Opening Devices The furrow opener follows immediately after the residue cutter/row-preparation device to open the furrow for placement of fertiliser and seed. The design of furrow openers on direct seeders usually incorporates a portion of the fertiliser and seed delivery tubes that facilitates fertiliser and seed placement in the furrow. The key requirements of a furrow opener are to open a furrow to the required depth, maintain uniformity of depth along the length of the furrow and cause minimum disturbance to the seedbed. Furrow openers should have provision for vertical adjustment to adjust planting depth and for horizontal adjustment to alter row spacing. Several types and designs of openers exist to suit varying crop requirements and soil types. The main furrow openers are double-end pointed shovel type for light-to-medium soils, pointed bar type for heavy soils, shoe type for black soils and runner or sword type for shallow sowing.

Fertiliser Metering Devices The most common types of fertiliser metering devices for hand, animal and small-scale motorised seeders are rotating bottom, star wheels, fluted roller and auger type. The discharge rate for rotating bottom type is controlled by adjustable outlets. Star wheels need to be replaced with smaller or larger sizes. Fertiliser calibration options are determined by the sizes of the star wheel fertiliser distributors available. Auger types are controlled by changing the speed of rotation relative to the ground speed; for example, by changing drive wheels or sprockets. The lengths of flutes exposed on the roller determine the amount of fertiliser metered.

Seed germination and emergence are affected if fertiliser is mixed with seed during placement in the furrow. Available options to separate the two are: (i) deeper placement of fertiliser, partial cover with soil followed by placement of seed on top within the same row, (ii) banding of fertiliser within the same but wider row with a seed–fertiliser spacing of 4–5 cm, (iii) precision metering of fertiliser being placed beside or in between seeds. Banding of fertiliser is possible with wider furrows, but this requires more power not usually available with animal-drawn or manually operated planters.

Secondary applications of top-dressing fertiliser differ when the soil is covered with residues. Devices with the dibbler or jabbing characteristics are, therefore, needed to ensure that the fertiliser is metered correctly, placed closer to the plant and below the residues. The alternative is to apply the full dose of fertilisers at planting. While this could be perceived as being inefficient, nutrient immobilisation by desiccated and decomposing vegetation under CA could warrant the full-dose fertiliser application at planting.

Seed-Metering Devices The function of the seed-metering device is to distribute varying sizes and shapes of seeds uniformly to attain the desired plant population per hectare. In precision seeders, seed metering is intended to meet the seed-to-seed spacing and, at times, the number of seeds per planting station (hill).

Common types of metering devices used on direct seeders are (Fig. 5.9):

a. *Fluted roller*. The metering mechanism uses either axial or helical flutes on an aluminium or plastic roller. Rotation of the fluted roller in a housing filled with medium-sized seeds like maize, wheat, soybean, sunflower and safflower will

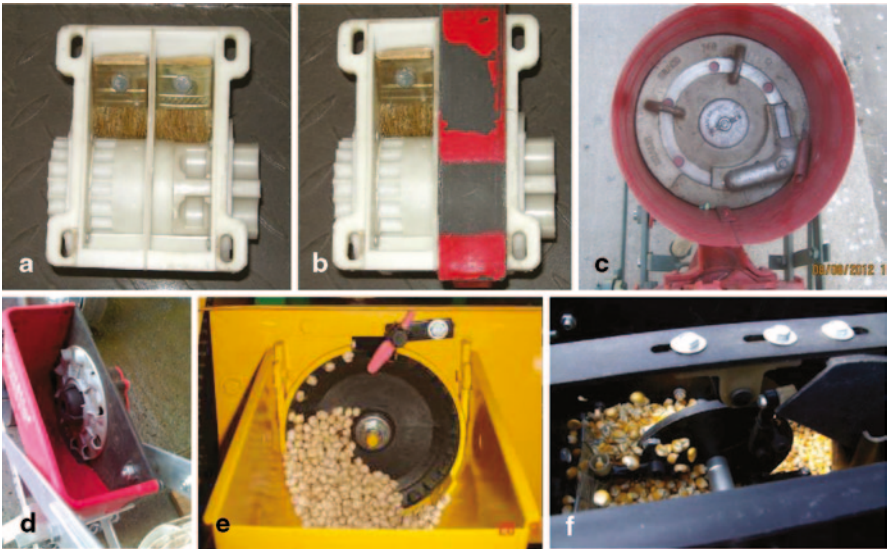


Fig. 5.9 Different types of seed-metering mechanisms for standard and small seeds

cause the seeds to flow out from roller housing continuously. By changing the exposed length of fluted roller in contact with seeds, a fairly accurate seed rate of 20–120 kg ha^{-1} can be achieved.

b. *Fluted roller (small flutes)*. For sowing small seeds like rapeseed, mustard and sesame. Fluted rollers with small flutes have been developed to deliver low seed rates of 3–5 kg ha^{-1}. The standard and small flute rollers are sometimes incorporated in one unit and by closing the standard side (Fig. 5.9b) the smaller left flutes are put into use.
c. *Adjustable orifice with agitator*. Seed flow is regulated by changing the size of the opening at the bottom of the hopper. An agitator fixed above the seed opening helps the continuous flow of seeds. This mechanism is simple and low cost, but does not produce precise metering of seeds.
d. *Plate with cells*. Horizontal, inclined or vertical seed plate with cell-type-metering mechanism picks and drops individual seeds or a number of seeds per hill as required. Spacing between seeds and hills is controlled by changing either the drive gears and hence the drive ratio or seed plate with a different number of seed cells/holes. Separate plates are required for sowing different crops. Seeds must be graded and have a high germination percentage to achieve the desired plant population.
e. *Cup feed*. Seed-picking cups are provided on the periphery of a vertical plate. When the plate rotates, cups pick up seeds from the seed hopper and drop them in the seed funnel. The size of the cups depends on the size and number of seeds per hill. The metering mechanism is useful when seed damage by mechanical devices is likely and needs to be avoided.

It is essential that the selected metering system does not damage the seed while in operation. The speed of the metering device is an important factor with regard to damage. Seed damage can be avoided by selecting the proper spring-loading rate of the cut-off device and knockout device in the case of plate-type planters. Seeds should be handled in such a way that physical injury is avoided. Metering devices, seed conveying tubes and their location on the machine affect the uniformity of seed distribution in the row.

Power Requirements Direct seeding is generally a much lighter operation compared to ploughing. A pair of donkeys or oxen should comfortably attain the typical field rates of 0.125 ha h^{-1} for maize. The rate is typically 0.2 ha h^{-1} for 2WTs for maize.

Adjustment, Maintenance and Challenges with Animal-Drawn Planters For animal-drawn seeders, animals should be well trained and guided to walk in a straight line during the planting operation. No force should be applied on the planter handles in an attempt to dig deeper. The coulter should be adjusted to exert adequate force for effective cutting of trash. If this is not done, trash will accumulate in front of the furrow opener and may hinder proper operation. The handles should be adjusted to suit the operator height.

Seed plates can be blocked with the largest seeds that could not be pushed by the ejector. In this way, the seed plate will keep rotating without metering any seeds and creating voids. This is a common problem when ungraded seeds are used. One way to address the problem is to routinely remove all seeds from the planter including blocked seeds. Using the next-sized seed would reduce blockages, but result in a higher seed rate and possible wastage.

CA seeders, like any other, need to be looked after to increase operational lifetime and perform optimally. It is important to remove seeds and leftover fertiliser after planting, clean the equipment after each use, sharpen or replace cutting parts when worn, lightly oil or grease joints, bolts and nuts for storage, store equipment under cover, calibrate direct seeders for desired seed/fertiliser rates before planting and keep children away from the equipment.

5.6.1 Two-Wheel-Tractor-Operated Direct-Seeding Equipment

Eliminating tillage, the most power-intensive operation in conventional farming, makes the use of smaller machines including 2WTs a viable option for farming. So et al. (2001) estimated that 13.58 million 2WT exist in the Asian countries of China (10 million), Thailand (3 million), Bangladesh (0.35 million), Sri Lanka (0.12 million) and India (0.11 million); almost a tenfold increase in the past 20 years. Mechanisation is spreading in Asia and Africa, replacing manual and animal-draught tillage. However, the proportion of these 2WTs being used for CA is very low. Challenges to adoption include inadequate demonstrated effectiveness, and physical and financial accessibility to suitable planters. Recent advancements mainly from Asia have produced several functional 2WT direct seeders.

Based on the same concept as animal-drawn direct seeders, 2WT direct seeders are designed to place seed and fertiliser into narrow (3–5 cm) slots of untilled and residue-covered soil without tillage, thereby providing an attractive alternative which is functionally better and costs less than full-inversion tillage systems.

The Fitarelli and Knapik Brazilian-made seeders (Fig. 5.10a, b) for two wheelers use horizontal seed-metering devices which adequately handle large-seeded crops such as maize and beans, but not small grains like wheat. Fig. 5.10c shows the ARC (A—Australian Centre for International Agricultural Research, Canberra Australia; R—Rogro Machinery Sales, Spring Ridge, NSW, Australia; C—China Agricultural University, Beijing) Gongli, currently under development and being adapted for African conditions. Some features of this seeder are: simple construction, suitable for zero tillage, sows up to four rows of most crops and variable tine layout available to suit different soil and residue conditions. Absence of a residue-cutting coulter reduces its ability to handle residues rendering it prone to blockages.

Similar to animal-traction-based direct seeders, when used in suitable conditions, 2WT direct seeders have several potential advantages compared to full tillage: (a) soil cover reduces soil water evaporation thus reducing the frequency of irrigation and saving water, (b) input costs (e.g. fuel, wear and tear on machinery) are reduced immediately and (c) improved labour costs. Challenges associated with adoption/use of 2WT seeders include: (a) the need for intensive training for operators, (b) not giving weeds a head start prior to planting and (c) uneven levelling of fields wastes irrigation water.

Fig. 5.10 2WT direct CA seeders. (**a**) Fitarelli; (**b**) Knapik; (**c**) ARC Gongli; (**d**) Bangladesh. 2WT two-wheel tractor; CA conservation agriculture

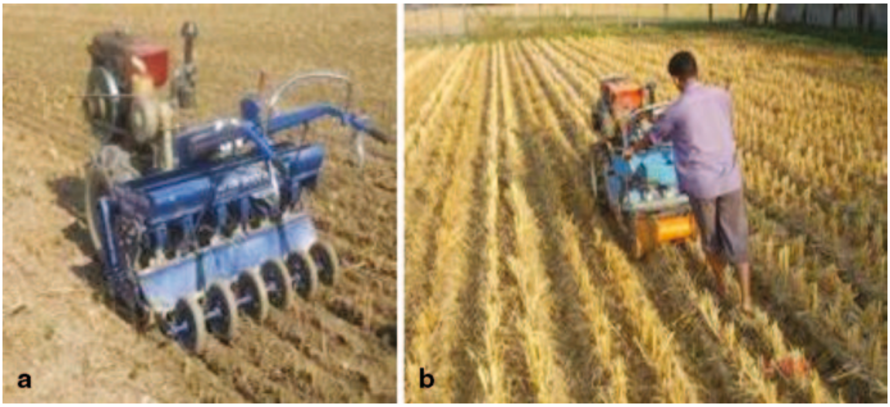


Fig. 5.11 **a** Strip-tillage-based drill and **b** bed reshaper/strip-till

With strip tillage, narrow strips of the soil surface are tilled, and seed and fertiliser are placed within. The depth of the strips varies, depending on the shape/selection of the rotavator blades to suit different crop species planted and the soil moisture status. Typical field surface conditions include cover with moderately dense mulch or anchored crop residues (Fig. 5.11a). Using the strip-till concept, a bed reshaper can be attached to a 2WT to rework permanent beds while simultaneously planting a crop (Fig. 5.11b).

5.6.2 Four-Wheel-Tractor-Operated Direct-Seeding Equipment

The basic functions for 2- and 4WT direct seeders are the same. Variations come with large-scale equipment whereby the seed metering systems are predominantly by air suction pressure (air seeders). Farm machines for large-scale CA are discussed by Saxton and Morrison (2003) and are beyond the scope of this chapter.

5.6.3 Recent Developments in CA Machinery and Implements

The past 15 years has seen rapid development in new CA machinery for both smallholder and large-scale farmers. Some new smallholder equipment are as follows:

- *Straw chopper:* This accessory has been introduced to help manage residues (particularly of rice) and enable easier planting on residue-covered fields. The equipment, normally attached to the combine harvester, chops the straw and spreads it uniformly in the field (Fig. 5.12a).
- *Straw reaper:* The straw reaper is a new development meant to utilise crop residues as livestock feed while retaining some for soil cover. The machine cuts the remaining straw 5–10 cm from ground level after harvesting by combine. Remaining residues cover the soil while their quantity and chopped sizes do not impede direct seeding (Fig. 5.12b).
- *Happy seeder:* The equipment has been developed in Punjab (India) to manage heavy loads of rice residues during seeding (Fig. 5.12c). Farmers generally burn rice residue prior to wheat sowing as the cheap and easy option for residue management, but burning leads to losses of soil organic matter and nutrients and creates environmental pollution (particulates and greenhouse gases; Singh et al. 2007). A powered cutter in front of the furrow opener of the seeder cuts all residues and allows the opening of seed furrow without clogging of the machine of displacement of the residues. The happy seeder technology provides an alternative to burning for managing rice residues and allows direct drilling of wheat in standing as well as loose residues (Gathala et al. 2009).

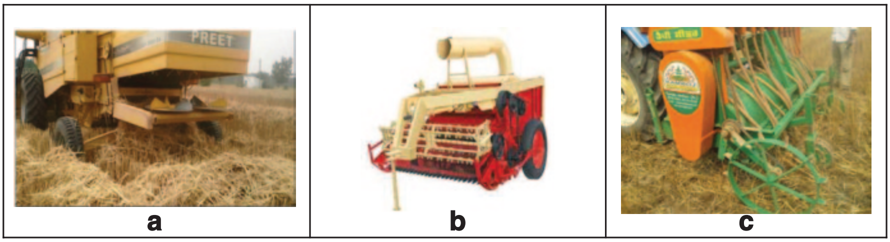


Fig. 5.12 **a** Straw chopper; **b** straw reaper and **c** happy seeder

5.7 Future Outlook

When CA has been established, seeding is by direct planters through mulch cover, and there is no need for soil tillage thus reducing power requirements for CA systems to the order of 50 %.

Less power requirements imply the machines can be lighter and of lower cost. The extensive use of CA machinery/implements is hampered by several problems including: low functional quality of available equipment, low purchasing power of most small-scale farmers, high cost of machinery, inadequate after-sales spares and repair services, lack of well-trained operators and mechanics and poor profitability of CA machinery services.

Adaptation of CA machinery to local farming systems requires investment and need to innovate lower cost, functional machinery particularly CA direct seeders and herbicide applicators. To develop equipment adapted to local environments, the academia, research institutions, NGOs and farmer organisations need to form platforms for joint innovation. The South–South linkages stand a chance to share valuable experiences from similar environments.

A supply chain of CA products' spares and repair services needs development. Support to rural workshops, better-trained mechanics, operators and service providers are essential to build the expansion structure of the enterprise.

Ripping is one of the most popular forms of reduced tillage and has been adopted on a wide scale. While ripping causes considerable soil disturbance, which damages soil structure and natural channel systems, it should be considered a step towards full CA and therefore encouraged at this stage of the adoption process. Rippers with disc coulters need to be developed to support the transition to full CA.

5.8 Conclusion

Two-wheel and small tractors have a unique role to play in mechanisation of smallholder rural farming under CA, given the tremendous reduction in power requirements for field operations compared to conventional tillage. This is exacerbated by the shortage of farm power due to rural–urban migration, the ageing farmer population and reductions in the number of work animals due to epidemics and pasture land pressure.

Given the small farm sizes (typically 2 ha) of smallholder farmers and high acquisition costs of farm machinery, the farmer-ownership model, whereby individual farmers are targeted and supported to own and use farm machinery has failed. Entrepreneurial CA service provision by traders and farmers for farmers holds promise for smallholder farmers to access a range of small-scale farm machinery services. Beside the CA services (direct seeding, herbicide application, combine harvesting and straw/stover spreading), other services include irrigation water pumping, threshing, shelling and farm transportation.

The benefits from adoption of CA need not necessarily be only in the long term, as long as the necessary preconditions to establish CA (e.g. amelioration of hard/plough pans, correction of soil pH, proper drainage) are taken care of. While biological options will solve a number of the challenges, they may take too long. Corrections by machinery will yield immediate results and encourage adoption of CA.

References

Araújo AG, Casão R, Jr, Figueiredo PRA (1993) Recomendações para dimensionamento e construção do rolo-faca. In: Encontro Latinoamericano sobre Plantio Direto na Pequena Propriedade, 1, 1993. Anais. Instituto Agronômico do Paraná, Ponta Grossa, pp 271–280

Baker CJ, Saxton KE, Ritchie WR, Chamen WCT, Reicosky DC, Ribeiro MFS, Justice SE, Hobbs PR (2007) No-tillage seeding in conservation agriculture, 2nd edn. FAO, Rome

Bmssaard L, van Faassen HG (1994) Effects of compaction on soil biota and soil biological processes. In: Soane BD, van Ouwerkerk C (eds) Soil compaction in crop production, Elsevier, Amsterdam, pp 215–235

Calegari A, Darolt MR, Ferro M (1998) Towards sustainable agriculture with a no-tillage system. Adv Geo Ecol 31:1205–1209

Casão R Jr, Araújo AG, Fuentes RL (2012) No-till agriculture in Southern Brazil. Factors that facilitated the evolution of the system and the development of the mechanisation of conservation farming. FAO and IAPAR 2012

Chen L, Dick WA (2011) Gypsum as an agricultural amendment: general use guidelines. School of Environment and Natural Resources,The Ohio State University

FAO (Food and Agriculture Organization of the United Nations) (2014) Conservation agriculture. Rome (Agriculture and Consumer Protection Department). http://www.fao.org/ag/ca/6c.html. Accessed 29 June 2014

GART (Golden Valley Agricultural Research Trust) (2003) How to use the Magoye ripper. Operators manual. http://www.gartzambia.org/files/. Accessed 29 June 2014

Gathala MK, Pathak H, Ladha JK, Kumar Vivak, Mishra D, Blackwell J, Roth C, Kumar V, Kumar Vipin, Sharma S (2009) Happy seeder technology provides an alternate to burning for managing rice loose straw after combine harvest. 4th World Congress on Conservation Agriculture, New Delhi, India, 4–7 February 2009

Hakansson I (2005) Machinery-inducted compaction of arable soils: incidence- consequence-counter-measures. SLU Service/Repro, Uppsala, ISSN:0348–0976

Hakansson I, Voorhees WB, Riley H (1988) Vehicle and wheel factors influencing soil compaction and crop response in different traffic regimes. Soil Tillage Res 11:239–282

Haque ME, Bell RW, Islam AKMS, Sayre K, Hossain MM (2011) Versatile multi-crop planter for two-wheel tractors: an innovative option for smallholders. In: Gilkes RJ, Nattaporn, Prakongkep (eds) 5th World Congress of Conservation Agriculture Incorporating 3rd Farming Systems Design Conference. Brisbane, Australia, 26–29 September 2011, pp 102–103

IIRR and ACT (2005) Conservation agriculture: a manual for farmers and extension workers in Africa. International Institute of Rural Reconstruction, Nairobi; African Conservation Tillage Network, Nairobi

Kassam AH, Friedrich T, Shaxson F, Reeves T, Pretty J, de Moraes Sá CJ (2011) Production systems for sustainable intensification integrating productivity with ecosystem services. Institut für Technikfolgenabschätzung und Systemanalyse

Lal R (1998) Soil erosion impact on agronomic productivity and environment quality. Crit Rev Plant Sci 17:319–464

Ley GJ, Mkomwa S, Mwakimbwala, Mbwaga AM, Mtakwa PW (2003) Diagnosis and amelioration of ploughpans in eastern and southern highlands zones of Tanzania: paper presented to the workshop on collaborative research for food security, organized jointly by Sokoine University of Agriculture and Ministry of Agriculture and Food Security, Morogoro, Tanzania, 28–30 May 2003, pp 138–147

Limon-Ortega Agustin (2011) Planting system on permanent beds; a conservation agriculture alternative for crop production in the Mexican plateau, soil erosion issues in agriculture, In: Dr. Danilo Godone (ed), ISBN: 978-953-307-435-1, InTech, doi: 10.5772/23489. http://www.intechopen.com/books/soil-erosion-issues-in-agriculture/planting-system-on-permanent-beds-a-conservation-agriculture-alternative-for-crop-production. Accessed 29 June 2014

MARTI (Ministry of Agriculture Research Institute) Uyole (2004) Annual progress report. Agricultural Engineering Research Programme. Unpublished

Mazvimavi K, Twomlow S (2009) Socioeconomic and institutional factors influencing adoption of conservation farming by vulnerable households in Zimbabwe. Agric Syst. 101(1–2):20–29. doi:10.1016/j.agsy.2009.02.002

Morrison J, Sellner H, Mutua J, McGill J (2014) Mechanisation inputs for sustainable conservation agriculture. In: Condensed papers, First Africa Congress on Conservation Agriculture; Lusaka Zambia, African Conservation Tillage Network, Nairobi Kenya, 18–21 March 2014

Murray JR, Tullberg JN, Basnet BB (2010) Planters and their components: types, attributes, functional requirements, classification and description. Australian Centre for International Agricultural Research, 2006

Ristow PL, Foster J, Ketterings QM (2010) Lime guidelines for field crops; tutorial workbook. Department of animal science. Cornell University, Ithaca, pp 47

Saxton KE, Morrison JE (2003) Farm machines for large-scale conservation agriculture. In: Garcia-Torres L, Benites J, Martinez-Vilela A, Holgado-Cabrera A (eds) Conservation agriculture: environment, farmers experiences, innovations, socio-economy, policy. Kluwer Academia, Dordrecht, pp 255–263

Singh B, Shan YH, Johnson-Beebout SE, Singh Y, Buresh RJ (2007) Crop residue management for lowland rice based cropping system in Asia. Adv Agronomy 98:118–186

So HB, Kirchhof G, Bakker R, Smith GD (2001) Low input tillage/cropping systems for limited resource areas. Soil Till Res 61:109–123

Van Es HM, Hill RL (1995) “Soil compaction and soil-structure degradation,” in crop residue management to reduce erosion and improve soil quality, conservation research report no. 41, U.S. Department of Agriculture: Agricultural Research Service, August 1995

Worster Donald (2004) Dust bowl—the southern plains in the 1930s. Oxford University Press, New York, p 50

Chapter 6
Insect Pest Management in Conservation Agriculture

Ahmad Nawaz and Jam Nazeer Ahmad

Abstract Insects are a dominant form of life on Earth with more than 1 million described species. Yet, only 1% competes with humans for food, shelter, and space. Various farming systems have been adopted for sustainable pest management but none have been entirely successful in managing insect pests. Chemical insecticides are still the predominant pest control measure but cause health hazard and environmental pollution. The long-term sustainability of agricultural and natural ecosystems depends upon the conservation of natural resources. Conservation agriculture (CA) is a novel approach with a series of practices that strives for acceptable profits together with high and sustained production levels while concurrently conserving the environment. It also increases biodiversity of both flora and fauna which helps to control insect pests, contradictory reports incite concerns regarding reduced yields, increased labor requirements due to avoiding herbicides, and insect pest problems. It is therefore necessary to integrate alternative cultural, biological, mechanical, and appropriate chemical and biotechnological control methods for pest management. The principle of integrated pest management (IPM) creates a balanced environment between sustainable environmental practices and profitable farming. Both IPM and CA work on the same principles to help increase biodiversity and conservation of natural resources. In addition, recent advances in insect pest management like bio-intensive IPM, precision agriculture (PA) and biotechnology can also synergize the insect pest management in the CA management system. Sustainable pest management for crop production is possible in CA management systems by using IPM in combination with biotechnology and PA.

Keywords Insect pests · IPM · Conservation agriculture · Precision agriculture · Natural enemies · Biodiversity

---

A. Nawaz
Integrated Pest Management Laboratory, Department of Entomology, University of Agriculture, Faisalabad, Pakistan
e-mail: nawazrajpoot@yahoo.com

J. N. Ahmad
Integrated Genomic, Cellular, Developmental and Biotechnology Laboratory, Department of Entomology, University of Agriculture, Faisalabad, Pakistan

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_6

6.1 Introduction

The twentieth and early twenty-first centuries brought incredible developments in the field of agriculture—subsistence farming, technology revolutions, and developments in machinery and chemicals—which enabled humans to clear and cultivate land faster, grow plants and feed animals quicker, and control insect pests and pathogenic diseases better. The twentieth century developments were like a godsend for the welfare of mankind and used to their fullest without considering any possible repercussions. Later, problems were revealed such as chemical residues on plants, animals, land, and water as well as soil erosion, salinity, soil acidification, loss of biodiversity, and reduced fertility for crop production. As we moved into the twenty-first century, our concerns about the environment, humans, plants, and other animal health forced us toward more sustainable farming (Mason 2003). In the past six decades, agricultural development programs have been launched to arrest erosion but were mostly unsuccessful. However, a number of experimental systems under both mechanized and unmechanized conditions on both small- and large-scale farms have indicated that significant improvements are indeed possible and acceptable to farmers when the basic principles of good farming practices (Table 6.1) are applied. The terminology adopted for this system is "conservation agriculture" (CA), which is now practiced on more than 1 million ha worldwide (Derpsch and Friedrich 2009).

No doubt, conventional, modern, or industrial farming delivered tremendous gains in food productivity through intensive agriculture. This intensification of agricultural practices brought ecological, economic, and social concerns including health hazards to humans and environmental pollution. Environmental illness included more than 400 insects and mites and 70 plant pathogens now resistant to one or more pesticides (Gold 1999). Intensive agriculture affects different plant and insect populations in the ecosystem and reduces genetic diversity due to the genetic uniformity in most crops. The intensity of soil tillage either increases or decreases antagonistic pressure depending on the pest concerned. Tillage alone cannot provide the solution, so integrating alternative cultural, biological, mechanical, and appropriate chemical control methods is needed. Integrated pest management (IPM), also known as integrated pest control (IPC), integrates different practices for economic control of pests to suppress pest populations below the economic injury level (EIL). The UN Food and Agriculture Organization defines IPM as "the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment" (FAO 2012).

IPM is not only compatible with CA but also works on similar principles. For example, IPM enhances biological processes and expands its practices from both crop and pest management to the whole process of crop production. The augmentation of soil microbiota would not be possible without adopting IPM practices. Similarly, CA depends on enhanced biological activity in the field to control insect pests and other disease-causing soil biota. IPM promotes the judicious use of crop rotations

Table 6.1 Influence of conservation agriculture (CA) on diversity of insects

Components of CA	Experimental details	Country	Crop(s)	Influence on insects	Duration	Reference
Tillage	Review of tillage practices on soil and their effect on organism populations, functions, and interactions	The USA		Reduced tillage increased the diversity and activity of predators as compared to intensive tillage		Kladivko 2001
	Comparison of plowed and fallow plots for the emergence of pollen beetle parasitoid	Sweden	Wheat and rapeseed	More emergence of parasitoids from fallow plots than plowed plots	4 years	Nilsson 1985
	Review of influence of different tillage practices on insect pest infestation	The USA		28% pest species increased, 29% showed no significant influence, 43% decreased with decreasing tillage		Stinner and House 1990
	A report about the influence of different tillage practices on insect-pest infestation	The USA	Maize	Northern corn rootworm beetle *Diabrotica longicornis* laid three to four times more eggs in no-tillage system than in conventional tillage (CT), but damage was significantly less in no-tillage system	2 years	Musick and Collins 1971
Crop rotation	Insect pest management through cultural practices	The USA	Maize and soybean	Effectively control corn rootworms	2 years	Wright 1995
	Comparison of conventional and diversified crop rotation	The USA	Maize, soybean, triticale–alfalfa, maize, soybean	Maize/soybean/triticale–alfalfa rotation for 4 years with low input showed carabid activity, density, and species richness were higher in 4-year rotation as compare to 2-year conventional rotation	2–4 years	O'Rourke et al. 2008

and other beneficial plant associations as well as agrochemicals to control insect pests and disease problems (FAO 2006). With the passage of time, enhanced biological activity brought on by CA technologies and IPM, results in less agrochemical use for crop protection. CA does not specify recommendations for pest control, so would benefit if combined with IPM which uses information on the life cycles of pests and their interaction with the environment. Thus, CA and IPM are economical and pose the least possible risk to human health, property, and the environment. In practicing IPM, a four-step approach is used: (1) setting action thresholds, (2) monitoring and identifying pests, (3) prevention, and (4) control (insect pests, rodents and diseases, etc.; Harford and Breton 2009).

This chapter reviews the positive and negative impacts of agriculture on insect pest management. The multifunctional role of plant and insect biodiversity on agriculture, including insect predators, parasitoids, and pathogens and their role in biological pest management are discussed. Advances in pest management such as precision agriculture (PA) and biotechnological developments are also highlighted. Overall, this chapter provides a comprehensive, updated view of economic and environmental advantages of IPM and CA integration for insect pest management.

6.2 CA and Insects

Insects are the dominant animals in the world, so it is not surprising that they interact with humans in more ways than any other group of organisms. More than 1 million insect species have been described. Most (99%) are innocuous or beneficial to mankind, such as silkworms, honeybees, pollinators, parasitoids, and predators. Only a small proportion (1%) is our competitors causing damage to our crops, stored products, other belongings, and acting as vectors for plant and animal pathogens (Grimaldi and Engel 2005; Pedigo and Rice 2009). While the number of insect pest species is small in comparison with the total described species, they still need significant funds, time, and effort to reduce their negative impact on crop production, crop protection, human health, and welfare.

Insects provide important ecological services as decomposers, consumers, predators, and parasites (Swift and Anderson 1989; Miller 1993). Decomposition of plant and animal matter by fly maggots (blow flies, muscid flies, small dung flies, etc.) and grub and adult beetles (dermestid beetles, scarab beetles, carrion beetles, etc.) is essential for recycling organic matter in ecosystems (Frost 1959). Other predators (green lacewing, lady beetles, predaceous diving beetles, ground beetles, etc.) and parasites (*Encarsia* ssp, *Ichneomids,* etc.) play an important role in regulating many phytophagous pest populations (Olembo and Hawksworth 1991). Insect pest management is divided into two parts: (1) natural control and (2) applied or artificial control (Fig. 6.1). Natural or automatic control includes abiotic (weather, climate) and biotic (predators, parasites, diseases, and other competitors) factors, while applied control includes control measures which are intentionally applied in the field according to need. Currently, due to the intensification of agricultural practices, only applied control is practiced for crop protection from insect pests.

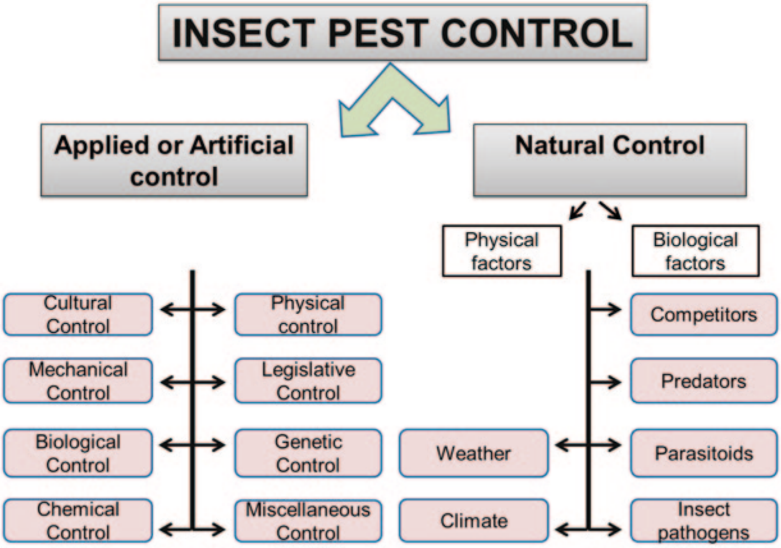


Fig. 6.1 Options for insect pest management

No doubt, CA is advantageous for controlling insect pests by increasing biodiversity. CA promotes biological diversity below- and above ground by making ground cover favorable to the natural biota (Jaipal et al. 2002), which helps to control insect pests. More beneficial insects (predators, parasitoids) have been observed in fields with ground cover and mulch (Kendall et al. 1995; Jaipal et al. 2002) which keep insect pests in check. There is no evidence of complete control of insect pests in CA farming systems, which remains a challenge for researchers, farmers, and agriculture policy makers. The best option in this regard is IPM by integrating different techniques to keep insect pest populations at acceptable levels in CA cropping systems.

6.3 Biodiversity and Insect Pest Management

The term biodiversity describes the variety of plants, animals, and microorganisms on Earth. Biodiversity provides resistant genes, anti-insect compounds, natural enemies (NEs: predators, parasitoids, entomopathogens) of pests, and community ecology-level effects to check pest attacks in the field (Gurr and Wratten 2012). Biodiversity does not function well under the common practices of conventional agriculture including burning of crop residues, continuous plowing and harrowing, deforestation, overgrazing, monocropping, misuse of pesticides, excessive use of fertilizers, and misuse of water. The consequences of these practices are loss of soil fertility, food insecurity, health risks, soil and surface water contamination, greenhouse gas release, pest invasion, and loss of biodiversity (Bot and Benites 2001). Traditional systems of agriculture are broadly linked to the decline in biodiversity due to agricultural practices of tillage and intensive use of pesticides.

The world's population will be approximately 9.7 billion in 2050. It is predicted that another 1 billion ha of natural ecosystems will be converted to agriculture by 2050, with a two- to threefold increase in nitrogen (N) and phosphorous (P), a twofold increase in water consumption, and a threefold increase in pesticide use primarily in the developing world (Tilman et al. 2001). This will reduce biodiversity in the natural environment which ultimately affects the biological management of insect pests in crop production systems. Agricultural systems such as CA which can conserve biodiversity needs to be more extensively adopted. The biodiversity of both plants and insects play an important role in pest management through top-down and bottom-up approaches (Gratton and Denno 2003), which is described below.

6.3.1 Plant Biodiversity

Plant biodiversity as a bio-resource allows development and exploitation of naturally occurring compounds as well as diverse plants for IPM. Conventional agriculture is the main cause of plant diversity loss in agroecosystems. Current research tends to focus on diversified cropping systems based on intercropping, agroforestry, and cover cropping systems because these systems are considered more stable and conserve resources. Plant diversity has had a positive impact on herbivore insects by favoring associated NEs (Thies and Tscharntke 1999). Increased parasitism was observed in flowering plants which provide pollen and nectar for normal fecundity and longevity of parasitoids (Vandermeer 1995). These plants also attract non-herbivore insects which serve as food for other predators. Wild vegetation around crops enhanced biological control and served as overwintering sites for predators including pollen and nectar from flowering plants (Leius 1967). A number of studies have showed the positive impact on the flora and fauna on field and farm levels in organic farming systems when compared with conventional farming systems (Fuller and Norton 2005; Hole and Perkins 2005). Similarly, an analysis of 66 scientific studies showed an average 30% more species and 50% more individuals in organically farmed areas (Bengtsson and Ahnström 2005).

The discovery and use of phytochemicals is a highly active area of science with an emphasis on the value of biodiversity as a bank of potentially useful bioactive phytochemicals. Several species in a wide range of plant families have anti-insect properties such as nicotine from *Nicotiana tabacum* (L.), derris dust from *Derris elliptica* (Wallich), Benth rotenone from *Lonchocarpus* sp., and pyrethrum from *Tanacetum cinerariifolium* (Gurr and Wratten 2012). Pepper seed extracts and *Piper amides*—found in species of *Piper* with neurotoxic properties and inhibition of cytochrome P450 enzymes—have potential for novel insecticides (Miyakado et al. 1989). These characteristics are useful as a defense strategy against herbivores and insects that are vectors of diseases (Scott et al. 2008) such as striped cucumber beetles, *Acalymma vittatum* (Fabricius), and lily leaf beetles, *Lilioceris lilii* (Scopoli; Scott et al. 2004). Similarly, bruceines derived from *Brucea antidysenterica* (Mill) are antifeedant compounds for tobacco budworms, Mexican bean beetles, and southern armyworms (Koul 2005). Azadirachtins which occur in seeds of the neem tree (*Azadirachta indica*) are the best known anti-insect compounds against a broad spectrum of insects with more than 400 species reported as susceptible (Isman 2006). In fact, neem is the most commercially exploited plant for insect pest management. Citrus limonoids act as insect repellents, feeding deterrents, growth disrupters, and reproduction inhibitors against several insect pest species across a wide range of agricultural crops (Alford and Murray 2000). Of these, limonin and nomilin deter feeding in lepidopterans and coleopterans with variable efficacies (Champagne and Koul 1992).

Phytochemical investigations of *Aglaia* revealed the presence of a variety of compounds including rocaglamides, bisamides, triterpenes, and lignans with interesting biological activities; rocaglamide was the first effective anti-insect compound identified (Proksch et al. 2001) mostly against neonate larvae of *Spodoptera littoralis, Ostrinia* species, and gram pod borer, *Helicoverpa armigera* (Koul et al. 2004). *Chloroxylon swietenia* (de Candolle) and its constituents deterred oviposition of *Spodoptera litura* (Fabricius) in laboratory experiments and *Chilo partellus* (Swinhoe) in greenhouse conditions (Singh et al. 2011). The insecticidal potential of these proteins has also been determined (Jennings et al. 2005) and a cyclotide gene has been transferred to crop plants in an attempt to improve the natural defense of the crop against pests (Gillon and Saska 2008).

In conclusion, by including these plants in existing cropping systems, crop protection may benefit. However, more research to exploit the pesticidal properties of these plants against insect pests is needed. The products may be then used in IPM to avoid using synthetic toxic pesticides.

6.3.2 Insect Biodiversity

Insect biodiversity represents a large proportion of world biodiversity with more than 1 million described insect species. Of these, only 10% have scientific names. Many taxonomic revisions are still required to verify the species classification becuase even common species are found to be multispecies complexes with the determination of their genetics, e.g., deoxyribonucleic acid (DNA; Hebert et al. 2004; Grimaldi and Engel 2005). The estimate of total living species named and recorded is still uncertain. It is predicted that about half a million insects may become extinct in the next 300 years, while some estimates suggest that a quarter of all insects are under threat of extinction (McKinney 1999). These facts highlight the importance of the biodiversity of insect pests and their NEs to control insect pests without using toxic chemicals.

Climate change also affects insect biodiversity. There is, however, evidence to suggest that evolution and survival occurs alongside continuous environmental variations. Trophic interactions including all components of food webs (pathogens, mycorrhizae, predators, and parasitoids) are affected directly and indirectly by climatic changes (Harrington et al. 1995; Gehring and Cobb 1997; Ayres and Lombardero 2000). But insects can adapt to changes in the environment as evidenced from recent reviews and meta-analysis studies (Parmesan and Yohe 2003; Root et al. 2003). A variety of ecological systems and taxa have already adopted changes consistent with climatic variations and many examples are drawn from research conducted on insects (Walther et al. 2002; Parmesan and Yohe 2003; Root et al. 2003).

6.3.2.1 Insect Biodiversity and Conventional Agriculture

Insect biodiversity and agriculture are indivisibly linked due to the large surface area occupied by agriculture, i.e., 5 billion ha of land is under agricultural management which exceeds the area covered by woodlands and forests. Agricultural expansion and intensification are considered the main cause of biodiversity loss. Conversion of land from natural forests, wetlands, and grasslands to agriculture has substantially reduced biodiversity, which plays an important role in crop production as well as crop protection. For example, biodiversity provides important pollinators and pest control agents on which agriculture depends. Insects cycle nutrients, pollinate plants and disperse seeds, maintain soil structure and fertility through decomposition, control populations of other organisms (insect pests), and are a major food source for other organisms in the agroecosystems such as birds. In recent decades, awareness on the role of predatory arthropods (spiders, insect predators, parasitoids) in controlling herbivorous insect pests in different crops has increased (Thorbek and Bilde 2004; Scudder 2009).

Pesticides, being the main tactic to control insect pests in conventional agriculture, are a principal reason for the decline in insect diversity. Pesticides eliminate target organisms after being released into the environment. Most pesticides also affect other nontarget organisms both directly (absorption, ingestion, respiration, etc.) and indirectly (using pesticide-contaminated water, food, etc.). Thus, the effect of pesticides on biodiversity including flora, aquatic and terrestrial fauna is undeniable (Altieri and Nicholls 2004). Broad-spectrum insecticides (organochlorines, carbamates, organophosphates, pyrethroids) can cause population decline in beneficial insects (predatory, parasitoids, bees, beetles, etc.) and spiders. Conventional management practices appear to affect the NEs of harmful insects. For example, moths were significantly more abundant with more species present in organic farms compared to conventional farms (Wickramasinghe et al. 2004). Bees are crucial for pollination. Honeybees are under pressure from parasitic mites, diseases, habitat loss, and pesticides. Intensive farming practices, habitat loss, and agrochemicals are considered major environmental threats to honeybees and other wildlife in Europe. Agricultural policies must reduce these pressures to ensure adequate pollinators for pollination (Kuldna et al. 2009). For example, in the USA, diverse communities of native wild bees provide complete pollination services at organic farms and near natural habitats as compared to farms with intensive agricultural practices (Kremen et al. 2002).

Threats to insect biodiversity are increasing and many are often synergistic. Insect biodiversity conservation requires modification of several aspects of the current approach. Adverse agricultural practices can be minimized without affecting yield by adopting environment-friendly farming systems and educating landowners and farmers. Recent research has identified some interrelated principles for ideal insect biodiversity management strategy: maintain reserves, promote habitat heterogeneity, set aside land for biodiversity, stimulate natural conditions and disturbances, and link good quality habitats with corridors (Samways 2007).

6.3.2.2 Insect Biodiversity and CA

Biodiversity of invertebrates and microorganisms is an essential component for agriculture to function worldwide. No doubt, threats to biodiversity indicate challenges ahead for food security and environment health. These threats can be modified with human involvement. In recent years, holistic and systematic approaches have evolved, which has improved knowledge and understanding of the importance of ecosystem sustainability, life support systems (nutrient, hydrological, and carbon cycle), and insect pest and disease management practices. During the past decade, both concepts and implementation themes embraced a significant change for sustainable agriculture and rural development (SARD). In SARD, the promising option is CA, which seeks to integrate crop rotation with soil, water, nutrient, disease, and insect pest management technologies. The integrated approach builds on farmers' knowledge, and developed technologies through farmer field school approach (FFSA) which is a participatory and interactive approach to social learning. This type of regenerative and effective CA can be highly productive by adopting multiple-use strategies of agricultural and natural systems. The use of diversified systems is sustainable being based on crop rotations, intercropping, agroforestry, livestock/crop or fish/crop combinations, and managing the "associate biodiversity" of insect pest and disease-modulating organisms and soil biota. The main challenge is to manage agroecosystems to ultimately enhance nutrient cycling, regulate biological pests, and conserve soil and water for crop production.

CA benefits also include improved soil and water resources, less pollution, increased carbon sequestration, and increased biodiversity through diversification in the agroecosystem. CA increases biomass due to zero or reduced tillage, compared with monocrop cultures in conventional tillage, which enhances microorganisms and soil-living insect populations thereby increasing biological activity (Hobbs et al. 2008). Ground cover promotes above- and belowground biological diversity and there are more beneficial insects in fields with ground cover and mulch (Kendall et al. 1995; Jaipal et al. 2002). Thus, CA not only favors insect biodiversity conservation but also has a positive impact on birds, small mammals, reptiles, and earthworms.

6.4 Conservation of NEs

The combined biotic impact of NEs often contributes to reducing pests below the EIL (Pimentel 1997). The modern concept of biological control is using living NEs to control insect pest species. There are two ways to accomplish this either through (1) classical biological control by importing exotic enemies for exotic or native pests or (2) conservation and augmentation of available NEs. Conservation of NEs is essential if biological control is to work. This involves manipulating the environment to favor NEs by mitigating or removing adverse factors and providing lacking requisites (Van Driesche and Hoddle 2009). To a large extent, the efficacy of NEs depends on the degree of permanence, stability, and environmental favorability. Intentional or incidental departure from the natural environment is often reflected in the degree of depredation of NEs. Environmental modifications that can increase the effectiveness of NEs include: (1) provision of artificial structures in the field, (2) provision of supplementary food in the absence of a host, (3) provision of alternative host, (4) enhanced synchronization of pest–NE, and (5) modification of adverse agricultural practices (Barbosa 1998). The important NEs of insect pests are described below.

6.4.1 Insect Parasitoids

Insect parasitoids are the NEs of insects and occupy an intermediate position between predators and true parasites. They have an immature life stage (larva) that develops on or within a single insect host. Parasitoids, in contrast to parasites, ultimately kill their host, and in contrast to predators, need only a single host to complete their development, while the adults are free living. Parasitoids often belong to poorly known groups of insects and represent 10% of all described insect species. Parasitoids are considered an important model for research and a number of insect pests have been effectively controlled around the world through parasitoid release in biological control programs. There are close to 64,000 described parasitoid species in ten super families of the order Hymenoptera, 15,000 in Diptera and 3400 in Coleoptera. Other insect orders with parasitoids are Lepidoptera, Neuroptera, and Trichoptera, but these orders have less described species (Eggleton and Belshaw 1992; Godfray 1994; Quicke 1997). The question arises as to why these parasitoids fail to control insect pests in the field. One reason for failure is the injudicious use of pesticides because adult parasitoids are usually more susceptible than their hosts (Rogers 1991). Other reasons include adverse agricultural practices, lack of alternative hosts, and hyperparastism (parasitized by other parasitoids). The phenomenon of hyperparasitism is a natural occurrence which may reduce the effectiveness of some beneficial parasitoid species. This can be managed by selecting parasitoid species with a low risk of hyperparasitism.

CA deals with a resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment from contamination. Parasitoids have potential for exploitation in the sustainable management of insect pests in the agroecosystem (Quicke 1997). Their short life cycle and potential for parasitization make them suitable for a minimally disturbed ecosystem such as the CA farming system. They can be provided with alternative food sources as refuge crops and even artificial food sources. This will not only increase the population size of the parasitoids but also have a positive impact on the natural biodiversity and biological equilibrium of insect pests and their NEs.

6.4.2 Predators

Predators are biological control agents that play an important role in the management of herbivore insects. Generally, animals that must consume more than one individual of another animal to complete their life cycle are known as predators. According to this definition, a wide range of insects have a predatory habit. Insect orders such as Odonata and Neuroptera are wholly or predominantly predaceous in nature. Other orders with large numbers of predatory insect species are Coleoptera, Hemiptera, Mecoptera, Diptera, and Hymenoptera, while orders such as Ephemeroptera, Orthoptera, Plecoptera, Thysanoptera, Lepidoptera, and Trichoptera have few species with predatory insects. Almost half of the described insect orders contain predatory insects (Clausen 1940).

Predators can be divided into different categories according to their predatory behavior. They can be monophagous, oligophgous, or polyphagous. Many insect predators are active hunters running over the ground to capture prey, e.g., tiger beetles (Cicindellidae), ground beetles (Carabidae), and many ants (Formicidae). Some insect predators feed on sedentary insects such as aphids and scale insects, e.g., ladybird beetles (Coccinellidae), green lace wings (Chrysopidae), and syrphid fly larvae (Syrphidae), while others are strong flyers and capture their prey in the air, e.g., dragon flies and damselflies (Odonata). Other insects such as bees, wasps, and robber flies catch and consume their prey. Some predators live in fresh water, while some live in soil and predate on water-living and soil-inhabiting organisms (Bell 1990; Lovei and Sunderland 1996; Obrycki and Kring 1998).

Despite many predators of herbivorous insects, only 11% of successful biological control projects have used predators as the major biological control agent. Many pest species are controlled by relatively few predators. Insect pests which are successfully controlled by predators usually include sessile, nondiapausing, and nonmigratory insect pests. These are associated with evergreen perennial plants or crops, e.g., scale insects, mealybugs, etc. The successfully introduced predators such as *Rodolia cardinalis* and *Cryptognatha nodiceps* have a narrow host range, high searching ability, etc. (Caltagirone and Doutt 1989). The reasons these predators fail include adverse agricultural practices, poor climate fit between origin and release areas, lack of alternative host, monoculturing, and lack of shelter. These factors can be minimized with good agricultural practices and by educating farmers and landowners. Therefore, predators have potential for exploitation in CA to control insect pests because this system discourages adverse agricultural practices, increases crop rotations, and provides a favorable environment for insects to survive in the agroecosystem.

6.4.3 Entomopathogens

Entomopathogens are microorganisms that invade and reproduce in insects. They also spread from one infected insect to other insects. These entomopathogens include viruses, bacteria, fungi, protists, and nematodes. Not all microorganisms can infect insects even after entering the insect's hemocoel, which may be due to host resistance or the inability of the microorganism to cause infection. As such, microorganisms can be separated into four broad categories of opportunistic, potential, facultative, and obligate pathogens (Onstad et al. 2006). The use of chemical pesticides is still the predominant method in most pest management systems. The decision to use microbial control should be weighed against other options. The safety of microbial control is based on the narrow host range, high specificity, and lack of side effects on other nontargeted organisms. Examples of narrow-host-range entomopathogens are nuclear polyhedrosis viruses (NPVs), granuloviruses, and Microsporidia, while those with a wider host range are nematodes, hypocrealean fungi, and bacteria (Cory and Evans 2007; Garczynski and Siegel 2007; Shapiro-Ilan and Gouge 2002).

A primary concern in pest management is human health and, with few exceptions, entomopathogens are considerably safer to humans compared to chemical insecticides which cause almost 220,000 human deaths every year (Westwood et al. 2006; Pimentel 2008). Another advantage of microbial control is the reduced potential to develop resistance in target pests. However, microbial control in pest management programs is still very low. Factors which affect the efficacy of microbial control include high specificity, environmental sensitivity, slow acting, and high costs. The efficacy of entomopathogens can be improved by choosing the best entomopathogen for a particular system, improving production and application methods, and improving environmental conditions for their survival. These microorganisms can play an important role in CA for insect pest management because they act as permanent mortality factors in the environment.

Weeds play an important role in agriculture and were mostly removed by manual labor until weedicides were discovered. Even weedicides temporarily suppress a particular group of weeds. The intimate relationship between weeds and host plants limits the positive impact of chemical, physical, and cultural control measures. Concerns have been raised with regard to reduced yields in CA due to increased labor requirements when herbicides are not used etc. (Giller and Witter 2009). Consequently, biological control of weeds using specific NEs (insects and microorganisms) is attractive and practical. There are a number of insects and microorganisms which feed specifically on weeds (Baloch 1974; Goeden and Andres 1999; Evans 2002). CA supports the biodiversity of both flora and fauna, so the introduction of these organisms would allow effective weed control without using toxic herbicides.

6.5 Biointensive Integrated Management of Insect Pests

The concept of combining different control techniques where each technique weakens the pest or disease by contributing to the overall control is known as IPM. The term biointensive integrated pest management (BIPM) is a variation on conventional IPM, where a more dynamic and ecologically informed approach is used that considers the farm as a part of the agroecosystem. BIPM has particular characters that need to be understood and managed in order to minimize pest damage (Reddy 2013). BIPM emphasizes the importance of understanding the ecological basis of pest infestations by asking the following questions:

- Why is the pest in the field, how did it get there and from where did it arrive?
- Why do NEs fail to control the pest?

BIPM reduces chemical use and costs of conventional IPM. It requires that the agricultural system be redesigned to favor NEs of pests and to actively disadvantage pests, e.g., implementing polyculture instead of monoculture.

The cost of cultivation is an important factor for crops grown in a resource-poor environment. Therefore, pest management should naturally regulate pests and diseases in any given field. In this context, the main focus should be the conservation and augmentation of NEs including predators, parasitoids, and pathogens. The biopesticide application in conjunction with the release of predators or parasitoids offers more effective control than chemical pesticides. Similarly, the integration of biocontrol options with other control measures like resistant varieties, etc. also performs well. Biopesticides—based on viral biopesticides, bacterial biopesticide, entomopathogenic fungi, and nematodes—are available to use as biocontrol pesticides, thereby fitting into BIPM initiatives, especially in food crops, to avoid health hazards of pesticide residues in those crops (Gupta and Dikshit 2010). The CA approach also increases microbiota below- and aboveground levels (Jaipal et al. 2002) on cultivated land, so BIPM has a synergistic effect for controlling insect pests and other crop-related diseases. The combined biotic impact of NEs often contributes to reducing pests below the EIL (Pimentel 1997) and there is little information on the effects of plowing on beneficial insects (Van Emden and Peakall 1996). However, many polyphagous predators occur in crops established using conservation tillage compared with plow-based systems (Jordan et al. 2000). Farmers adopting low-till techniques may have to adapt other practices such as sowing date manipulation, rotational changes, resistant cultivars, nutrient requirements, knowledge of crop susceptibility within rotation, and increased monitoring of pests for sustainable management.

6.6 Precision agriculture (PA) in CA

Most agricultural practices ignore the uniform application of practices across the field during fertilizer application, etc. resulting in the variation in nutrient availability due to overapplication in some areas and underapplication in others. Therefore, the variation in soil properties is common rather than exception (Mulla et al. 1997). These spatial variations can also be caused by diseases, weeds, pests, and previous land management practices. In addition, the lack of nutrient availability, water stress, plant diseases, or pests may form patterns that change from time to time and from year to year. PA is applicable to most agricultural applications and can be carried out at whatever level is required. It emerged in the mid-1980s as a way to apply the right treatment in the right place at the right time (Gavlak et al. 1994). More recently, advances in different technologies, such as the global positioning system (GPS) and geographic information systems (GIS), remote sensing and simulation modeling, are making it possible to assess spatial and temporal variability in a field including management with site-specific practices (Basso 2003). This kind of approach is known as PA or site-specific crop and soil management.

PA or information-based management of agricultural production systems consists of geo-referenced data collection to provide relevant information for management planning, analysis, decision making, and treatments at variable rates. The predictive or reactive approaches can be used in an agricultural field for differential treatment of inputs. Available information on yield history, soil maps, field topography, and other data records can be used to predict variable input needs for a predictive approach. Variable-rate technology can be used to eliminate yield-limiting factors such as low pH or soil compaction in a specific area. In the reactive approach, the variation in agrochemical rates depends upon crop status, place, and time which require real-time sensing and online application. It is mainly used for fertilizer application (nitrogen), agrochemical, and water management (Heege et al. 2008). Similarly, site-specific management tools are available to perform different tasks like tillage sawing, mechanical weeding, agrochemical application, and fertilizer distribution. Recently, auto-guidance systems and autonomous agricultural vehicles have become the next logical steps in automating crop production but safety and liability have halted their adoption. A management system is needed which identifies all these potentially limiting processes. PA can be applied to manage the problems of crop production, but it fundamentally needs information on field variability which is not always easy to obtain. Remote and proximal technologies in PA have improved spatial resolution. Peirce and Nowak (1999) identified the factors for successful implementation of PA: (1) the magnitude of conditions within a field must be known and manageable, (2) the adequacy of input recommendations, and (3) the degree of control application. In recent years, most of the agricultural industry agreed to follow the International Standard Organization Binary Unit System (ISOBUS), a universal protocol for electronic communication between implements, tractors, and computers (http://www.aef-online.org/) which allows farmers to control implements with one universal onboard computer.

Although PA is technology dependent, it could be helpful in CA where farming practices such as reduced tillage and crop residues can be varied. The depth of tillage can alleviate soil compaction and residue levels can be varied based on soil characteristics. The cultivars and seeding rate can also be varied based on soil characteristics. The key for making decisions is long-term simulation analysis in areas where PA technology is not available. By adopting best agriculture land management practices for each area, we can implement site-specific CA on a larger scale, as the ultimate basic objectives of PA and CA are natural resource conservation, productivity maintenance, and reduced costs.

6.7 Biotechnological Approaches for Insect Pest Management

Insect pests and plant diseases affect yield, so it is essential to control pests and to furnish the increasing demand for food and feed of the growing world population. Biotechnology and genetic engineering helps to generate crop plants with improved resistance against insect pests, pathogenic bacteria, and fungi. Insect pests and plant pathogens cause US $30–50 billion of crop losses worldwide every year (Cook 2006). Biotechnological and genetic engineering approaches have been launched to support plant health, stabilize yield, and increase food safety along with other strategies of crop production. Biotechnology uses living systems and organisms to develop or make useful products, or "any technological application that uses biological systems, living organisms or derivatives thereof, to make or modify products or processes for specific use" (Jhon and Maria 2001). Following are the major implementations of biotechnology to increase production by protecting crops from insect pests.

6.7.1 Insect Peptides

Peptides or proteins with an anti-pest infection activity have an immensely high potential for sustainable plant protection. For instance, microbial peptides from the bacterium *Bacillus thuringiensis* (*Bt*) have strong insecticidal potential against certain insects (Tabashnik et al. 2008; James 2008). Insecticidal *Bt* peptides are being widely used in combination with other traits like herbicide tolerance (Marcos et al. 2008). During the past decade, a lot of progress has been made on the expressions of lectins in response to herbivory by phytophagous insects. Insecticidal properties of plant lectins are useful tools that can contribute to the development of IPM strategies with minimal effect(s) on nontarget organisms (Killiny and Rashed Almeida 2012).

Many of the toxin proteins expressed in agricultural crops provide strong resistance against the major insect pests. Spider venoms are a complex cocktail of toxins that have evolved specifically to kill insects. The venoms of insectivorous spiders are a complex mixture of compounds that have remained largely untapped for biotechnology application (Tedford et al. 2004). For instance, the venom of the Australian funnel web spider (*Hadronyche versuta*), the x-ACTX-Hv1a toxin (Hvt), killed *H. armigera* and *S. littoralis* caterpillars when applied topically and further transgenic expression of Hvt in tobacco effectively protected the plants from

H. armigera and *S. littoralis* larvae, with 100% mortality (Khan et al. 2006). Some polypeptides from insect parasitoids are being identified and used to control insect pests. Baculoviruses or nucleopolyhedroviruses are pathogens having double-stranded DNA, which codes for genes required for virus establishment and reproduction. They are usually extremely small and attack insects and other arthropods. Their genetic material is easily destroyed by exposure to sunlight or by conditions in the host's gut; an infective baculovirus particle (*virion*) is protected by protein coat called a *polyhedron,* which is typically fatal to the insect. The majority of baculoviruses used as potential biological control agents are in the genus *Nucleopolyhedrovirus*. *S. littoralis* NPV, *Helicoverpa zea* NPV (Lacey 2007; Mahr et al. 2008).

6.7.2 RNA Interference

Insect-resistant transgenic crops that express *B. thuringiensis* (*Bt*) toxins technology have been deployed commercially to protect crops against lepidopteran and coleopteran pests, excluding many other important pest species as dipteran pests like flies (Toenniessen et al. 2003). Technical problems have prevented transgenic plants being protected against sap-sucking pests such as plant bugs, aphids, etc. Novel strategies are still needed because no *Bt* toxin with adequate insecticidal effects against sap-sucking insects has been found (Gatehouse 2008). Ribonucleic acid (RNA) interference (RNAi) technique, discovered in the nematode *Caenorhabditis elegans,* is caused by exogenous double-stranded RNA (dsRNA), a powerful technique for down-regulating gene expression in a wide range of organisms. Suppression of the expression of specific gene(s) in the pest by the RNAi effect, through a plant-delivered RNA, offers the possibility of effective protection against any species, since genes necessary for survival, growth, development, reproduction, or feeding success can be targeted. The recent appearance of two reports on the protection of plants against insect pests, by endogenous expression of RNA corresponding in sequence to pest genes, showed feasibility of this technique (Mao et al. 2007). Down-regulation of gene expression through the delivery of dsRNA to insects can cause mortality by interfering with developmental processes, metabolism, or responses to the environment. Some systemic and persistent RNAi effects have been reported. For example, the red flour beetle (*Tribolium castaneum*) shows a robust systemic RNAi response which can be transmitted to progeny (Tomoyasu and Denell 2004). Further, expression of dsRNAs directed against insect genes in transgenic plants has resulted in RNAi effects and afforded protection against insect herbivory. Gene suppression by RNA feeding is a technique used in bee (*Apis mellifera*) larvae (Nunes and Simões 2009) and termite (*Reticulitermes flavipes*) juveniles (Zhao et al. 2008). The suppression of gene expression by specific dsRNAs was extended to herbivorous insects such as herbivorous lepidopteran larvae, *Epiphyas postvittana,* fed with dsRNAs in solution by droplet feeding (Turner et al. 2006). Kumar et al. (2009) demonstrated that a diet incorporating feeding of synthesized small interfering RNA (siRNA) to larvae of corn earworm (*H. armigera*) resulted in specific suppression of expression of an acetylcholinesterase gene with effects observed at mRNA and protein levels. Feeding dsRNA to larvae of diamondback moth (*Plutella xylostella*) also produced RNAi-mediated gene suppression (Bautista and Miyata 2009; Kumar et al. 2009). Chemically synthesized siRNAs had a silencing effect when fed to *H. armigera* (Kumar 2009). RNAi effects mediated by feeding insects are likely to receive increased attention as a method for identifying phenotypes produced by specific genes, but the prospect of engineered crop plants protected from attack by insect pests through RNAi effects developed for commercial use looks remote at present (Shakesby et al. 2009). Realizing the potential of this RNAi technology requires more research at both fundamental and applied levels.

Specific gene suppression through RNAi effects by feeding dsRNA is possible in insects, but the efficacy of the technique varies from species to species, and criteria for predicting its success or failure in particular cases are yet to be formulated. A more systematic approach to examining the factors responsible for determining the success of the technique includes investigating the stability of input RNA in the insect diet and insect gut, transport of RNA across the insect gut, and uptake of RNA into insect cells in vivo which will lead to a better understanding of how to maximize the effects produced.

6.7.3 Transgene-Improved Sterile Insect Technique

Establishing applicable insect transgenesis systems will enable analysis of gene function in various insect species to understand diverse aspects of biology not yet functionally addressable. Moreover, insect transgenesis will provide novel strategies for insect pest management. In particular, the sterile insect technique (SIT) may be improved by using transgenic approaches. Although SIT has been successfully applied for some species (Dyck et al. 2005), each step—like mass rearing, sex separation for only-male releases, sterilization and marking for monitoring—can be improved biotechnologically to optimize efficiency and reduce costs of ongoing programs or to transfer this effective technique to a wider range of species. This powerful transgenic technology must be applied with great care to avoid harming our environment. Genetic-control-based SIT uses the release of mass-reared, sterile insects to cause infertile mating that reduce the level of the pest population (Klassen and Curtis 2005). SIT is considered an environment friendly alternative to insecticides for insect species that can be mass reared in artificial settings. SIT has been successfully employed in area-wide approaches to suppress or eradicate insect pests such as pink bollworm (*Pectinophora gossypiella*) in California (Henneberry 2007), tsetse fly (*Glossina austeni*) in Zanzibar (Vreysen 2000), New World screwworm (*Cochliomyia hominivorax*) in North and Central America (Wyss and Tan 2000) and various tephritid fruit fly species in various regions of the world (Klassen and Curtis 2005). The use of biotechnology has many advantages to control insect pests that cause severe damage to agricultural crops.

The above-mentioned biotechnological approaches may be exploited in agriculture farming systems such as CA to manage insect pest populations without using toxic chemicals. No doubt, considerable research is needed on the use of genetically modified insects in the field to avoid any harmful effects on nontarget organisms.

6.8 Conclusion and Future Perspectives

The objectives of IPM and CA are the same: sustain productivity, conserve natural resources, reduce production costs, improve environmental health, maintain biodiversity, and reduce agrochemical use for crop production/protection. The past decades have brought incredible developments in the field of agriculture. Technological developments have shifted agriculture from subsistence farming to highly developed PA. The use of pesticides still dominates the management of insect pests and is a health hazard for humans and the environment (Nawaz et al. 2013). IPM requires knowledge of crop-susceptible stages and the nature of insect pests, as well as increased monitoring. Increased diversity of plants, microorganisms, and insects will be effective at keeping the insect pest population at acceptable level. A single method of insect pest management will not provide effective control, so an integrated approach is a better option. In addition, PA can be helpful for monitoring insect pests and managing input (fertilizer) distribution. Furthermore, biotechnological approaches (insect peptides, RNAi, SIT) will be effective tools for managing the insect pest population in the future.

Agriculture needs the cooperation of international development agencies that often have solutions for agricultural problems. Integration of interdisciplinary projects with new satellite technology available for these agencies can bring positive change to agricultural production. Crop simulation, landscape analysis models, and biotechnological approaches may offer higher success rates for agriculture management systems to achieve high profitability in addition to conserving resources. In future, the focus will be on those farming systems which provide high-quality food with low risks to the environment and public health. CA is the best choice in this regard.

References

Alford AR, Murray KD (2000) Prospects for citrus limonoids in insect pest management. ACS Symp series 758(178):201–211

Altieri M, Nicholls C (2004) Biodiversity and pest management in agroecosystems. Food Products Press, New York

Ayres MP, Lombardero MJ (2000) Assessing the consequences of global change for forest disturbance from herbivores and pathogens. Sci Total Environ 262(3):263–286

Baloch G (1974) Phytophagous organisms associated with bindweeds, *Convolvulus* spp. in Pakistan. Tech Bull, Commonwealth Inst Biol Control 1976(17):29–36

Barbosa PA (1998) Conservation biological control. Academic, San Diego

Basso B (2003) Perspectives of precision agriculture in conservation agriculture. In: Luis GT, José B, Armando MV, Antonio HC (eds) Conservation agriculture. Springer, Netherlands, pp 281–288

Bautista MAM, Miyata T (2009) RNA interference-mediated knockdown of a cytochrome P450, CYP6BG1, from the diamondback moth, *Plutella xylostella*, reduces larval resistance to permethrin. Insect Biochem Mol Biol 39(1):38–46

Bell WJ (1990) Searching behavior patterns in insects. Ann Rev Entomol 35(1):447–467

Bengtsson J, Ahnström J (2005) The effects of organic agriculture on biodiversity and abundance: a meta-analysis. Appl Ecol 42(2):261–269

Bot A, Benites J (2001) Conservation agriculture: case studies in Latin America and Africa. FAO Soil Bulletin #78. Rome, Italy.

Caltagirone L, Doutt R (1989) The history of the vedalia beetle importation to California and its impact on the development of biological control. Ann Rev Entomol 34(1):1–16

Carin J, Karl-Heinz K (2007) Insect antimicrobial peptides as new weapons against plant pathogens. In: Vilcinskas A (ed) Insect biotechnology. Springer, Dordrecht

Champagne DE, Koul O (1992) Biological activity of limonoids from the Rutales. Phytochem 31(2):377–394

Clausen CP (1940) Entomophagous insects. McGraw-Hill, New York, p 668

Cook RJ (2006) Toward cropping systems that enhance productivity and sustainability. Proc Natl Acad Sci 103(49):18389–18394

Cory JS, Evans HF (2007) Viruses. In: Lacey LA, Kaya HK (eds) Field manual of techniques in invertebrate pathology. Springer, Netherlands, pp 149–174

Derpsch R, Friedrich T (2009) Global overview of conservation agriculture no-till adoption. 4th World Congress on Conservation Agriculture, New Delhi, India

Dyck VA, Hendrichs J, Robinson AS (2005) Sterile insect technique, principles and practice in area-wide integrated pest management. Springer, Dordrecht

Eggleton P, Belshaw R (1992) Insect parasitoids: an evolutionary overview. Philos Trans R Soc London B Biol Sci 337(1279):1–20

Evans HC (2002) Biological control of weeds. In: Kemp-ken D (ed) The Mycota XI: agricultural applicatons. Springer, Berlin, pp 135–152

FAO (2006) Conservation Agriculture; Agriculture and Consumer Protection Department. Rome, Italy. http://www.fao.org/ag/magazine/0110sp.htm

FAO (2012) Agriculture growth programm (AGP)—Integrated Pest Management. http://www.fao.org/agriculture/crops/thematic-sitemap/theme/pests/ipm/en/

Frost SW (1959) Insect life and insect natural history, 2nd edn. Dover, New York

Fuller R, Norton L (2005) Benefits of organic farming to biodiversity vary among taxa. Biol Lett 1(4):431–434

Garczynski SF, Siegel JP (2007) Bacteria. In: Lacey LA, Kaya HK (eds) Field manual of techniques in invertebrate pathology. Springer, Netherlands, pp 175–197

Gatehouse JA (2008) Biotechnological prospects for engineering insect-resistant plants. Plant Physiol 146(3):881–887

Gavlak RG, Horneck DA, Miller RO (1994) Plant soil and water reference methods for the western region. Univ. of Alaska, Fairbank. WREP 125

Gehring CA, Cobb NS (1997) Three-way interactions among ectomycorrhizal mutualists, scale insects, and resistant and susceptible pinyon pines. Am Nat 149(5):824–841

Giller KE, Witter E (2009) Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crop Res 114(1):23–34

Gillon AD, Saska I (2008) Biosynthesis of circular proteins in plants. The Plant J 53(3):505–515

Godfray HCJ (1994) Parasitoids: behavioral and evolutionary ecology. Princeton University, New Jersey

Goeden R, Andres L (1999) Biological control of weeds in terrestrial and aquatic environments. In: Bellows TS, Fisher TW, Caltagirone LE, Dahlsten DL, Gordh G, Huffaker CB (eds) Handbook of Biological Control. Academic, London, pp 871–890

Gold MV (1999) Sustainable agriculture: definitions and terms. Special Reference Briefs Series No. SRB 99-02. National Agricultural Library. http://warp.nal.usda.gov/afsic/AFSIC_pubs/srb9902.htm [Geo −2-181]

Gratton C, Denno RF (2003) Seasonal shift from bottom-up to top-down impact in phytophagous insect populations. Oecologia 134(4):487–495

Grimaldi D, Engel MS (2005) Evolution of the insects. Cambridge University Press, Cambridge. ISBN 0-521-82149–5

Gupta S, Dikshit A (2010) Biopesticides: an eco-friendly approach for pest control. J Biopes 3(1):186–188

Gurr GM, Wratten SD (2012) Biodiversity and insect pests: key issues for sustainable management. Wiley, Oxford, pp 347

Harford N, Breton JL (2009) Farming for the future, a guide to conservation agriculture in Zimbabwe. Zimbabwe Conservation Agriculture Task Force

Harrington R, Bale JS, Tatchell GM (1995) Aphids in a changing climate. Insects in a changing environment. In: Harrington R, Stork NE (eds) Insect in a changing environment. Academic, London, pp 125–155.

Hebert PDN, Penton EH, Burns JM, Janzen DH, Hallwachs W (2004) Ten species in one: DNA barcoding reveals cryptic species in the neotropical skipper butterfly *Astraptes fulgerator*. Proc Natl Acad Sci U S A 101(41):14812–14817

Heege HJ, Reusch S, Thiessen E (2008) Prospects and results for optical systems for site-specific on-the-go control of nitrogen-top-dressing in Germany. Precision Agric 9(3):115–131

Henneberry T (2007) Integrated systems for control of the pink bollworm *Pectinophora gossypiella* in cotton. In: Vreysen MJB, Robinson AS, Hendrichs J (eds) Area-wide control of insect pests. Springer, Netherlands, pp 567–579

Hobbs PR, Sayre K, Gupta R (2008) The role of conservation agriculture in sustainable agriculture. Philos Trans R Soc B Biol Sci 363(1491):543–555

Hole D, Perkins A (2005) Does organic farming benefit biodiversity? Biol Cons 122(1):113–130

Isman MB (2006) Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. Annu Rev Entomol 51:45–66

Jaipal S, Singh S, Yadav A, Malik RK, Hobbs PR (2002) Species diversity and population density of macro-fauna of rice-wheat cropping habitat in semi-arid subtropical northwest India in relation to modified tillage practices of wheat sowing. Herbicide-resistance management and zero-tillage in the rice-wheat cropping system. Proceedings of International Workshop, Hissar, India

James C (2008) Global status of commercialized Biotech/GM crops 2008. The International Service for the Acquisition of Agri-biotech Applications, ISAAA, Ithaca, NY

Jennings CV, Rosengren KJ, Daly NL, Plan M, Stevens J, Scanlon MJ, Waine C, Norman DG, Anderson MA, Craik DJ (2005) Isolation, solution structure, and insecticidal activity of kalata B2, a circular protein with a twist: do Möbius strips exist in nature? Biochem 44(3):851–860

Jhon R, Maria Z (2001) Agricultural biotechnology for developing countries—results of an electronic forum. FAO, Rome

Jordan VWL, Leake AR, Ogilvy S, Cook SK, Cormack WF, Green M, Holland JM Welsh JP (2000) Agronomic and environmental implications of soil management practices in integrated farming systems. Asp Appl Biol (62):61–66

Kendall DA, Chinn NE, Glen DM, Wiltshire CW, Winstone L, Tidboald C (1995) Effects of soil management on cereal pests and their natural enemies. In: Glen DM, Greaves MP, Anderson HH (eds) Ecology and integrated farming systems. Wiley, Chichester, pp 83–102

Khan SA, Zafar Y, Briddon RW, Malik KA, Mukhtar Z (2006) Spider venom toxin protects plants from insect attack. Transgenic Res 15:349–357

Killiny NA, Rashed Almeida RPP (2012) Disrupting of the transmission of a vector-borne plant pathogen. Appl Environ Microbiol 78:638–643

Kladivko EJ (2001) Tillage systems and soil ecology. Soil Tillage Res 61(1):61–76

Klassen W, Curtis C (2005) History of the sterile insect technique. In: Dyck VA, Hendrichs J, Robinson AS (eds) Sterile insect technique. Springer, Dordrecht, pp 3–36

Koul O (2005) Insect antifeedants. CRC Press, Bota Raton

Koul O, Kaur H, Goomber S, Wahab S (2004) Bioefficacy and mode of action of rocaglamide from *Aglaia elaeagnoidea* (syn. *A. roxburghiana*) against gram pod borer, *Helicoverpa armigera* (Hübner). Appl Entomol 128(3):177–181

Kremen C, Williams NM, Thorp RW (2002) Crop pollination from native bees at risk from agricultural intensification. Proc Natl Acad Sci 99(26):16812–16816

Kuldna P, Peterson K, Poltimäe H, Luig J (2009) An application of DPSIR framework to identify issues of pollinator loss. Ecol Econom 69(1):32–42

Kumar MG, Gorakh PR, Manchikatla V (2009) Silencing of acetylcholinesterase gene of *Helicoverpa armigera* by siRNA affects larval growth and its life cycle. Insect Physiol 55(3):273–278

Lacey LA, Kaya HK (2007) Field manual of techniques in invertebrate pathology, 2nd edn. Springer, Dordrecht

Leius K (1967) Influence of wild flowers on parasitism of tent caterpillar and codling moth. Can Entomol 99(04):444–446

Lovei GL, Sunderland KD (1996) Ecology and behavior of ground beetles (Coleoptera: Carabidae). Ann Rev Entomol 41(1):231–256

Mahr DL, Whitaker P, Ridgway NM (2008) Biological control of insects and mites: an introduction to beneficial natural enemies and their use in pest management. University of Wisconsin Cooperative Extension, No A3842

Mao YB, Cai WJ, Wang JW, Hong GJ, Tao XY, Wang LJ, Huang YP, Chen XY (2007) Silencing a cotton bollworm P450 monooxygenase gene by plant-mediated RNAi impairs larval tolerance of gossypol. Nat Biotechnol 25(11):1307–1313

Marcos JF, Muñoz A, Pérez-Payá E, Misra S, López-García B (2008) Identification and rational design of novel antimicrobial peptides for plant protection. Annu Rev Phytopathol 46:273–301

Mason J (2003) Sustainable agriculture, 2nd edn. Landlinks Press, Collingwood.

McKinney ML (1999) High rates of extinction and threat in poorly studied taxa Conserv Biol 13(6):1273–1281

Miller JC (1993) Insect natural history, multi-species interactions and biodiversity in ecosystems. Biodiv Conserv 2(3):233–241

Miyakado M, Nakayama I, Ohno N (1989) Insecticidal unsaturated isobutylamides. From natural products to agrochemical leads. In: Arnason JT, Philogène BJR, Morand P (eds) Insecticide and plant origin. ACS Symposium series 387, Washington, pp 173–187

Mulla DJ, Schepers JS, Pierce FJ, Sadler EJ (1997) Key processes and properties for site-specific soil and crop management. In: Pierce FJ, Sadler EJ (eds) The state of site specific management for agriculture. American Society of Agronomy, Madison, pp 1–18

Musick GJ, Collins DL (1971) Northern corn rootworm affected by tillage, Ohio report on research and development in agriculture, Home Econ Natl Resour 56(4): 88–91

Nawaz A, Razpotnik A, Rouimi P, de Sousa G, Cravedi JP, Rahmani R (2013) Cellular impact of combinations of endosulfan, atrazine and chlorpyrifos on human primary hepatocytes and HepaRG cells after short and chronic exposure. Cell Biol Toxicol 30(1):17–29

Nilsson C (1985) Impact of ploughing on emergence of pollen beetle parasitoids after hibernation. Appl Entomol 100(1-5):302–308

Nunes FMF, Simões ZLP (2009) A non-invasive method for silencing gene transcription in honeybees maintained under natural conditions. Insect Biochem Mol Biol 39(2):157–160

Obrycki JJ, Kring TJ (1998) Predaceous coccinellidae in biological control. Ann Rev Entomol 43(1):295–321

Olembo R, Hawksworth D (1991) Importance of microorganisms and invertebrates as components of biodiversity. Biodiversity of microorganisms and invertebrates: its role in sustainable agriculture. In: Proceedings of the First Workshop on the Ecological Foundations of Sustainable Agriculture (WEFSA 1), CAB International, London, UK, 26–27 July 1990

Onstad DW, Fuxa JR, Humber RA, Oestergaard J, Shapiro-Ilan DI, Gouli VV, Anderson RS, Andreadis TG, Lacey LA (2006) An abridged glossary of terms used in invertebrate pathology, 3rd edn. Society for Invertebrate Pathology. http://www.sipweb.org/glossary. Accessed 23 Jun 2014

O'Rourke ME, Liebman M, Rice ME (2008) Ground beetle (Coleoptera: Carabidae) assemblages in conventional and diversified crop rotation systems. Environ Entomol Feb 37(1):121–130

Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421(6918):37–42

Pedigo LP, Rice ME (2009) Entomology and pest management, 6th edn. Prentice Hall, Upper Saddle River

Pierce FJ, Nowak P (1999) Aspects of precision agriculture. Adv Agron 87:1–85

Pimentel D (1997) Techniques for reducing pesticide use: economic and environmental benefits. Wiley, Chichester. ISBN: 978-0-471-96838–2

Pimentel D (2008) Preface special issue: conservation biological control. Biol Control 45(2):171

Proksch P, Edrada R, Ebel R, Bohnenstengel FI Nugroho BW (2001) Chemistry and biological activity of rocaglamide derivatives and related compounds in *Aglaia* species (*Meliaceae*). Curr Org Chem 5(9):923–938

Quicke DL (1997) Parasitic wasps. Chapman & Hall, London

Reddy PP (2013) Biointensive integrated pest management. In: Recent advances in crop protection. Springer, New York, pp 223–244

Rogers CE (1991) Arthropod biological control agents and pesticides. Environ Entomol 20(5):1492–1492

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421(6918):57–60

Samways MJ (2007) Insect conservation: a synthetic management approach. Annu Rev Entomol 52:465–487

Scott IM, Jensen H, Nicol R, Lesage L, Bradbury R, Sanchez-Vindas P, Poveda L, Arnason JT Philogène BJR (2004) Efficacy of Piper (*Piperaceae*) extracts for control of common home and garden insect pests. Econ Entomol 97(4):1390–1403

Scott IM, Jensen HR, Philogène BJR Arnason JT (2008) A review of *Piper spp*. (*Piperaceae*) phytochemistry, insecticidal activity and mode of action. Phytochem Rev 7(1):65–75

Scudder GGE (2009) The importance of insects. In: Foottit R, Adler P (eds). Insect biodiversity science and society, pp 7–32. Wiley, Chichester

Shakesby AJ, Wallace IS, Isaacs HV, Pritchard J, Roberts DM Douglas AE (2009) A water-specific aquaporin involved in aphid osmoregulation. Insect Biochem Mol Biol 39(1):1–10

Shapiro-Ilan D, Gouge D (2002) Factors affecting commercial success: case studies in cotton, turf and citrus. In: Entomopathogenic nematology, pp 333–356. CAB International, New York

Singh R, Koul O, Rup PJ, Jindal J (2011) Oviposition and feeding behavior of the maize borer, Chilo partellus, in response to eight essential oil allelochemicals. Entomol Exp Appl 138(1):55–64

Stinner BR, House G (1990) Arthropods and other invertebrates in conservation-tillage agriculture. Ann Rev Entomol 35(1):299–318

Swift M, Anderson J (1989) Decomposition. In: Lieth H, Werger MJA (eds) Tropical rain forest ecosystems. Biogeographical ecological studies. Elsevier, Amsterdam, pp 547–569

Tabashnik BE, Gassmann AJ, Crowder DW, Carrière Y (2008) Insect resistance to Bt crops: evidence versus theory. Nat Biotechnol 26(2):199–202

Tedford HW, Sollod BL, Maggio F, King GF (2004) Australian funnel-web spiders: master insecticide chemists. Toxicon 43:601–618

Thies C, Tscharntke T (1999) Landscape structure and biological control in agroecosystems. Science 285(5429):893–895

Thorbek P, Bilde T (2004) Reduced numbers of generalist arthropod predators after crop management. Appl Ecol 41(3):526–538

Tilman D, Fargione J, Wolff B, D'Antonio C, Dobson A, Howarth R, Schindler D, Schlesinger WH, Simberloff D, Swackhamer D (2001) Forecasting agriculturally driven global environmental change. Science 292(5515):281–284

Toenniessen GH, O'Toole JC, DeVries J (2003) Advances in plant biotechnology and its adoption in developing countries. Curr Opin Plant Biol 6(2):191–198

Tomoyasu Y, Denell RE (2004) Larval RNAi in Tribolium (*Coleoptera*) for analyzing adult development. Dev Genes Evol 214:575–578

Turner CT, Davy MW, MacDiarmid RM, Plummer KM, Birch NP, Newcomb RD (2006) RNA interference in the light brown apple moth, *Epiphyas postvittana* (Walker) induced by double-stranded RNA feeding. Insect Mol Biol 15(3):383–391

Van Driesche R, Hoddle M (2009) Control of pests and weeds by natural enemies. In: An introduction to biological control. Wiley, Oxford

Van Emden HF, Peakall DB (1996) Beyond silent spring: integrated pest management and chemical safety. Chapman & Hall, London

Vandermeer J (1995) The ecological basis of alternative agriculture. Annu Rev Ecol Syst 26(1):201–224

Vreysen M (2000) Principles of area-wide integrated tsetse fly control using the sterile insect technique. Med Trop (Mars) 61(4-5):397–411

Walther G, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin J, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416(6879):389–395

Westwood GS, Huang S, Keyhani NO (2006) Molecular and immunological characterization of allergens from the entomopathogenic fungus Beauveria bassiana. Clin Mol Allergy 4(1):12

Wickramasinghe LP, Harris S, Jones G, Vaughan Jennings N (2004) Abundance and species richness of nocturnal insects on organic and conventional farms: effects of agricultural intensification on bat foraging. Conserv Biol 18(5):1283–1292

Wright RJ (1995) Use of cultural practices in crop insect pest management. Nebraska cooperative extension, bulletin, EC95-1560, pp 11

Wyss JH, Tan KH (2000) Screw-worm eradication in the Americas-overview. Area-wide control of fruit flies and other insect pests. Joint proceedings of the international conference on area-wide control of insect pests, 28 May–2 June, 1998 and the fifth international symposium on fruit flies of economic importance, Penerbit Universiti Sains Malaysia, Penang, Malaysia, 1-5 June 1998

Zhao Y, Yang G, Wang-Pruski G, You M (2008) *Phyllotreta striolata* (Coleoptera: Chrysomelidae): arginine kinase cloning and RNAi-based pest control. Eur J Entomol 105(5):815–812

Part III
Modeling and Crop Improvement for Conservation Agriculture

Chapter 7
Crop Breeding for Conservation Agriculture

Tariq Mahmood and Richard Trethowan

Abstract Cropping area under conservation agriculture (CA) has increased significantly worldwide with most located in South and North America and Australia. CA was initially introduced to control soil erosion but has become increasingly popular as the practice conserves soil moisture, reduces fossil fuel use, lowers cost and, once established, increases yield. In some countries, such as Australia, CA is practised on more than two thirds of the total cropped area. The new practice is more sustainable and environment friendly as microbial activity and soil organic matter increase, thus improving soil health and crop yields. Optimised crop rotations in CA help control weeds and improve nutrient availability, thus contributing to farming system sustainability. However, most crop cultivars currently grown under CA have been developed on conventional or full tillage and it is likely that valuable genetic variation for adaptation to CA has been lost. Some genetic studies found significant genotype × tillage practice interactions under CA; however, the trend has not been consistent over environments or across studies. The relatively weak genetic response to tillage practice is probably a function of selection under conventional tillage over thousands of years. Even early farmers tilled the soil and made seed selections for the next crop based on the best adapted and most vigorous plants. If a stronger response to CA is to be achieved, then germplasm resources that extend adaptive trait variability must be characterised and integrated with crop breeding. It is vital that crop improvement strategies are developed that incorporate CA as the interaction between improved crop genotype and an optimised farming system in order to produce the higher yields needed to keep pace with human population growth.

Keywords Conservation agriculture · Zero till · G × T interaction · Genetic improvement · Seedling vigour · Crop residue · Crop rotation · Allelopathy

---

T. Mahmood (✉) · R. Trethowan
Plant Breeding Institute, The University of Sydney, Cobbitty, NSW 2570, Australia
e-mail: tariq.chattha@sydney.edu.au

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_7

7.1 Introduction

Conservation agriculture (CA) is defined as minimised tillage, maintenance of crop residues in the field, intercropping, and optimised crop rotations that improve the sustainability and efficiency of resource use. According to FAO (2011), CA is a powerful option for meeting future food demands while contributing to sustainable agriculture and rural development. CA was initially introduced to protect land from erosion (Francis and Barber 2003) but soon became a popular farming practice in many parts of the world because of reduced costs and better management of soil available water. CA was introduced in the1960s and 1970s in the USA and Brazil, respectively, and then spread exponentially in South America from the 1990s onwards (Friedrich et al. 2012).

A key component of CA is the retention of crop biomass on the soil surface post harvest; this organic matter is incorporated into the soil with subsequent cropping. The organic matter remains in the farming system, thus improving soil structure, soil water-holding capacity, and ultimately crop growth and yield (Francis and Barber 2003).

An additional advantage of CA is reduced input costs compared to conventional agriculture. Reduced inputs largely refer to labour, fuel and, when the rotation includes a leguminous crop, fertilizer costs. However, these efficiencies are to some extent offset by increased herbicide usage, particularly in the early stages of CA adoption. Nevertheless, once the CA system is stabilized (often after a few years), the improved soil structure and moisture availability result in higher crop yields and greater profits (Young et al. 1994; Pretty et al. 2006).

Crop rotations are an important aspect of CA as they lower input costs, improve soil health and fertility, improve water availability, and ultimately increase crop yields (PSU 1996; Peters et al. 2004; Vita et al. 2007). Although not completely understood yet, to maintain better soil health, nutrition-optimised crop rotations are more important in CA compared to conventional agriculture. Studies on barley reported better yields under zero tillage in average and below average rainfall years; however, yield tended to be higher under conventional tillage in high rainfall conditions (Martin-Rueda et al. 2007). A possible reason for this observation was the greater available soil moisture under zero tillage in drier years; an advantage that is minimised when moisture is not limiting due to high rainfall. This increased water availability is augmented by increased organic matter, N, P, K, Fe, Mn, Cu, and Zn in the upper soil layers in CA. While these nutritional advantages may be offset to some extent by less-effective N application under CA, this can be mitigated by introducing legumes in the rotation (Mupangwa et al. 2011).

Root and shoot systems can be manipulated genetically to provide either deep or shallow roots for better nutrient and water scavenging, depending on soil type and depth or to design plant canopy more conservative in input use. Remodelling the plant ideotype that is compatible with changed conditions under CA is the logical way forward.

7.2 Crop Breeding for CA

Despite the fact that CA is widely practised globally, there is little evidence of CA-targeted crop breeding. While the potential for CA-specific breeding has been discussed (Trethowan et al. 2012) and breeders in some countries test their fixed line products or hybrids under CA, the development of new lines is rarely conducted under CA, nor have CA-specific cultivars been released to farmers. Clearly, new cultivars developed for CA should match the changed farming conditions and field operations. The changed operations include the management of higher crop residues in the field, new crop rotations, increased weed competition, and changed fertilizer application and distribution in the soil.

Most CA literature largely focuses on crop management whereas studies of the genetics of crop adaptation are limited. A key aspect of crop adaptation to CA is the existence of a genotype × tillage practice (G × T) interaction; such interactions indicate that cultivars better adapted to CA can be developed. However, studies show that G × T interaction is in many cases weak or non-existent (Ullrich and Muir 1986; Elmore 1990; Melo et al. 2005; Duiker et al. 2006; Gutierrez 2006; Zamir et al. 2010). The absence of a G × T interaction indicates either a low frequency or absence of genes that govern adaptation to CA. Crops have been grown on conventional tillage for thousands of years and genes governing adaptation to CA either have been lost over time through untargeted selection or have become redundant.

Other studies, however, reported significant G × T interactions (Kharub et al. 2008; Trethowan et al. 2012) when a more diverse group of genotypes was tested. In one of the few molecular studies on the genetics of adaptation to CA, a mapping population based on a biparental cross between parents varying for yield under CA was evaluated under contrasting tillage regimes on different soil types over time (Trethowan et al. 2012). The authors identified quantitative trait loci (QTLs) and linked molecular markers associated with tillage practice (Table 7.1). Those QTLs associated with zero tillage were located on chromosomes 2D and 5B. The QTL on the terminal end of the long arm of 5B overlaps with that reported earlier for *Tsn1* (Oliver et al. 2009; Farisa et al. 2010). This gene confers a degree of resistance to yellow spot (*Pyrenophora tritici-repentis*), a disease commonly found in CA systems when crop residues are retained. However, little disease infestation was noted in these trials and the *Tsn1* gene may have other effects on yield under CA. These CA-specific QTLs were discovered in a cross between two polymorphic but adapted wheat cultivars. If more diverse ancestral wheat genotypes are evaluated, then it may be possible to identify more QTLs that work additively to improve overall adaptation to CA.

Currently, the breeding programs in many countries breed wheat cultivars under conventional tillage and test fixed lines in the target environment under both conventional tillage and CA. The current wisdom is that cultivars developed under conventional tillage perform well under CA (personal communication with Australian wheat breeders). However, it is unclear how much variation for adaptation to CA has been lost through breeding and how much still exists in the less well-adapted gene pool.

Table 7.1 Significant QTL effects for yield under contrasting tillage regimes on two soil types in 2 years. (Trethowan et al. 2012)

Chr	Interval	Treatment	Soil type	Additive effect %	Allele
1B	gwm268/wPt-3475	CT	Grey v	8	K
1B	wPt-1313/gmw140	CT	Grey v	10	K
1D	cdf19/wmc216	CT	Red k	10	K
2D	wPt-3728/cfd44	ZT	Grey v	9	K
2D	gmw484/wmc27	ZT	Red k	9	B
5A	cfa2155/wPt1370	ZT	Grey v	25	B
5A	cfa2115/wPt1370	CT	Grey v	14	B
5A	cfa2115/wPt1370	CT	Red k	9	B
5B	wmc99/wPt2373	ZT	Grey v	12	B

7.3 The Implications of Higher Crop Residues

Crop residues are retained on the ground in a CA system (Fig. 7.1). The thickness of the ground cover depends on the biomass produced by the preceding crop. This biomass contributes to soil organic matter and improves soil water-holding capacity and porosity (Wasson et al. 2012). Stubble cover reduces soil crust formation, protects soil aggregates from direct raindrop impact and reduces run off (Verhulst et al. 2009). However, these residues also present a problem for seedling emergence and establishment in the following crop.

Seedling vigour and coleoptile length and thickness are potentially important traits for effective crop establishment in CA systems with high crop residues (Rebetzke et al. 2004; Trethowan et al. 2005; Joshi et al. 2007). Modern semi-dwarf wheat varieties are based on the gibberellic acid (GA) insensitive Green Revolution dwarfing genes *Rht1* and *Rht2*; these genes not only reduce plant height but also reduce coleoptile length (Trethowan et al. 2001). Crop breeders therefore need to select short-statured non-*Rht1* or non-*Rht2* wheat genotypes with improved emergence characteristics or introduce alternative sources of dwarfism (including *Rht7*, *8*, *12*, *13*), which are not GA insensitive (Ellis et al. 2004; Gasperini et al. 2012). Genotypes, with early vigour may also have the capacity to emerge through stubble better, thus improving their adaptation in CA systems (Olesen et al. 2004). Traits that have been reported to improve crop establishment better under CA are presented in Table 7.2.

A cultivar improvement strategy for adaptation to CA could follow the general breeding principles used in conventional breeding with greater emphasis on the traits in Table 7.2 and selection under CA; particularly using crop residues and the rotations most likely to be managed by farmers in the target environment. Chapman et al. (2003) used the concept of 'target population of environments' (TPE) to

Fig. 7.1 Berkut-Krichauff (*BK*) wheat populations under conventional and zero tillage at IA Watson Grains Research Centre, Narrabri, The University of Sydney

classify environment types in time and space. According to this concept, environments could be classified on the basis of their similarities and dissimilarities to identify a group of correlated environments—the TPE. The selection of parents and the screening of progeny would then be more precise once the underlying stresses and constraints in the target environment were understood (Greene et al. 1999). In CA, this would likely entail the classification of TPE on the basis of soil type and weather patterns but could also include crop rotation, crop residues and density, and the probability of incidence and severity of stubble-borne diseases. Selection thus conducted in one environment may therefore be applicable to other similar environments. The TPE could be confirmed using multi-environment data to estimate association among sites and genotypes using either balanced or unbalanced meteorological (MET) data (Crossa et al. 1993; DeLacy et al. 1996; Yan and Tinker 2006).

7.4 Expanding the Genetic Variability for Adaptation to CA

Genetic variability serves as the basis for genetic improvement of any economically important trait. To improve adaptation to CA it is necessary to expand genetic diversity for traits linked to improved performance under CA. Focused identification of germplasm strategy (FIGS), as suggested by Bhullar et al. (2009), is one way to identify desired genetic variability in gene pools. Using geo-referencing, this strategy offers a basis for allele estimation and identification in gene bank collections. FIGS allows subsets of germplasm from genetic resource collections to be selected that maximize the likelihood of capturing a specific trait. The expression of a specific trait (of a target crop) is linked to the eco-geographic parameters of the original collection sites (Endresen et al. 2012). The trait–environment relationship can then be further refined using modelling to expand the search for new alleles (El Bouhssini et al. 2009; Bari et al. 2012). Traits for FIGS in a breeding program targeting CA could include those in Table 7.2 linked to specific environmental conditions, for example, geographic regions where tan spot, low temperature at emergence, or nutrient deficiencies are likely to occur.

Table 7.2 Plant traits useful under conservation agriculture

Trait	Target use	Reference
Coleoptile length	Longer coleoptiles emerge better through ground cover	Trethowan et al. (2001, 2009, 2012); Richards et al. (2001); Rebetzke et al (2007); Liatukas and Ruzgas (2011)
Emergence from depth	Deep seeding may benefit under moisture stress conditions	Trethowan et al. (2005); Joshi et al. (2007)
Coleoptile thickness	Thicker and stronger seedling can emerge better through thick crop residues	Rebetzke et al. (2004)
Seed size and seedling vigour	Stronger seedlings can establish better than weaker ones	Liang and Richards (1999); Trethowan et al. (2005); Bertholdsson, (2005); Erayman et al. (2006); Maydup et al. (2012)
Rapid height growth	Faster growing seedlings can establish earlier than slower growing ones	Olesen et al. (2004)
Rapid root growth	Rapid root growth helps plants establish earlier	Trethowan and Reynolds (2005); Singh et al. (2007)
Deeper roots	Deep roots help get moisture from depth	Uphoff (2003); Reynolds et al. (2007); Wasson et al. (2012)
Faster stubble decomposition	Faster decomposition of previous crop residues benefit next crop establishment	Joshi et al. (2007)
Fertilizer-use efficiency	Better use of fertilizer helps crop establishment	Van Ginkel et al. (2001); Trethowan et al. (2005); Makhziah et al. (2013); Rose et al. (2013)
Disease resistance	Resistance to disease may enhance adaptation under higher disease pressure under CA	Trethowan et al. (2005, 2012); Joshi et al. (2007); Yadav et al. (2010)
Seedling temperature tolerance	Seedlings with temperature stress tolerance at early stages can establish better under CA	Boubaker and Yamada (1991); Dell'Aquila and Spada (1994); Sanghera et al. (2011); Ranawake and Nakamura (2011)
Root mass distribution in soil	Deeper and homogeneous root distribution in the soil helps better absorption of water and nutrients	Dwyer et al. (1996); Qin et al. (2006); Reynolds et al. (2007)

CA conservation agriculture

The search for new alleles could also extend to synthetic wheat. These reconstituted hexaploid bread wheats are made by crossing tetraploid wheat (either adapted *Triticum durum* or the cultivated and wild emmer wheat) with *Aegilops tauschii,* the donor of the D-genome, followed by embryo rescue and chromosome doubling. A summary of the potential of synthetic wheat for crop improvement is in Trethowan and Mujeeb-Kazi (2008). These hexaploid primary synthetic wheats can be crossed directly with adapted wheat to extend allelic variation for key traits considered important for adaptation to CA. It was interesting to find suitable genetic variation for seedling vigour and growth in wheat lines derived from D-genome introgression

(Landjeva et al. 2010). Better emergence (Joshi et al. 2007), larger seeds and greater early vigour (Blanco et al. 2001), and deeper roots (Reynolds et al. 2007) are all characteristics found in synthetic-derived wheat that could improve adaptation to CA. Dwarfing genes, with no pleiotropic effect on GA responsiveness (Ellis et al. 2005) and producing longer coleoptiles, may be targeted to create new genetic variability in coleoptile length, a trait important for adaptation under CA (Liatukas and Ruzgas 2011; Trethowan et al. 2012).

7.5 The Implications of Crop Rotation in CA

Crop rotation is a vital aspect of CA. Suitable rotations increase soil fertility, improve soil health, decrease weed and disease pressure, and produce higher yields (Florentín et al. 2010; Mupangwa et al. 2011; CAST 2012). Crop rotation also provides soil cover, stabilizes soil temperature, stimulates biological activity, improves crop nutrient-use efficiency, and breaks pest and disease cycles (Duiker and Myers 2006; Hobbs et al. 2008). Incorporation of deep-rooted crops in the rotation improves nutrient recycling from deeper soil layers thus increasing nutrients for shallow-rooted crops. Crop rotation also improves soil microbial activity and increases the diversity of soil flora (FAO 2014). The choice of crop sequence is dependent on the environment, soil type, and market opportunities. However, crop maturity is an important consideration when choosing rotation crops; a trait that can be manipulated through breeding. According to Cook and Ellis (1987), three general principles apply to crop rotation, viz. (1) practising a rotation is better than monoculture, (2) rotations with legumes are more useful than those without legumes, and (3) crop rotations need to be supplemented with additional nutrients to maintain productivity.

Crop cultivars suitable for one rotation under a particular environment may not necessarily be suitable for another environment. The new CA crop rotations may produce different volumes and quality of crop residues necessitating the development of adapted cultivars. For example, in Australia where wheat is grown under relatively dry, rainfed conditions, short-statured cultivars are favoured by farmers to assist with crop residue management (Evans and Fischer 1999). This contrasts with environments in North Africa and other parts of the world where taller cultivars are favoured because of the high value of the straw as animal feed (Annicchiarico et al. 2005); in these situations it is difficult to maintain sufficient residue in the farming system. Under high volumes of crop residue, cultivars with longer and stronger coleoptiles may perform better. Similarly, the allelopathic effects of crop residues also necessitate the deployment of suitably adapted crop cultivars (USDA 2008; Farooq et al. 2011). The straw decomposition generates chemical substances (allelochemicals) that may affect the next crop in the rotation. Residues of cereal crops are particularly allelopathic to legumes such as lupin (Acevedo et al. 2009). Genetic variability for allelopathic effects has been reported in wheat (Kimber 1967). Therefore, breeding new wheat cultivars with low allelopathic capacity or lupins with high tolerance to allelopathic chemicals may provide a solution (Silva 2007). Faster seedling growth, temperature stress tolerance, and resistance to diseases are also potentially useful traits in crop rotations (Duiker and Myers 2006).

7.6 The Problem of Weed Competition in CA

One of the challenges that crops generally face during early development under CA is weed competition (Chauhan et al. 2012). While the weed seed bank reduces over time with optimised CA, it is particularly important that weeds be controlled in the early phase of CA. There may be some weed/crop cultivar specificity, and some weeds will not be common across the target environment (Lemerled et al. 2001). The competitiveness of a cultivar to a specific weed type may also change across environments (Cousens and Mokhtari 1998) further complicating crop improvement and cultivar deployment. Developing cultivars capable of competing with weed pressure is generally considered one of the most important breeding objectives under CA. Seedling vigour and faster seedling growth are important traits that could help crops compete with weeds during early development under CA (Olesen et al. 2004; Trethowan et al. 2012). Useful sources of genetic variation are available in wheat for seedling vigour and early growth (Richards and Lukacs 2002; Watt et al. 2005). Spielmeyer et al. (2007) reported a QTL on chromosome 6A that accounted for 14% of seedling leaf width and was associated with increased plant height in early development. They also reported a gene marker, NW3106, associated with greater leaf width and seedling vigour.

However, early vigour does not completely replace the need for effective chemical weed control under CA (Duiker and Myers 2006). Crop cultivars deployed under CA should be resistant to the broad spectrum of herbicides available to farmers and may need to be evaluated before release, given the greater dependence on herbicides in CA systems.

Herbicide-resistant weeds can pose a weed-control problem under CA (CAST 2012). The weeds found in CA tend to invest more in their root systems rather than seed production (Trichard et al. 2013). Therefore, a stronger root system and greater seed production may improve crop competition with weeds. Greater plant investment in root systems is a feature often seen in perennial crops (McLaughlin et al. 2006); however, in annual crops like wheat, a balance between above- and below-ground biomass selections is needed.

7.7 The Incidence of Disease and Insect Pests in CA

The impact of conservation tillage on disease incidence is not clearly understood, with some authors suggesting an increase in incidence while others report no change (Gonzales and Dave 1997; Leake 2003; Hobbs et al. 2008; Raaijmakers et al. 2009; Kassam et al. 2009). However, it is clear that more research is needed as healthy soils with more microbial activity can potentially discourage pathogen development.

Balota et al. (1996) reported an increase in disease and insect pressure under CA. However, suitable agronomic practices, appropriate crop varieties, farm machinery hygiene, and other soil health measures can help reduce the pressure to a large extent (Bailey and Lazarovits 2003; Twomlow et al. 2008). The changed conditions under CA could favour some microbes while discouraging others. A reduced level of *Rhizoctonia* stem canker has been reported in conservation tillage systems in certain environments (Gudmestad et al. 1989; Leach et al. 1993). Regular monitoring of insects, diseases, and pests is required under CA (LNR-ARC 2013).

The breeding objectives for disease resistance, however, may not be very different to conventional crop breeding for disease and insect resistance. The focus for crop improvement should be on those diseases projected to increase under CA. For example, yellow spot of wheat (*P. tritici-repentis*) is found at low levels in many conventional tillage systems (Rees and Platz 1979); however, this pathogen survives on crop residues year to year under CA and the inoculum load steadily increases to yield-limiting levels (Annone 1997; Fischer et al. 2002). Genetic variation for resistance is available (e.g. *Tsn1*), which may be used in breeding to buffer crop performance. Other insects and diseases that increase in CA systems are termites and stem borers in rice (Jaipal et al. 2005), crown rot in wheat, maize, and sugar beet (Wildermuth et al. 1997; Cotton and Munkvold 1998; Guillemaut 2003), and charcoal rot in soybean (Baird et al. 2003).

Organic amendments can reduce disease incidence or severity (Bailey and Lazarovits 2003). To enhance the suppressive potential of composts and to improve disease control, it has been proposed to inoculate composts with specific strains of antagonistic microorganisms. Although promising, this strategy has not yet been successfully applied (Raaijmakers et al. 2009).

7.8 The Impact of CA on Product Nutritional and Processing Quality

The nutrient status of soil affects the nutritional and processing quality of the product (Wang et al. 2008). Fertilizer applied in CA may stay in the upper layers of the soil with lower concentrations in the deeper root zone (Martin-Rueda et al. 2007). Evidence shows that early-season nutrient deficiencies can be mitigated by the decomposition of crop residues which provides nutrients that are available to the growing plant (Mrabet et al. 2001). Thus, less fertilizer may be needed in these systems. However, the optimal placement of fertilizer in CA is often more difficult than under conventional systems (Triplett and Dick 2007) and this can lead to less-efficient N use and lower grain protein (Grant and Flaten 1998). Lower grain protein will reduce dough strength and extensibility thus impacting product quality. There is variation for N-use efficiency in wheat (Gouis et al. 2000; Van Ginkel et al. 2001) which can be manipulated genetically to improve N uptake and processing quality.

Nevertheless, the genetics of dough rheology is well known and high and low molecular weight glutenin and gliadin gene combinations can be optimised (Branlard et al. 2001) to reduce the impacts of less-efficient N uptake in CA systems.

7.9 Breeding for Conservation Agriculture

7.9.1 Genetic Variation

Identifying genetic variation for adaptation to CA is the first and vital step in crop improvement. It is always better to first exploit variation in the adapted gene pool as these materials can be easily manipulated. However, there appears to be insufficient genetic variation in the adapted wheat gene pool to facilitate significant improvements in crop adaptation. For this reason, it may be desirable to expand the search for genetic variation to both adapted and less-adapted materials (Trethowan et al. 2009). The important sources of genetic variation in a crop such as wheat could include:

1. *The adapted gene pool*
   In this instance, the breeder would evaluate greater diversity in the adapted wheat gene pool including materials not targeted to the TPE. For example, a spring bread wheat breeder may find additional diversity in winter wheat or in tetraploid durum wheat that can be easily manipulated, thus extending breeding program diversity.
2. *Landrace collections*
   Landraces are traditional cultivars grown by farmers before the application of modern plant breeding. These materials represent potential new variation for traits important in CA. These traditional cultivars can be crossed directly with modern wheat thus facilitating the transfer of traits. To identify the right material, the collections need to be evaluated in the target environment with appropriate crop residues in a crop rotation practised by farmers. Once the TPE is defined, the germplasm can be shortlisted for testing on the basis of geographic information and environmental data. El Bouhssini et al. (2009, 2011) reported the use of FIGS to identify germplasm for the selection of insect tolerance in wheat. They concluded that this strategy was more effective than conventional methods based on political boundaries. Approximately, 77 % of the wheat area in developing countries is sown to the International Maize and Wheat Improvement Center (CIMMYT)-related bread wheat materials; however, the genetic diversity of these modern semidwarf wheats has not decreased since 1965 (Smale et al. 2002). The national programs regularly use local germplasm in their hybridization programs with CIMMYT materials and this helps maintain genetic diversity.
3. *Synthetic wheat genotypes*
   Synthetic wheat offers a useful source of genetic variation (Trethowan and Mujeeb-Kazi 2008). Hexaploid bread wheat (AABBDD) arose from crosses

among three separate genomes which occurred in nature, thousands of years ago. When reconstituted from these parental genomes in the laboratory, this new synthetic wheat represents a reservoir of new genetic variation (Villareal and Kazi 1998). To make a primary synthetic, modern durum wheat, *Triticum dicoccum* or *Triticum dicoccoides* (AABB) is crossed with *A. tauschii* (DD) followed by chromosome doubling to make hexaploid wheat ($2n=6x=42$, AABBDD). Large genetic variation has been reported in synthetic wheats for a whole range of traits including biotic and abiotic stress tolerance, crop morphology, and grain quality parameters (Blanco et al. 2001; Yang et al. 2002; Reynolds et al. 2007; Kunert et al. 2007; Lage and Trethowan 2008; Bibi et al. 2012). The primary synthetics are usually agronomically poor, hard to thresh, and have inferior grain quality but offer useful diversity for CA (Dreisigacker et al. 2008; Trethowan et al. 2010). Useful genetic variation for seed and seedling traits has been reported in wheat lines carrying D-genome introgression segments (Landjeva et al. 2010). Trait variation in synthetic wheat that may improve adaptation to CA include higher yield (CAST 2012), larger seed (Maydup et al. 2012), longer coleoptiles (Trethowan et al. 2012), improved nutrient-use efficiency (Makhziah et al. 2013), temperature tolerance (Ranawake and Nakamura 2011), and a deeper or more extensive root system (Wasson et al. 2012).

4. *Alien introgression*
Alien introgression is the introduction of new genes from distantly related species and has proved to be a valuable source of variation, particularly for disease resistance. A good example of alien introgression is the 1B/1R translocation in wheat (Trethowan and Mujeeb-Kazi 2008). The long arm of the 1B chromosome has been replaced with the short arm of 1R chromosome from rye. This translocation was found in the winter wheat cultivar Kavkaz and is associated with improved root vigour and better water uptake (Ehdaie et al. 2003). The translocation was later introduced into spring bread wheat and some of the most broadly adapted wheat cultivars globally were subsequently developed and deployed (Trethowan et al. 2007). The 1B/1R translocation was also linked to a larger root system (Hoffmann 2008) and this may improve adaptation to CA. However, as the translocation is also associated with poorer processing quality, it has limited use in countries where market quality is important. Other alien wheat translocations may include many of the rust resistance genes like *Sr36, Sr40, Sr39/Lr35,* and *Sr32* (Bariana et al. 2007). These translocations may carry useful variation for adaptation to CA; however, apart from rust resistance and some reports of yield depression/improvement in specific backgrounds (Villareal et al. 1991; Foulkes et al. 2007; Peake et al. 2011), little is known of their response to CA.
5. *Mutation breeding*
Induced mutations have been successfully used in agricultural crops around the world with intensive use in Asia, Europe, and North America. More than 300 mutant crop varieties have been released in India alone (Maluszynski 2001; Kharkwal and Shu 2009). However, the probability of success using mutation is low as the changes occur randomly across the genome. More recently, a technique called targeting induced local lesions in genomes (TILLING) has been

used to detect mutations in known genes (Wu et al. 2005; Comai and Henikoff 2006). Wheat has only a few functional waxy genes (granule-bound starch synthase (GBSSI) gene), however, more than 200 alleles of these genes have been detected through TILLING (Slade et al. 2005). Once the genes controlling the key CA adaptive characters have been identified, it may be possible to enhance or suppress their expression using TILLING. Known genes controlling plant morphology, such as the tillering inhibition gene (*Tin*; Spielmeyer and Richards 2004), the GA-insensitive Rht genes, and genes controlling seed size and seedling vigour could be targeted through TILLING.

6. *Transgenics*
   Transgenesis is a useful technique with potential application under CA. Transgenesis has been used to develop new genotypes better adapted to high insect and disease pressure (Huesing and English 2004). Transgenic wheat expressing the *HVA1* gene from barley had significantly more root fresh and dry weight, and homozygous lines for the gene performed better under water deficit compared to heterozygous lines (Sivamani et al. 2000). Genes conferring longer coleoptile length, increased seedling vigour, rapid growth, deeper or more extensive root systems, fertilizer-use efficiency, disease resistance, and better temperature tolerance could be targeted to improve adaptation to CA through transgenesis. Anand et al. (2003) reported the field performance of transgenic wheat lines expressing genes for thaumatin-like proteins, chitinase and glucanase, against *Fusarium graminearum,* an important disease in some CA systems. Under field conditions, they found a moderate level of resistance against the pathogen (type II resistance) in one of the lines.

7.9.2 Breeding Strategy

Once the parental lines combining the desired genetic variation for CA have been identified, it is necessary to implement a suitable breeding strategy to combine the diversity in elite materials suitable for release to farmers. A possible breeding strategy is outlined below:

1. *Crossing* When selecting parents for recombination, the physiological, genetic, and agronomic parameters influencing CA and market quality are vital. It is therefore essential that a plant ideotype for adaptation to CA be developed. The plant ideotype may vary between environments; however, for the purposes of this chapter, we target wheat crop in northwestern New South Wales (NSW). Northwestern NSW has a subtropical climate with annual summer-dominant rainfall of 500–700 mm. The soil is generally a clay loam with high water-holding capacity. Wheat grows in rotation with other crops and is sown in the autumn on stored soil moisture. The mid-season conditions are generally favourable, although terminal heat and moisture stress prevail post flowering. Both irrigated and dry-land farming exist in the region, but dry-land farming is mostly practiced. Wheat

is the principal dry-land crop in the region, while barley, sorghum, chickpeas, and sunflower are the major crops used in rotation with wheat. Winter–summer crop rotations are limited by overlapping harvesting/sowing times and the availability of moisture to support summer–winter rotations (Scott et al. 2004). CA is practiced across this region. Low moisture in the upper soil and high crop residues on the surface require wheat plants with longer and thicker coleoptiles in order to emerge from deep-sown seeds (Rebetzke et al. 2004; Joshi et al. 2007; Rebetzke et al. 2007; Liatukas and Ruzgas 2011). Seedling vigour is an important parameter (Liang and Richards 1999; Erayman et al. 2006) that will help crop establishment. Larger seed size is required as this is linked to more vigorous early growth. Larger seeds could be selected for sowing using sieves. Rapid plant growth leads to better crop establishment under CA (Olesen et al. 2004; Trethowan and Reynolds 2005). The faster early growth, if combined with early maturity, may help the crop escape terminal heat and moisture stress (Al-Karaki 2012). Similarly, faster early-growth changes the root mass distribution (Reynolds et al. 2007) and subsequently improves tolerance to biotic (Yadav et al. 2010; Trethowan et al. 2012) and abiotic stress (Ranawake and Nakamura 2011), largely by outgrowing the constraint or foraging for deeper moisture stored in the soil from summer rainfall. A wheat ideotype better adapted to CA in the region would therefore have longer coleoptiles, larger seed, more rapid germination and emergence, good resistance to stubble-borne pathogens, such as yellow spot, deeper roots that access stored soil moisture, and improved tolerance to abiotic stresses such as terminal heat and drought.

2. *Selection and evaluation* A vital step in breeding for CA is identifying the best possible selection environment. The selection environment should represent farmer CA practice. For example, selection for long coleoptiles, an important trait in CA, needs to be conducted in conjunction with high crop residues. Selection for the right phenology is important as CA affects crop development (Merrill et al. 1996), particularly in dry environments such as northern NSW, as water is used more efficiently. Marker-assisted selection (MAS) can assist the development of wheats (Fig. 7.2) better adapted to CA as markers are available for rust resistance (Bariana et al. 2007), *Fusarium* blight (Zhou et al. 2003; Buerstmayr et al. 2009), tiller inhibition (*tin*) genes (Spielmeyer and Richards 2004); alternate dwarfing genes for longer coleoptiles (Ellis et al. 2005) and seedling vigour (Spielmeyer et al. 2007). All standard wheat breeding techniques and strategies are amenable to the inclusion of CA as a selection criterion. The most important step is the development and management of suitable field-based screening using reduced or zero tillage. This can be augmented with MAS for known genes that influence adaptation and in situ tests for key characters such as coleoptile length and seed size which have a high heritability and correlate well with field performance. Inoculation of field experiments with stubble-borne diseases or the selection of sites with a high recorded incidence will ensure that populations are skewed towards resistance. Advanced materials developed using the above strategies must be assessed on farmers' fields, under local CA practices, in

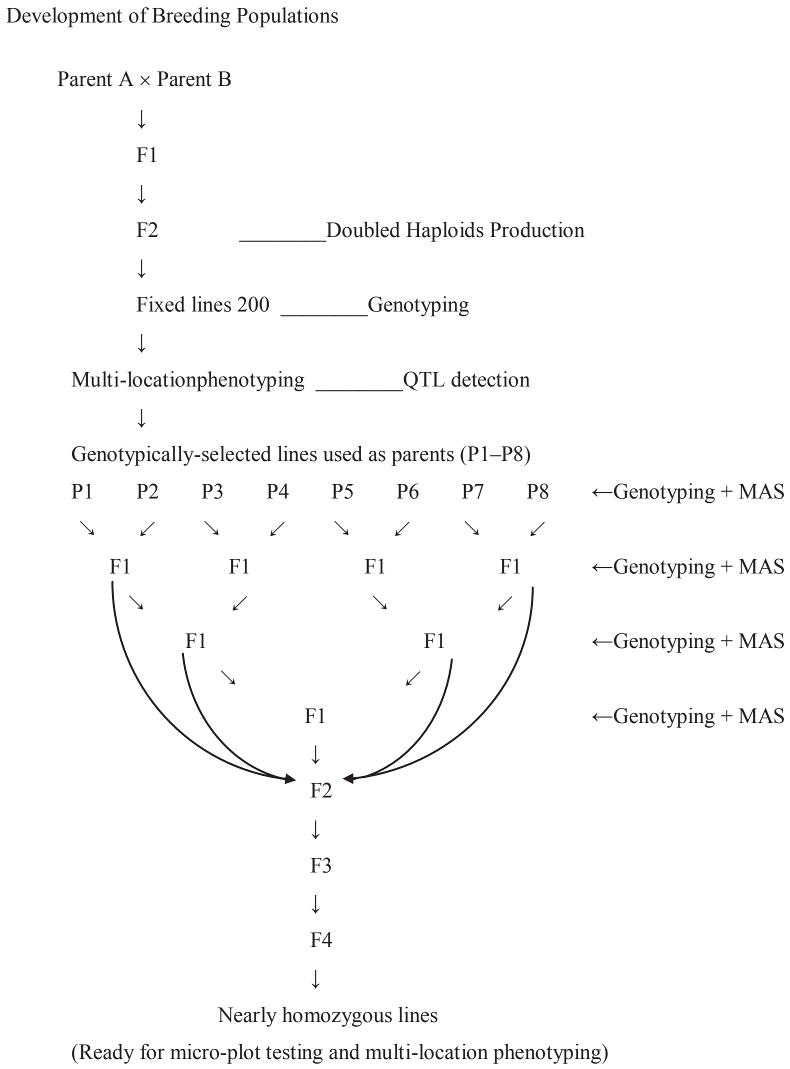


Fig. 7.2 Marker-assisted recurrent selection scheme to improve wheat adaptation to conservation agriculture. MAS marker-assisted selection; QTL quantitative trait locus

multi-environment trials using standard cultivars to compare performance. Once materials that maintain their yield and quality advantage over sites and years are identified, they can be recommended for release to farmers. While target is the improved performance under CA, it is also necessary to evaluate materials across the range of farming practices in the region. Ideally, a genotype that performs well in CA will also yield well under conventional tillage thus reducing the risk of adoption of the new cultivars to the farming community.

7.10 Conclusions

CA is a widely adopted practice around the world and enough is now known about adaptation to CA to implement targeted breeding strategies. The introduction of CA in breeding does not require a major change in breeding method. The changes apply only to the selection environment and may include a range of new traits for selection. However, many of these traits are amenable to MAS which will assist in their integration. Perhaps the greatest challenge to introducing CA is the change in machinery required. Many programs, particularly in developing countries, do not have pre-existing sowing equipment that can be modified to cope with residues. However, this problem is not insurmountable and novel solutions, such as the modified Chinese tractor and hand-propelled seeders for larger-seeded crops, have been developed and deployed (Hobbs 2007; Erenstein and Laxmi 2008; Johansen et al. 2012). Nevertheless, lack of a G × T interaction should not discourage the implementing of CA in breeding programs. It likely reflects a lack of genetic variability and this can be corrected through targeted introduction of germplasm and trait selection.

References

Acevedo E, Martínez E, Silva P (2009) Constraints to zero tillage in Mediterranean environments. In: Lead papers; 4th World Congress on Conservation Agriculture, 4-7 Feb 2009, pp 195–206

Al-Karaki GN (2012) Phenological development-yield relationships in durum wheat cultivars under late-season high-temperature stress in a semiarid environment. ISRN Agron 2012:7 pages. Article ID 456856. http://www.hindawi.com/journals/isrn.agronomy/2012/456856/

Anand A, Zhou T, Trick HN, Gill BS, Bockus WW, Muthukrishnan S (2003) Greenhouse and field testing of transgenic wheat plants stably expressing gene;s for thaumatin-like protein, chitinase and glucanase against *Fusarium graminearum*. J Exp Bot 54:1101–1111

Annicchiarico A, Abdellaoui Z, Kelkouli M, Zerargui H (2005) Grain yield, straw yield and economic value of tall and semi-dwarf durum wheat cultivars in Algeria. J Agric Sci 143:57–64

Annone JG (1997) Tan spot of wheat in Argentina: importance and disease management strategies. In: Helminthosporium blights of wheat: spot blotch and tan spot. Proceedings of an international workshop held at CIMMYT El Batan, 9-14 Feb 1997, Mexico, pp 339–345

Bailey KL, Lazarovits G (2003) Suppressing soil-borne diseases with residue management and organic amendments. Soil Tillage Res 72:169–180

Baird RE, Watson CE, Scruggs M (2003) Relative longevity of *Macrophomina phaseolina* and associated mycobiota on residual soybean roots in soil. Plant Dis 87:563–566

Balota EL, Kanashiro M, Calegari A (1996) Adubos verdes de inverno na cultura do milho e a microbiologia do solo. In: I Congresso Brasileiro de Plantio Direto para uma Agricultura Sustentável. Ponta Grossa. Resumos expandidos, pp 12–14

Bari A, Street K, Mackay M, Endresen DTF, Pauw ED, Amri A (2012) Focused identification of germplasm strategy (FIGS) detects wheat stem rust resistance linked to environmental variables. Genet Resour Crop Evol 59:1465–1481

Bariana HS, Brown GN, Bansal UK, Miah H, Standen GE, Lu M (2007) Breeding triple rust resistant wheat cultivars for Australia using conventional and marker assisted selection technologies. Aust J Agric Res 58:576–587

Bertholdsson NO (2005) Early vigour and allelopathy—two useful traits for enhanced barley and wheat competitiveness against weeds. Weed Res 45:94–102

Bhullar NK, Street K, Mackay M, Yahiaoui N, Keller B (2009) Unlocking wheat genetic resources for the molecular identification of previously undescribed functional alleles at the Pm3 resistance locus. Proc Nat Acad Sci USA 106:9519–9524

Bibi A, Rasheed A, Kazi AG, Mahmood T, Ajmal S, Ahmed I, Mujeeb-Kazi A (2012) High-molecular-weight (HMW) glutenin subunit composition of the Elite-II synthetic hexaploid wheat subset (*Triticum turgidum* × *Aegilops tauschii*; 2n = 6x = 42; AABBDD). Plant Genet Resour 10:1–4

Blanco IAdel, Rajaram S, Kronstad WE (2001) Agronomic potential of synthetic hexaploid wheat-derived populations. Crop Sci 41:670–676

Boubaker M, Yamada T (1991) Screening spring wheat genotypes (*Triticum* sp.) for seedling emergence under optimal and suboptimal temperature conditions. Jpn J Breed 41:381–387

Branlard G, Dardevet M, Saccomano R, Lagoutte F, Gourdon J (2001) Genetic diversity of wheat storage proteins and bread wheat quality. Euphytica 119:59–67

Buerstmayr H, Ban T, Anderson JA (2009) QTL mapping and marker-assisted selection for Fusarium head blight resistance in wheat: a review. Plant Breed 128:1–26

CAST (Council for Agricultural Science and Technology) (2012) Herbicide-resistant weeds threaten soil conservation gains: finding a balance for soil and farm sustainability. Issue Paper, 49, CAST, Ames

Chapman S, Cooper M, Podlich D, Hammer G (2003) Evaluating plant breeding strategies by simulating gene action and dryland environment effects. Agron J 95:99–113

Chauhan BS, Singh RG, Mahajan G (2012) Ecology and management of weeds under conservation agriculture: a review. Crop Prot 38:57–65

Comai L, Henikoff S (2006) TILLING: practical single-nucleotide mutation discovery. Plant J 45:684–694

Cook RL, Ellis BG (1987) Soil management: a world view of conservation and production. Wiley, New Jersey

Cotton TK, Munkvold GP (1998) Survival of *Fusarium moniliforme*, *F. proliferatum*, and *F. subglutinans* in maize stalk residue. Phytopathology 88:550–555

Cousens RD, Mokhtari S (1998) Seasonal and site variability in the tolerance of wheat cultivars to interference from *Lolium rigidum*. Weed Res 38:301–307

Crossa J, Cornelius PL, Sevedsadr M, Byrne P (1993) A shifted multiplicative model cluster analysis for grouping environments without genotype ranking change. Theor Appl Genet 85:577–558

DeLacy IH, Basford KE, Cooper M, Bull JK, McLaren CG (1996) Analysis of multi-environment trials, a historical perspective. In: Cooper M, Hammer GL (eds) Plant adaptation and crop improvement. CAB, Wallingford, pp 39–124

Dell'Aquila A, Spada P (1994) Effect of low and high temperatures on protein synthesis patterns of germinating wheat embryos. Plant Physiol Biochem 32:65–73

Dreisigacker S, Kishii M, Lage J, Warburton M (2008) Use of synthetic hexaploid wheat to increase diversity for CIMMYT bread wheat improvement. Aust J Agric Res 59:413–420

Duiker SW, Myers JC (2006) Steps toward a successful transition to no-till. The Pennsylvania State University, Pennsylvania

Duiker SW, Haldeman JF, Johnson DH (2006) Tillage × maize hybrid interactions. Agron J 98:436–442. doi:10.2134/agronj2005.0063

Dwyer LM, Ma BL, Stewart DW, Hayhoe HN, Balchin D, Culley JLB, McGovern M (1996) Root mass distribution under conventional and conservation tillage. Can J Soil Sci 76:23–28

Ehdaie B, Whitkus RW, Waines JG (2003) Root biomass, water-use efficiency and performance of wheat-rye translocations of chromosome 1 and 2 in spring bread wheat Pavon. Crop Sci 43:710–717

El Bouhssini M, Street K, Joubi A, Ibrahim Z, Rihawi F (2009) Sources of wheat resistance to Sunn pest, Eurygaster integriceps Puton, in Syria. Genet Resour Crop Evol 56:1065–1069

El Bouhssini M, Street K, Amri A, Mackay M, Ogbonnaya FC, Omran A, Abdalla O, Baum M, Dabbous A, Rihawi F (2011) Sources of resistance in bread wheat to Russian wheat aphid (*Diuraphis noxia*) in Syria identified using the Focused Identification of Germplasm Strategy (FIGS). Plant Breed 130:96–97

Ellis MH, Rebetzki GJ, Chandler P, Bonnett D, Spielmeyer W, Richards RA (2004) The effect of different height reducing genes on the early growth of wheat. Funct Plant Biol 31:583–589

Ellis MH, Rebetzke GJ, Azanza F, Richards RA, Spielmeyer W (2005) Molecular mapping of gibberellin-responsive dwarfing genes in bread wheat. Theor Appl Genet 111:423–430

Elmore RW (1990) Soybean cultivar response to tillage systems and planting date. Agron J 82:69–73

Endresen DTF, Street K, Mackay M, Bari A, Pauw ED (2012) Predictive association between biotic stress traits and eco-geographic data for wheat and barley landraces. Genet Resour Crop Evol 59:1465–1481

Erayman M, Abeyo BG, Baenziger PS, Budak H, Eskridge KM (2006) Evaluation of seedling characteristics of wheat (*Triticum aestivum* L.) through canonical correlation analysis. Cereal Res Commun 34:1231–1238

Erenstein O, Laxmi V (2008) Zero tillage impacts in India's rice-wheat systems: a review. Soil Tillage Res 100:1–14

Evans LT, Fischer RA (1999) Yield potential: its definition, measurement, and significance. Crop Sci 39:1544–1551

FAO (2011) What is conservation agriculture? FAO, Rome. FAO CA website http://www.fao.org/ag/ca/1a.html. Accessed 5 Feb 2014

FAO (2014) The main principles of conservation agriculture. http://www.fao.org/ag/ca/1b.html. Accessed 20 Jan 2014

Farisa JD, Zhangb Z, Lub H, Lua S, Reddyc L, Cloutierd S, Fellerse JP, Meinhardtb SW, Rasmussenb JB, Xua SS, Oliverf RP, Simonsa KJ, Friesena TL (2010) A unique wheat disease resistance-like gene governs effector-triggered susceptibility to necrotrophic pathogens. Proc Nat Acad Sci USA 107:13544–13549

Farooq M, Flower KC, Jabran K, Wahid A, Siddique KHM (2011) Crop yield and weed management in rainfed conservation agriculture. Soil Tillage Res 117:172–183

Fischer RA, Santiveri F, Vidal IR (2002) Crop rotation, tillage and crop residue management for wheat and maize in the sub-humid tropical highlands I. Wheat and legume performance. Field Crop Res 79:107–122

Florentín MA, Peñalva M, Calegari A, Derpsch R (2010) Green manure/cover crops and crop rotation in Conservation Agriculture on small farms. FAO Report, Integrated Crop Management, vol 12

Foulkes MJ, Snape JW, Shearman VJ, Reynolds MP, Gaju O, Sylvester-Bradley R (2007) Genetic progress in yield potential in wheat: recent advances and future prospects. J Agric Sci 145:17–29

Francis S, Barber R (2003) Conservation agriculture. In: Francis S, Barber R (eds) Optimizing soil moisture for plant production. FAO, Rome, ISBN 92-5-104944–0

Friedrich T, Derpsch R, Kassam A (2012) Overview of the global spread of conservation agriculture. FAO report. http://factsreports.revues.org/1941. Accessed 25 Dec 2013

Gasperini D, Greenland A, Hedden P, Dreos R, Harwood W, Griffiths S (2012) Genetic and physiological analysis of Rht8 in bread wheat: an alternative source of semi-dwarfism with a reduced sensitivity to brassinosteroids. J Exp Bot 63:4419–4436

Gonzales A, Dave RD (1997) Comparison of egg parasitism of *Empoaska kraemeri* by *Anagrus* sp. in common beans under no-tillage and conventional tillage. CEIBA 38:49–54

Gouis JL, Béghin D, Heumez E, Pluchard P (2000) Genetic differences for nitrogen uptake and nitrogen utilisation efficiencies in winter wheat. Eur J Agron 12:163–173

Grant CA, Flaten DN (1998) Fertilizing for protein content of wheat. In Fowler DB et al (ed) Proceedings of Wheat Protein Symposium, University of Saskatchewan, Saskatoon, SK, Canada, 9-10 March, Univ. Ext. Press, Saskatoon, pp 151–168

Greene SL, Thomas CH, Afonin A (1999) Using geographic information to acquire wild crop germplasm for ex situ collections: II. Post-collection analysis. Crop Sci 39:843–849

Gudmestad NC, Stack RW, Salas B (1989) Colonization of potato by *Rhizoctonia solani* as affected by crop rotation. In: Vos J, Van Loon CD, Bollen GJ (eds) Effects of crop rotation on potato production in the temperate zones. Kluwer Academic , Dordrecht, pp 247–252

Guillemaut C (2003) Identification et étude de l 'écologie de *Rhizoctonia solani* responsable de la maladie de pourriture brune de la betterave sucrière. PhD thesis, Université Claude Bernard-Lyon I, Lyon

Gutierrez A (2006) Adaptation of bread wheat to different tillage practices and environments in Mexico. PhD thesis, Chapingo University, Texcoco

Hobbs PR (2007) Conservation agriculture: what is it and why is it important for future sustainable food production? J Agric Sci 145:127–137

Hobbs PR, Sayre K, Gupta R (2008) The role of conservation agriculture in sustainable agriculture. Philos Trans R Soc B 363:543–555

Hoffmann B (2008) Alteration of drought tolerance of winter wheat caused by translocation of rye chromosome segment 1RS. Cereal Res Commun 36:269–278

Huesing J, English L (2004) The impact of *Bt* crops on the developing world. Ag Bio Forum 7:84–95

Jaipal S, Malik RK, Yadav A, Gupta R (2005) IPM Issues in zero-tillage system in rice-wheat cropping sequence. Technical Bulletin (8). CCS Haryana Agricultural University, Hisar, p 32

Johansen C, Haque ME, Bell RW, Thierfelder C, Esdaile RJ (2012) Conservation agriculture for small holder rainfed farming: opportunities and constraints of new mechanized seeding systems. Field Crop Res 132:18–32

Joshi AK, Ortiz-Ferrara G, Crossa J, Singh G, Sharma RC, Chand R, Parsad R (2007) Combining superior agronomic performance and terminal heat tolerance with resistance to spot blotch (*Bipolaris sorokiniana*) of wheat in the warm humid Gangetic Plains of South Asia. Field Crop Res 103:53–61

Kassam A, Friedrich T, Shaxson F, Pretty J (2009) The spread of conservation agriculture: justification, sustainability and uptake. Int J Agric Sustain 7:292–320

Kharkwal MC, Shu QY (2009) Induced plant mutations in the genomics era. FAO, Rome, pp 33–38

Kharub AS, Chatrath R, Shoran J (2008) Performance of wheat (*Triticum aestivum*) genotypes in alternate tillage environments. Indian J Agric Sci 78:884–886

Kimber RWL (1967) Phtotoxicity from plant residues: I. The influence of rotted wheat straw on seedling growth. Aust J Agric Res 18:361–374

Kunert A, Naz AA, Dedeck O, Pillen K, Léon J (2007) QTL analysis in winter wheat: I. Synthetic hexaploid wheat (*T. turgidum* ssp. *dicoccoides* x *T. tauschii*) as a source of favourable alleles for milling and baking quality traits. Theor Appl Genet 115:683–695

Lage J, Trethowan RM (2008) CIMMYT's use of synthetic hexaploid wheat in breeding for adaptation to rainfed environments globally. Aust J Agric Res 59:461–469

Landjeva S, Lohwasser U, Börner A (2010) Genetic mapping within the wheat D genome reveals QTL for germination, seed vigour and longevity, and early seedling growth. Euphytica 171:129–143

Leach SS, Porter GA, Rourke RV, Clapham WM (1993) Effects of moldboard plowing, chisel plowing and rotation crops on the *Rhizoctonia* disease of white potato. Am Potato J 70:329–337

Leake AR (2003) Integrated pest management for conservation agriculture. In: Garcia-Torres L, Benites J, Martinez-Vilela A, Holgado-Cabrera A (eds) Conservation agriculture: environment, farmers experiences, innovations, socio-economy, policy. Kluwer Academia, Dordrecht, pp 271–279

Lemerled D, Verbeek B, Orchard B (2001) Ranking the ability of wheat varieties to compete with *Lolium rigidum*. Weed Res 41:197–209

Liang YL, Richards RA (1999) Seedling vigor characteristics among Chinese and Australian wheat. Commun Soil Sci Plant Anal 30:159–165

Liatukas Z, Ruzgas V (2011) Coleoptile length and plant height of modern tall and semi-dwarf European winter wheat varieties. Acta Soc Bot Pol 80:197–203

LNR-Instituut vir Graangewasse/ARC-Grain Crops Institute (2013) Soil cultivation and conservation agriculture. Maize Information Guide

Makhziah, Rochiman K, Purnobasuki H (2013) Effect of nitrogen supply and genotypic variation for nitrogen use efficiency in maize. Am J Exp Agric 3:182–199

Maluszynski M (2001) Officially released mutant varieties—the FAO/IAEA database. Plant Cell Tissue Org 65:175–177

Martin-Rueda I, Mun˜oz-Guerra LM, Yunta F, Esteban E, Tenorio JL, Lucena JJ (2007) Tillage and crop rotation effects on barley yield and soil nutrients on a Calciortidic Haploxeralf. Soil Tillage Res 92:1–9

Maydup ML, Graciano C, Guiamet JJ, Tambussi EA (2012) Analysis of early vigour in twenty modern cultivars of bread wheat (*Triticum aestivum* L.). Crop Pasture Sci 63:987–996

McLaughlin SB, Kiniry JR, Taliaferro CM, Ugarte DDLT (2006) Projecting yield and utilisation potential of switchgrass as an energy crop. Adv Agron 90:267–297

Melo PGS, Melo LC, Soares AA, De Lima LM, De S, Reis M, Juliatti FC, Cornelio VMO (2005) Study of the genotypes × environments interaction in the selection process of upland rice. Crop Breed Appl Biotechnol 5:38–46

Merrill SD, Black AL, Bauer A (1996) Conservation tillage affects root growth of dryland spring wheat under drought. Soil Sci Soc Am J 60:575–583

Mrabet R, Ibno-Namr K, Bessam F, Saber N (2001) Soil chemical quality changes and implications for fertilizer management after 11 years of no-tillage wheat production systems in semiarid morocco. Land Degrad Develop 12:505–517

Mupangwa W, Twomlow S, Walker S (2011) Cereal and legume yield responses to conservation agriculture under semi-arid conditions of southern Zimbabwe. Abstracts: Regional Conservation Agriculture Symposium, Johannesburg, 8–10 Feb

Olesen JE, Hansen PK, Berntsen J, Christensen S (2004) Simulation of above ground suppression of competing species and competition tolerance in winter wheat varieties. Field Crop Res 89:263–280

Oliver RP, Rybak K, Solomon PS, Ferguson-Hunt M (2009) Prevalence of ToxA-sensitive alleles of the wheat gene Tsn1 in Australian and Chinese wheat cultivars. Crop Pasture Sci 60:348–352

Peake AS, Gilmour A, Cooper M (2011) The 1BL/1RS translocation decreases grain yield of spring wheat germplasm in low yield environments of north-eastern Australia. Crop Pasture Sci 62:276–288

Peters RD, Sturz AV, Carter MR, Sanderson JB (2004) Influence of crop rotation and conservation tillage practices on the severity of soil-borne potato diseases in temperate humid agriculture. Can J Soil Sci 84:397–402

Pretty JN, Noble AD, Bossio D, Dixon J, Hine RE, Penning DVriesFW, Morison JI (2006) Resource-conserving agriculture increases yields in developing countries. Environ Sci Technol 40:1114–1119

PSU (1996) Crop rotations and conservation tillage. Conservation tillage series (Number one), Pennsylvania State University, Pennsylvania

Qin RJ, Stamp P, Richner W (2006) Impact of tillage on maize in a cambisol and luvisol in Switzerland. Soil Tillage Res 85:50–61

Raaijmakers JM, Paulitz TC, Steinberg C, Alabouvette C, Moënne-Loccoz Y (2009) The rhizosphere: a playground and battlefield for soilborne pathogens and beneficial microorganisms. Plant Soil 321:341–361

Ranawake AL, Nakamura C (2011) Cold tolerance of an inbred line population of rice (O. sativa L) at different growth stages. Trop Agric Res Extension 14:25–33

Rebetzke GJ, Richards RA, Sirault RR, Morrison AD (2004) Genetic analysis of coleoptile length and diameter in wheat. Aust J Agric Res 55:733–743

Rebetzke GJ, Richards RA, Fettell NA, Long M, Condon AG, Forrester RI, Botwright TL (2007) Genotype increases in coleoptile length improves stand establishment, vigour and grain yield of deep sown wheat. Field Crop Res 100:10–23

Rees RG, Platz GJ (1979) The occurrence and control of yellow spot of wheat in north-eastern Australia. Aust J Exp Agric Anim Husb 19:369–372

Reynolds M, Dreccer F, Trethowan R (2007) Drought adaptive traits derived from wheat wild relatives and landraces. J Exp Bot 58:177–186. doi:10.1093/jxb/erl250

Richards RA, Lukacs Z (2002) Seedling vigour in wheat-sources of variation for genetic and agronomic improvement. Aust J Agric Res 53:41–50

Richards RA, Condon AG, Rebetzke GJ (2001) Traits to improve yield in dry environments. In: Reynolds MP, Ortiz-Monasterio, McNab A (eds) Application of physiology in wheat breeding. CIMMYT, Mexico, pp 88–100

Rose TJ, Liu L, Wissuwa M (2013) Improving phosphorus efficiency in cereal crops: is breeding for reduced grain phosphorus concentration part of the solution? Front Plant Sci 4:444

Sanghera GS, Wani SH, Hussain W, Singh NB (2011) Engineering cold stress tolerance in crop plants. Curr Genomics 12:30–43

Scott JF, Farquharson RJ, Mullen JD (2004) Farming systems in the northern cropping region of NSW: an economic analysis. NSW Department of Primary Industries, Economic Research Report No. 20

Silva P (2007) Cero labranza: Alelopatía del rastrojo de trigo sobre lupino. Tesis para optar al grado Académico de Doctor en Ciencias Silvoagropecuarias y Veterinarias. Universidad de Chile, p 99

Singh G, Tyagi BS, Singh GP, Chatrath R, Shoran J, Nagarajan S, Singh SK (2007) Identification of early state traits as markers for high yielding wheat genotypes under zero tillage conditions of rice wheat cropping system. Indian J Agric Sci 77:432–437

Sivamani E, Bahieldinb A, Wraith JM, Al-Niemi T, Dyer WE, Ho THD, Qu R (2000) Improved biomass productivity and water use efficiency under water deficit conditions in transgenic wheat constitutively expressing the barley *HVA1* gene. Plant Sci 155:1–9

Slade AJ, Fuerstenberg SI, Loeffler D, Steine MN, Facciotti D (2005) A reverse genetic, nontransgenic approach to wheat crop improvement by TILLING. Nat Biotechnol 23:75–81

Smale M, Reynolds MP, Warburton M, Skovmand B, Trethowan R, Singh RP, Ortiz-Monasterio I, Crossa J (2002) Dimensions of diversity in modern spring bread wheat in developing countries from 1965. Crop Sci 42:1766–1779

Spielmeyer W, Richards RA (2004) Comparative mapping of wheat chromosome 1AS which contains the tiller inhibition gene (tin) with rice chromosome 5 S. Theor Appl Genet 109:1303–1310

Spielmeyer W, Hyles J, Joaquim P, Azanza F, Bonnett D, Ellis ME, Moore C, Richards RA (2007) A QTL on chromosome 6 A in bread wheat (*Triticum aestivum*) is associated with longer coleoptiles, greater seedling vigour and final plant height. Theor Appl Genet 115:59–66

Trethowan RM, Reynolds M (2005) Drought resistance: genetic approaches for improving under stress. In: Proceedings of the 7th International wheat conference, 27 November−2 December, Mar del Plata, Argentina

Trethowan RM, Mujeeb-Kazi A (2008) Novel Germplasm resources for improving environmental stress tolerance of hexaploid wheat. Crop Sci 48:1255–1265

Trethowan RM, Singh RP, Huerta-Espino J, Crossa J, Van Ginkel M (2001) Coleoptile length variation of near-isogenic Rht lines of modern CIMMYT bread and durum wheats. Field Crop Res 70:167–176

Trethowan RM, Reynolds M, Sayre K, Ortiz-Monasterio I (2005) Adapting wheat cultivars to resource conserving farming practices and human nutritional needs. Ann Appl Biol 146:405–413

Trethowan RM, Reynolds MP, Ortiz-Monasterio JI, Ortiz R (2007) The genetic basis of the ongoing Green Revolution in wheat production. Plant Breed Rev 28:38–58

Trethowan R, Manes Y, Chattha T (2009) Breeding for improved adaptation to conservation agriculture improves crop yields. Lead Papers, 4th World congress on conservation agriculture. 4–9 Feb, New Delhi 2009

Trethowan RM, Turner MA, Chattha TM (2010) Breeding strategies to adapt crops to a changing climate. In: Lobell D, Burke M (eds) Climate change and food security. Springer, New York, pp 155–174 (Chap. 9)

Trethowan R, Mahmood T, Ali Z, Oldach K, Garcia AG (2012) Breeding wheat cultivars better adapted to conservation agriculture. Field Crop Res 132:76–83

Trichard A, Alignier A, Chauvel B, Petit S (2013) Identification of weed community traits response to conservation agriculture. Agric Ecosyst Environ 179:179–186

Triplett GB, Dick WA (2007) No-tillage crop production: a revolution in agriculture. Agron J 100:153–165

Twomlow S, Urolov JC, Jenrich M, Oldrieve B (2008) Lessons from the field— Zimbabwe's conservation agriculture task force. J SAT Agric Res 6(1):1–11

Ullrich SE, Muir CE (1986) Genotypic response of spring barley to alternative tillage systems. Cereal Res Commun 14:161–168

Uphoff N (2003) Higher yields with fewer external inputs? The system of rice intensification and potential contributions to agricultural sustainability. Int J Agric Sustain 1:38–50

USDA (2008) Effect of cover crop extracts on cotton and radish radicle elongation. http://handle.nal.usda.gov/10113/19204

Van Ginkel M, Ortiz-Monasterio I, Trethowan R, Hernandez E (2001) Methodology for selecting segregating populations for improved N-use efficiency in bread wheat. Euphytica 119:223–230

Verhulst N, Govaerts B, Verachtert E, Kienle F, Limon-Ortega A, Deckers J, Raes D, Sayre KD (2009) The importance of crop residue management in maintaining soil quality in zero tillage systems; a comparison between long-term trials in rainfed and irrigated wheat systems. Lead Papers, 4th World congress on conservation agriculture, New Delhi, 4–9 Feb

Villareal RL, Kazi AM (1998) Exploiting synthetic hexaploids for abiotic stress tolerance in wheat. In: Proceedings of the tenth regional wheat workshop for Eastern, Central and Southern Africa, 14–18 Sep, University of Stellenbosch, South Africa, pp 542–552

Villareal RL, Rajaram S, Mujeeb-Kazi A, Toro ED (1991) The effect of chromosome lB/lR translocation on the yield potential of certain spring wheats (*Triticum aestivum* L.). Plant Breed 106:77–81

Vita PD, Paolo ED, Fecondo G, Fonzo ND, Pisante M (2007) No-tillage and conventional tillage effects on durum wheat yield, grain quality and soil moisture content in southern Italy. Soil Tillage Res 92:69–78

Wang ZH, Li SX, Malhi S (2008) Effects of fertilization and other agronomic measures on nutritional quality of crops. J Sci Food Agric 88:7–23

Wasson AP, Richards RA, Chatrath R, Misra SC, Sai Prasad SV, Rebetzke GJ, Kirkegaard JA, Christopher J, Watt M (2012) Traits and selection strategies to improve root systems and water uptake in water-limited wheat crops. J Exp Bot 63:3485–3498

Watt M, Kirkegaard JA, Rebetzke GJ (2005) A wheat genotype developed for rapid leaf growth copes well with the physical and biological constraints of unploughed soil. Funct Plant Biol 32:695–706

Wildermuth GB, Thomas GA, Radford BJ, McNamara RB, Kelly A (1997) Crown rot and common root rot in wheat grown under different tillage and stubble treatments in southern Queensland, Australia. Soil Tillage Res 44:211–224

Wu JL, Wu C, Lei C, Baraoidan M, Bordeos A, Madamba MRS, Ramos-Pamplona M, Mauleon R, Portugal A, Ulat VJ, Bruskiewich R, Wang G, Leach J, Khush G, Leung H (2005) Chemical- and irradiation-induced mutants of indica rice IR64 for forward and reverse genetics. Plant Mol Biol 59:85–97

Yadav R, Singh SS, Jain N, Singh GP, Prabhu KV (2010) Wheat production in India: technologies to face future challenges. J Agric Sci 2:164–173

Yan W, Tinker NA (2006) Biplot analysis of multi-environment trial data: principles and applications. Can J Plant Sci 86:623–645

Yang J, Sears RG, Gill BS, Paulsen GM (2002) Growth and senescence characteristics associated with tolerance of wheat-alien amphiploids to high temperature under controlled conditions. Euphytica 126:185–193

Young DL, Kwon TJ, Young FL (1994) Profit and risk for integrated conservation farming systems in the palouse. J Soil Water Conserv 49:601–606

Zamir MSI, Ahmad AUH, Javeed HMR (2010) Comparative performance of various wheat (*Triticum aestivum* L.) cultivars to different tillage practices under tropical conditions. Afr J Agric Res 5:1799–1803

Zhou W-C, Kolb FL, Bai GH, Domier LL, Boze LK, Smith NJ (2003) Validation of a major QTL for scab resistance with SSR markers and use of marker-assisted selection in wheat. Plant Breed 122:40–46

Chapter 8
Modeling Conservation Agriculture

Bruno Basso, Ryan Nagelkirk and Luigi Sartori

Abstract A sustainable land management should aim at high production, while minimizing risk, maintaining quality of soil and water. Excessive tillage can decrease soil carbon storage and influence the soil environment of a crop. The evaluation of the impact of tillage systems on soil biophysical properties and on the growth crops requires a system approach. In this chapter, we introduce the system approach to land use sustainability (SALUS) model and its tillage component to evaluate the effects of tillage on soil on water infiltration and time to ponding and soil biophysical properties.

Keywords Conservation tillage · Soil biophysical properties · SALUS model · Ponding

8.1 Introduction

A major component of sustainable agriculture is conservation tillage. By recycling crop residues and minimizing disturbance to the soil, conservation tillage increases the soil organic carbon (SOC) content and structure of soils, both of which have been shown to improve soil quality. SOC has become the most common metric used to evaluate soil quality because it plays a central role in many physical, chemical, and biological processes (Reeves 1997), leading to improvements in food production and water quality, and reductions of CO_2. In fact, it is estimated that the mismanagement of soils has led to the release of 4 ± 1 gigatons of soil carbon in the USA. Worldwide, losses amount to 7812 gigatons (Lal 2004). Meanwhile, the projected changes in the Earth's climate due to such anthropogenic inputs raise questions that are difficult for traditional science to answer, leading most climate scientists to the use of climate models.

B. Basso (✉) · R. Nagelkirk
Department of Geological Sciences, Michigan State University, USA
e-mail: basso@msu.edu

L. Sartori
Department of Landscape and Agroforestry Systems, University of Padua, Italy

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture*,
DOI 10.1007/978-3-319-11620-4_8

Like climate scientists, agricultural scientists have turned to computational models of agricultural systems to help answer the questions posed by 21st century challenges, one of them being how to feed a growing world population despite water shortages and a changing climate while also getting agricultural practices to pollute less, and sequester more carbon. Conservation tillage is likely to be a part of the solution, and models are needed to test this because traditional field studies covering all variables cannot be carried out fast enough. Instead, the knowledge gained by past field studies is used to develop models that can then quickly simulate different scenarios at the temporal and spatial resolutions needed to address 21st century challenges.

Models make it possible to project the long-term effects of conservation tillage systems, and while the effects of tillage on soil properties are fairly well understood, there are not many robust, widely used tillage models in existence. By incorporating the few tillage models that do exist into crop models that account for management effects on yields and the environment, farmers and policy makers are able to make informed decisions about management strategies and their long-term economic and environmental impacts. This chapter will focus on how tillage is modeled, case studies documenting the effects of tillage on crop yield and the soil, and the projected long-term impacts of conservation tillage in the face of a changing climate.

8.2 A System Approach to Conservation Tillage

The system approach to land use sustainability (SALUS) model simulates tillage as part of a system approach that can be run for multiple years, modeling daily changes in plant, soil, and nutrient conditions in response to varied management strategies. Along with the user being able to model different tillage practices, simulations can vary in the types of crops planted and their rotations, planting date and population, irrigation and fertilizer applications, soil type, and atmospheric/climatic conditions. For any weather sequence that contains daily values of maximum and minimum temperature, solar radiation, and precipitation, SALUS is able to calculate daily outputs for crop and soil conditions, even during fallow periods. For each day of simulation, all the components of SALUS are calculated. The components are heat balance, soil organic matter (SOM), nitrogen and phosphorus dynamics, water balance management practices, and plant growth and development. Management practices are input by the user and the rest of the parameters are calculated within an interactive structure of three biophysical modules incorporating the aforementioned individual components of SALUS. The components are grouped into a soil water balance and temperature module; a SOC and nutrient cycling module; and a series of crop growth modules. These will be described more in their respective sections.

With the modules working in unison, SALUS is able to give daily outputs of variables such as nitrogen (N) and SOC fluxes, soil water drainage, water and N stress, crop dry mass, and final grain yields. Adding to SALUS's capabilities, several management strategies can be run simultaneously, outputting results for immediate comparison. This enables users to directly compare the effects of single or multiple changes in management using the same field with the same weather. Users can also compare the effects of changes in physical parameters such as soil type, soil depth, or position in the landscape. These capabilities enable the user to run multiple scenarios at the level of detail desired for their specific application, whether it is farm management, scientific inquiry, or public policy.

8.3 Modeling Tillage Systems and Residues Management

Tillage alters four soil properties in the model: bulk density, saturated hydraulic conductivity, ponding capacity, and water content at saturation. These variables change dynamically after irrigation or precipitation events.

Bulk density and saturated hydraulic conductivity change in similar ways when precipitation occurs, because both are affected when the precipitation causes the soil to settle. The values for both change exponentially based on the amount of energy imparted on the soil surface by rainfall since the most recent tillage event:

$$\mathrm{Xvar} = \mathrm{Xstl} + (\mathrm{Xtill} - \mathrm{Xstl}) \times \mathrm{EXP}\ (-\mathrm{RSTL} \times \mathrm{SUMKE})$$

where Xvar represents either bulk density or saturated hydraulic conductivity depending on which the user is modeling, Xtill is the variable's value after tillage, Xstl represents the value for the newly settled soil, RSTL determines how quickly the property changes per J cm^{-2} of rainfall energy, and SUMKE the total amount of energy imparted since the most recent tillage event, also in J cm^{-2}. RSTL, as shown below, is entirely a function of a soil's aggregate stability (AS). AS is a unitless value representing the strength of cohesion within soil aggregates, which itself is a function of the amount of organic matter in the soil (Tisdall and Oades 1982):

$$\mathrm{RSTL} = 10 \times (1 - \mathrm{AS})$$

$$\mathrm{AS} = 0.005 \times \mathrm{OC}\ (\mathrm{L})$$

where OC(L) is layer L's percent organic carbon content. In this equation, AS values can range from 0 to 1, with a value of 1 representing highly stable aggregates and 0 representing extremely fragile aggregates. SUMKE was estimated using a known relationship between it and cumulative precipitation. The relationship is described in the next three equations:

$\mathrm{SUMKE} = \sum (1 - \mathrm{SOILCOV}) \times \mathrm{KE} \times \mathrm{EXP}(-0.15 \times \mathrm{depth}$ (Basso and Ritchie 2006)

$\mathrm{KE} = 3.812 + 0.812 \times \ln(\mathrm{RAIN}/\mathrm{TIME}) \times \mathrm{RAIN}$ (Wishmeier and Smith 1978)

$\mathrm{SOILCOV} = \mathrm{CANCOV} + \mathrm{FC} \times (1 - \mathrm{CANCOV})$ (Wishmeier and Smith 1978) where KE is kinetic energy of the rain, and surface cover (SOILCOV) represents the amount of soil sheltered from the kinetic energy of the rainfall. SOILCOV is dependent on both residue (FC) and crop canopy (CANCOV). The equation for SUMKE is written as a sum because the equation needs to be run for each layer in the model and then summed.

When these equations are run to determine bulk density in the model, the saturation water content of each layer is calculated using the equation below (Dadoun 1993):

$$\text{SAT (L)} = 0.92 \times (1 - \text{BD(L)} / 2.66)$$

where SAT(L) and BD(L) are an individual layer's saturation water content and bulk density, respectively. Additionally, the effective porosity of the soil is set at 92 % and the standard particle density, 2.66 g cm^{-3}, are used in the calculation as constants.

8.3.1 Effects on Soil Physical, Biological, and Chemical Properties

Algorithms for the tillage model within SALUS were adopted from CERES-Till model (Dadoun 1993), which is capable of simulating the effects residue cover and tillage have on plant development and soil surface properties. The model requires three inputs: tillage date, tillage depth, and tillage instrument. The tillage instrument used determines how much crop residue remains at the surface after each season. Then the portion of the soil surface that is still covered by the residues (FC) is calculated by the equation below:

$$\text{FC} = 1.0 - \text{EXP}\left(-\text{AM} \times \text{Mulch}\right)$$

where Mulch represents the previously mentioned material remaining after tillage (kg/ha), and AM is a measure of how much area is covered per kilogram of residue (ha/kg). The results become an input to subsequent equations determining the surface albedo and the susceptibility of the soils to the effects of rainfall kinetic energy at the soil surface. Last, residue thickness is calculated using a separate algorithm that assumes the residues are present in layers of a given thickness. Then, by knowing the area covered and mass of the residues from the equations above, the thickness can also be calculated. Residue thickness is important because of the negative relationship it has with soil evaporation.

8.3.2 Effects on Water Dynamics

Studies on conservation tillage have shown that no-till increases the rate and amount of infiltration (Fig. 8.1) while also decreasing cumulative runoff and increasing the

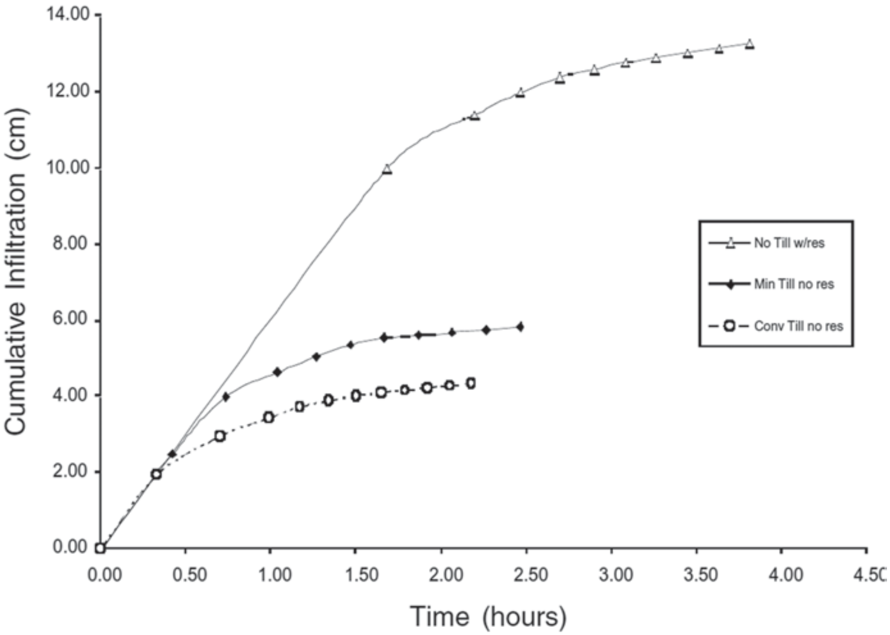


Fig. 8.1 Field measurements from experiments in El Batan, Mexico. No-till systems show more cumulative infiltration over time than both minimum tillage and conventional tillage systems. (Source: Basso and Ritchie 2006)

time-to-ponding (Fig. 8.2), all compared to conventional tillage systems (Basso and Ritchie 2006). The reduced runoff has been attributed to the residues intercepting the rainfall and reducing impact to the soil (Langdale et al. 1992). The increase in total infiltration is due the fact that tilled soils develop a layer with significantly lower hydraulic conductivity, known as a hard pan, which is absent in no-till soils (Rasmussen et al. 1998). In the tilled soils, the hard pan slows infiltration once the saturation front reaches the depth of the hard pan and the water backs up, causing pooling and runoff at the soil's surface (Basso et al. 2011; Franzluebbers 2002). SALUS's soil water balance module was modified to incorporate these findings.

In addition to the physical changes in the soil, it has also been found that the surface residues play an important role in the water balance. Residues can hold water in amounts up to 3.8 times their dry weight (Dadoun 1993), thereby reducing soil evaporation and making more available for the plants (Dadoun 1993; Riley et al. 1994; Andales et al. 2000; Basso and Ritchie 2006).

Like the crop growth model, the soil water balance module in SALUS is an extrapolation of the CERES model calculations, but with key revisions to the calculations for evaporation, drainage, runoff, and infiltration. The revisions replaced the need for SCS runoff curves with a concept called time-to-ponding (TP). Finally, soil temperature is modeled in the temperature module, allowing the accurate simulation of freezing and thawing events whose effects can vary depending on the amount of crop residues, the tillage regime, and water content of the soils.

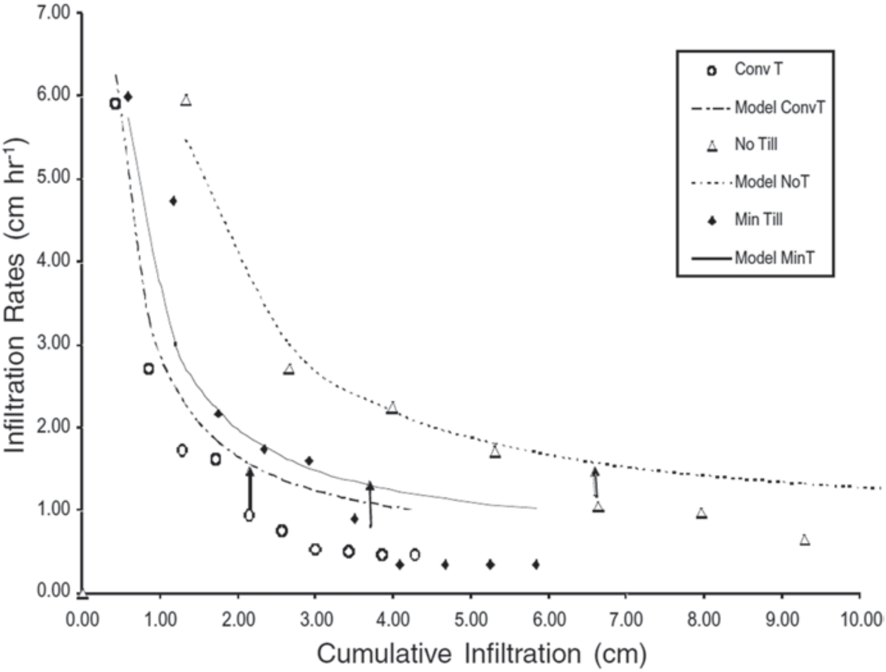


Fig. 8.2 Measured and SALUS-simulated infiltration rates show that no-till systems maintain a high infiltration longer than other systems, thereby increasing no-till's time-to-ponding. Measurements were made in El Batan, Mexico. SALUS the system approach to land use sustainability. (Source: Basso and Ritchie 2006)

Surface residues left behind by conservation tillage practices increase infiltration and decrease soil evaporation, causing a net increase in the plant available soil water. This is due to the residues increasing rainfall interception and retaining water up to 3.8 times the residue's dry weight (Dadoun 1993). The amount retained during a rainfall event is a function of the amount of water already retained in the residues and the total amount the residues can hold. Both the water in the residues and the soil are available for evaporation; however, energy for evaporation is preferentially allotted to the water in the residues, with potential soil evaporation decreasing as a function of increased residue water content. In this way, surface residues allow more water to stay in the soil for use by the plants.

As mentioned before, another component of SALUS is the time-to-ponding concept describing the amount of time it takes for the water to pond at the surface given a fixed rate of rainfall (White et al. 1989). Water ponds at the surface when either the rainfall rate is higher than the infiltration rate, or when the soil becomes saturated and the rainfall rate is higher than the saturated hydraulic conductivity of the least conductive layer in the soil. Once the water starts to pond, both soil and nutrients have the potential to be washed away via erosion and water that could have otherwise been stored in the soil profile is lost via runoff. At the same rates of rainfall, SALUS is able to simulate what would be expected when comparing time-to-ponding in no-tillage versus conventional tillage and minimum tillage: no-till has a highly significant longer time-to-ponding than both conventional and minimum tillage practices, meaning that no-till systems both reduce the possibility for erosion and minimize water loss through runoff and evaporation (Basso and Ritchie 2006).

8.3.3 *Effects on Carbon Turnover and Nutrient Dynamics*

No-till can have a significant impact on carbon levels in the soil. Among no-tillage, minimum tillage, and conventional tillage, the no-tillage system stores much more carbon (Fig. 8.3)—sometimes as much as 20,000 kg ha^{-1} more—than the minimum and conventional tillage systems (Recisosky et al. 1995; Lal 1997, 2004; Basso and Ritchie 2006). No-till has also been shown to be the most effective method for reducing nitrate leaching losses when compared to other mitigation strategies such as cover crops and increased use of biologically based inputs (Syswerda et al. 2012). One of the major advantages of modeling with SALUS is that this change in carbon

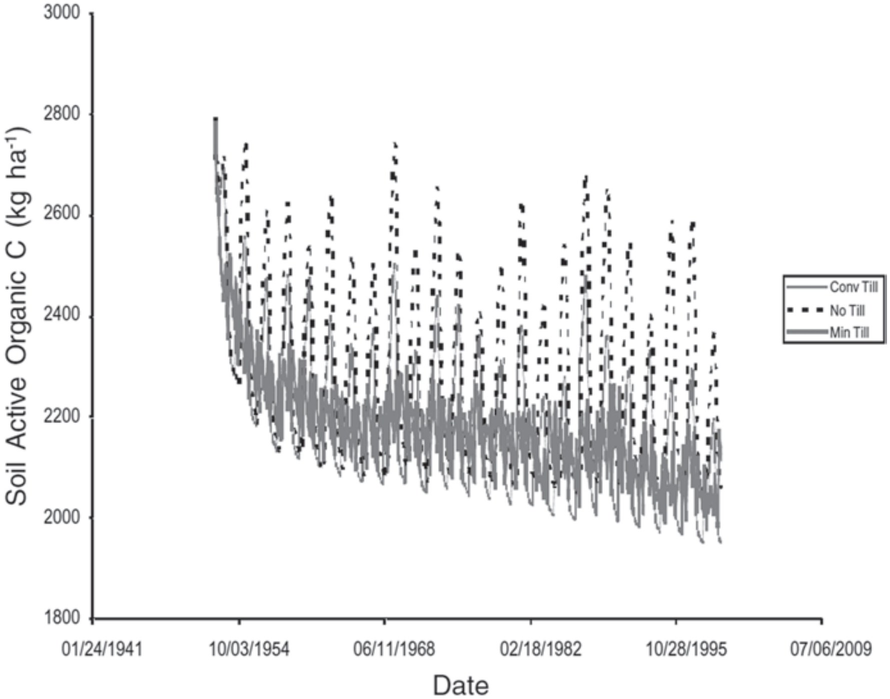


Fig. 8.3 SALUS simulations of soil active organic carbon showing the increased organic carbon storage of a no-till system compared to others, all in a clay soil in Foggia, Italy. SALUS the system approach to land use sustainability. (Source: Basso and Ritchie 2006)

storage can be simulated, along with the effects it has on other parameters such as the water and nutrient balances.

The SALUS model bases its SOM and nutrient cycling modules on the Century model, but with modifications made to include the crop growth and soil water balance modules. The module simulates SOM and N processes within active, slow, and passive SOM pools. Phosphorus (P) is treated in a similar way, with inorganic P being separated into labile, active, and stable pools.

8.3.4 Effects on Crop Yield

Crop growth within SALUS is modeled using equations that had their roots, or beginnings, in the CERES (Ritchie et al. 1985, 1989) and IBSNAT crop models (Jones and Ritchie 1991). The original models were developed to run only a single year and crop at a time. Their algorithms were restructured and linked to the management, soil water, and nutrient submodels within SALUS. Within the crop growth module are all the plant species that can be modeled, each with its own specific genetic coefficients that determine the photoperiod and number of degree-days the plant needs for each stage of development. During each stage, the amount of carbon assimilated and dry matter produced is determined by the amount of light intercepted and the growth potentials set for the particular variety. The growth is then tempered by water and/or nitrogen (N) limitations.

The thermal time calculations of the CERES model were also modified before they were incorporated into SALUS. They were first modified by Vinocur and Ritchie (2001) to predict meristematic temperature. Meristematic temperature was included because leaves, stems, and reproductive organs are differentiated in the meristem, and meristematic activity is driven by temperature. Therefore, when the meristem is 1–2 cm below the soil surface, early phenological changes can be modeled based on soil temperatures at that depth. However, surface residues change soil temperatures, necessitating the second change conducted by Vinocur and Ritchie (2001) accounting for soil temperature changes due to the insulating effect of crop residues.

Much of the science behind no-till agriculture and its effects on yield is just starting to come in. In 2013, a 32-year study comparing the net profitability of no-till systems in Central Iowa, USA, found that when all costs were accounted for in the corn and soybean rotations studied, the no-till system was more profitable than conventional tilled systems (Karlen et al. 2013). In northern China—a region known to be drought-prone—it was found that during dry years, no-till maize yields were 19 % higher than conventionally tilled systems. However, because of the increased water retention of no-till soils, the yields also dropped 7 % in wet years (Wang et al. 2011). Additionally, in no-till systems in the same region of China, the insulating effect of any added crop residues was found to increase the risk of delayed emergence in spring maize if the residues are not incorporated in the fall, as they would be in a reduced tillage practice. In such instances, reduced tillage practices were found to be optimal, with 13–16 % higher maize yields than both no-till and conventional tillage (Wang et al. 2012). However, neither of these took into account the net costs/gains like the first study. Even so, these differences re-enforce the fact that best management practices are spatially dependent—they are different depending on your location and climate—and unless field studies are to be conducted at every possible field site on Earth, modeling will be the only practical approach when trying to determine the best practices for any given location.

8.4 Climate Change and Long-Term Impact of Conservation Tillage

In 1990, one of the first studies to link models from atmospheric science, plant science, and agricultural economics found that increases in atmospheric CO_2 concentrations would offset most potential losses due to temperature and precipitation changes (Adams et al. 1990). However, such certainties have since become mottled. More recent studies have shown that while increased CO_2 concentrations provide the opportunity for increased yields, increased weather variability and pests could entirely negate this positive effect of climate change (Karl et al. 2009). Heavy downpours could delay spring planting, increase root diseases, and reduce the quality of many crops at harvest time due to excess moisture and heavy winds lodging crops (Karl et al. 2009; Easterling et al. 2007; Field et al. 2007). These effects are already being felt in the US, where excess soil moisture/precipitation has caused increased losses in corn yields, with models showing a doubling in losses during the next 30 years, costing an estimated additional US $3 billion per year (Rosenzweig et al. 2002). Besides heavy precipitation, extreme temperatures are another major concern. Warmer summers leave less time for grain filling and increase respiration rates at night, reducing the amount of carbon captured by plants (Karl et al. 2009). In one study, three general circulation models found that increased levels of CO2 did not increase US dryland corn yields enough (2–5 % increase) to compensate for losses due to increased temperatures (6–20 % decrease; Brown and Rosenberg 1999). Similar results have been found in Chile (Meza et al. 2008) and the North China Plain (Mo et al. 2009).

Despite the increasingly fatalistic outlook of climate change, the IPCC reports that overall yields of soybeans and corn in the US are still most likely to increase. Climate-related yields are likely to increase 5–20 % over the first few decades of the century, with the positive effects going late into the century or even through it before they are overwhelmed by the negative effects of climate change (Field et al. 2007). This is an important finding, because under current climate change projections, developed nations like the USA will have to increase their percentage of world agricultural production, as agriculture in developing nations will likely suffer large-scale losses (Parry et al. 2004).

Despite any positive effects of climate change in the USA, they are relatively short-lived compared to the time span humans will have to cope with climate change. In order to minimize the long-term negative effects, atmospheric CO_2 concentrations need to be reduced. Conservation agriculture, namely no-till, offers a solution with its ability to sequester carbon in soils. No-till also reduces runoff and erosion, which is important, because soil erosion could increase 33–274 % by 2040–2059 because of changes in management, increased precipitation, and heat-stressed crops providing less protection for the soil (Oneal et al. 2005). If the soil is continually lost, one of the largest potential sinks for atmospheric CO_2 will be lost as well.

No-till practices, which have already been shown to increase infiltration and reduce evaporation, could also establish a buffer for plants against variability in precipitation and higher temperatures. The increased storage will make more water available during droughts and high temperatures, when plants need to transpire more water to stay cool. The benefits of no-till are thus twofold: it can be used to mitigate climate change while also minimizing the impacts of climate change on agricultural production.

8.5 Future Outlook

The positive prognosis for US agriculture exists mostly due to explicit control over a key variable in agriculture: management. According to a review of past challenges, agricultural practices have adapted to changes comparable to climate change and should be able to continue to do so into the future, but not without the aid of a large portfolio of assets in terms of land, water, energy, genetic diversity, and technology (Easterling 1996). As a part of that large portfolio, irrigation is predicted to increase 5–20 % by 2080 in order to offset the increased evaporative demands of a longer growing season (Easterling et al. 2007). However, the increasing demand for fresh water by society and agriculture will strain an already depleting supply (Xie et al. 2008), limiting the amount of irrigation available to agriculture.

Besides increasing irrigation, another strategy that has limitations is the poleward movement of crops, because northern soils tend to be less fertile than their southern counterparts (Field et al. 2007; Roberts and Schlenker 2010). Agriculture is further limited by the fact that forested lands have become more protected (Schneider et al. 2011), and boundaries, such as the USA/Canada border and the Great Lakes, mean that movement can only go so far for American farmers (Ainsworth and Ort 2010; Roberts and Schlenker 2010). Because of these limitations, production on already existing land will have to increase to match future demand (Parry et al. 2004; Schneider et al. 2011).

Perhaps one of the most widely adopted management strategies has been early planting in reaction to earlier spring thaws. Twenty-five years of records show that US farmers have been using longer season cultivars and planting crops earlier, with harvest times remaining unchanged (Sacks and Kucharik 2011). These long season cultivars are likely to continue increasing yields under climate change (Southworth et al. 2000; Field et al. 2007; Karl et al. 2009). However, there is strong evidence indicating that between 1950 and 2005, there has been little adaptation of neither seed varieties nor management to cope with warmer temperatures. Additionally, there is little that can be done about more extreme storms and precipitation.

No-till agriculture is likely to be one of the best tools in a farmer's portfolio for coping with the temperatures and precipitation of the future. Unlike most other solutions, it does increase a crop's resilience to extreme temperatures and precipitation through its ability to increase water infiltration and retention, limit erosion, and sequester $CO_{2\_}$ mitigating climate change itself.

8.6 Conclusions

Conservation tillage, whether it is reduced tillage or no-tillage, has been shown to increase profits and yields, while also minimizing negative environmental impacts of agriculture, such as nitrate leaching, carbon dioxide and nitrous oxide emissions, and over-irrigation. While results are not always the same, conservation tillage is a definite candidate for any farmer considering ways to increase profits while also maximizing his or her operation's environmental efficacy. And it is precisely because of the differences in results that crop models such as SALUS are needed. Models help us determine the best practices for any given location, along with the impacts of current and historical practices. The predictive abilities of models are crucial at the current point in time, when agricultural practices dominate much of the Earth's land surface and human activities are driving global changes. Models have become a way, if not the way, to inform our current and future best practices, which will have impacts for years to come.

References

Adams RM, Rosenzweig C, Peart RM, Ritchie JT, McCarl BA, Glyer JD, Curry RB, Jones JW, Boote KJ, Allen LH Jr (1990) Global climate change in US agriculture. Nature 345(6272):219–224

Ainsworth EA, Ort DR (2010) How do we improve crop production in a warming world? Plant Physiol 154(2):526–530

Andales AA, Batchelor WD, Anderson CE, Farnham DE, Whigham DK (2000) Incorporating tillage effects into a soybean model. Agric Syst 66:69–98

Basso B, Ritchie J (2006) Simulation of tillage systems impact on soil biophysical properties using the SALUS model. Ital J Agron/Riv Agron 4:677–688

Basso B, Sartori L, Bertocco M, Cammarano D, Grace PR (2011) Economic and environmental evaluation of site-specific tillage in a maize crop in NE Italy. Eur J Agron 35:83–92

Brown RA, Rosenberg NJ (1999) Climate change impacts on the potential productivity of corn and winter wheat in their primary United States growing regions. Clim Change 41:73–107

Dadoun FA (1993) Modeling tillage effects on soil physical properties and maize development and growth. Ph.D. thesis, Michigan State University, MI

Easterling WE (1996) Adapting North American agriculture to climate change in review. Agric For Meteorol 80(1):1–53. doi:10.1016/0168-1923(95)02315-1

Easterling WE, Aggarwal PK, Batima P, Brander KM, Erda L, Howden SM, Kirilenko A, Morton J, Soussana J-F, Schmidhuber J, Tubiello FN (2007) Food, fibre and forest products. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 273–313

Field CB, Mortsch LD, Brklacich M, Forbes DL, Kovacs P, Patz JA, Running SW, Scott MJ (2007) North America. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 617–652

Franzluebbers AJ (2002) Water infiltration and soil structure related to organic matter and its stratification with depth. Soil Tillage Res 66:197–205

Jones JW, Ritchie JT (1991) Crop growth models. In: Hoffman GJ, Howell TA, Soloman KH (eds) Management of farm irrigation systems. ASAE, St. Joseph

Karlen DL, Kovar JL, Cambardella CA, Colvin TS (2013) Thirty-year tillage effects on crop yield and soil fertility indicators. Soil Tillage Res 130:24–41

Karl TR, Melillo JM, Peterson TC (eds) (2009) Global climate change impacts in the United States. Cambridge University Press, Cambridge

Lal R (1997) Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO2-enrichment. Soil Tillage Res 43(1–2):81–107

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 604:1623–1627

Langdale GW, West LT, Bruce RR, Miller WP, Thomas AW (1992) Restoration of eroded soil with conservation tillage. Soil Technol 5:81–90

Meza F, Silva D, Vigil H (2008) Climate change impacts on irrigated maize in Mediterranean climates: evaluation of double cropping as an emerging adaptation alternative. Agric Syst 98(1):21–30

Mo X, Liu S, Lin Z, Guo R (2009) Regional crop yield, water consumption and water use efficiency and their responses to climate change in the North China Plain. Agric Ecosyst Environ 134:67–78

Oneal M, Nearing M, Vining R, Southworth J, Pfeifer R (2005) Climate change impacts on soil erosion in Midwest United States with changes in crop management. Catena 61(2–3):165–184

Parry M, Rosenzweig C, Iglesias A, Livermore M, Fischer G (2004) Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Glob Environ Change 14(1):53–67

Rasmussen PE, Goulding KWT, Brown JR, Grace PR, Janzen HH, Korschens M (1998) Long-term agroecosystem experiments: assessing agricultural sustainability and global change. Science 282:893–896

Recisosky DC, Cassel DK, Blevins RL, Gill WR, Naderman GC (1977) Conservation tillage in the southeast. J Soil Water Conserv 32:13–20

Reeves DW (1997) The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Tillage Res 43:131–167

Riley H, Bùrresen T, Ekeberg E, Rydberg T (1994) Trends in reduced tillage research and practice in Scandinavia. In: Carter MR (ed) Conservation tillage in temperate agroecosystems. Lewis, Boca Raton, pp 23–45

Ritchie JT, Godwin DC, Otter-Nacke S (1985) CERES- wheat: a simulation model of wheat growth and development. A & M University Press, College Station

Ritchie JT, Singh U, Godwin DC, Hunt L (1989) A user's guide to CERES Maize-V.2.10. Muscle Shoals, AL., International Fertilizer Development Center

Roberts MJ, Schlenker W (2010) Is agricultural production becoming more or less sensitive to extreme heat? Evidence from U.S. corn and soybean yields. National Bureau of Economic Research. http://www.nber.org/papers/w16308. Accessed 28 Sep 2014

Rosenzweig C, Tubiello FN, Goldberg R, Mills E, Bloomfield J (2002) Increased crop damage in the US from excess precipitation under climate change. Glob Environ Change 12:197–202

Sacks WJ, Kucharik CJ (2011) Crop management and phenology trends in the U.S. Corn Belt: impacts on yields, evapotranspiration and energy balance. Agric For Meteorol 151(7):882–894. doi:10.1016/j.agrformet.2011.02.010 (Elsevier B.V.)

Schneider UA, Havlík P, Schmid E, Valin H, Mosnier A, Obersteiner M, Böttcher H et al (2011) Impacts of population growth, economic development, and technical change on global food production and consumption. Agric Syst 104(2):204–215. doi:10.1016/j.agsy.2010.11.003

Southworth J, Randolph JC, Habeck M, Doering OC, Pfeifer RA, Rao DG, Johnston JJ (2000) Consequences of future climate change and changing climate variability on maize yields in the midwestern United States. Environment 82:139–158

Syswerda SP, Basso B, Hamilton SK, Tausig JB, Robertson GP (2012) Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA. Agric Ecosyst Environ 149:10–19

Tisdall JM, Oades JM (1982) Organic matter and water stable aggregates. J Soil Sci 33:141–163

Vinocur M, Ritchie JT (2001) Maize leaf development biases caused by air-apex temperature differences. Agron J 93:767–772

Wang X, Dai K, Zhang D, Zhang X, Wang Y, Zhao Q, Oenema O (2011) Dryland maize yields and water use efficiency in response to tillage/crop stubble and nutrient management practices in China. Field Crops Res 120(1):47–57

Wang X, Wu H, Dai K, Zhang D, Feng Z, Zhao Q, Hoogmoed WB (2012) Tillage and crop residue effects on rainfed wheat and maize production in northern China. Field Crops Res 132:106–116

White I, Sully MJ, Melville MD (1989) Use and hydrological robustness of time-to-incipient-ponding. Soil Sci Soc Am J 29:1343–1346

Wishmeier WH, Smith DD (1978) Predicting rainfall- erosion-a guide to conservation planning. Agriculture Handbook. Science and Education Administration, U.S. Department of Agriculture, Washington, DC, p 537

Xie H, Eheart JW, An H (2008) Hydrologic and economic implications of climate change United States. J Water Resour Plan Manag 134:205–213

Part IV

Status of Conservation Agriculture: Some Case Studies

Chapter 9
Evolution and Adoption of Conservation Agriculture in the Middle East

Stephen Loss, Atef Haddad, Yaseen Khalil, Abdulsattar Alrijabo, David Feindel and Colin Piggin

Abstract Agriculture commenced in the Fertile Crescent about 6,000 BC probably using a form of minimum tillage, no till, or zero tillage (ZT), and over the millennia, tillage in the Middle East increased and reached a peak in the mid- to late 1900s when cheap fuel and tractors became widely available. As part of an Australian-funded project developing conservation agriculture (CA) for Iraq, more than 40 adaptive research experiments investigated the suitability of elements of CA to northern Syria and Iraq during 2005–2013. These verified that ZT seeding without prior plowing produced similar or better crop growth and grain yields than the conventional tillage (CT) system requiring two or three cultivations before sowing. As was the case in Australia, the elimination of plowing enabled earlier sowing which resulted in improved water-use efficiency and significant yield increases in cereals and legumes especially in dry seasons. In addition, more accurate seed placement and metering with ZT seeders meant seed rates could be reduced. Several research and development projects in North Africa and the Middle East had demonstrated benefits with CA compared to CT, but they did not generate significant farmer adoption, mainly because of a lack of suitable ZT seeders, particularly for small poor farmers. Most imported ZT seeders used for the demonstration trials were too heavy for the size of tractors available, expensive, and complicated to use and maintain. So, the Australian project worked with several machinery workshops to manufacture a number of simple, effective, and affordable seeders in Syria, while in northern Iraq, the initial focus was on the conversion of existing conventional seeders to ZT using parts made locally. When the ZT seeders were available, it was decided to actively promote a flexible cropping package centered on ZT with early sowing

---

S. Loss (✉) · A. Haddad · Y. Khalil · D. Feindel
International Center for Agricultural Research in Dry Areas, Amman, Jordan
e-mail: s.loss@cgiar.org

A. Alrijabo
University of Mosul, Ninevah, Iraq

C. Piggin
Australian Centre for International Agricultural Research, Canberra, Australia

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_9

and reduced seed rates, while the retention of crop stubbles and crop rotation were encouraged but not depicted as essential. Participatory extension groups were established in Iraq and Syria whereby farmers were able to borrow a local ZT seeder to test on their farm. In the vast majority of cases, farmers' yields were as good, if not better, with the ZT and early sowing technology than nearby fields sown conventionally, and farmers benefited from significant input savings. On an average, over all three seasons, the grain yield increase with ZT compared to CT was 0.26 t/ha for barley ($n=278$), 0.33 t/ha for wheat ($n=264$), and 0.23 t/ha for lentil ($n=88$). Since 2006/2007, the area under ZT has grown from zero to more than 30,000 ha in Syria and 10,000 ha in northern Iraq in 2012/2013. Many researchers, extensionists, and farmers are convinced that CA is a profitable and sustainable technology which can be applied to a wide range of crops in most areas of the Middle East, and that CA is one of the few methods capable of increasing the resilience of farming systems to climate change. Adoption in other Middle East countries is relatively minor, so more work is needed throughout the region and other dry areas to further raise awareness and encourage adoption of CA using the flexible approach. While ZT plus early sowing may not meet the rigid concept of CA used by some authors, it is a significant change that most small poor farmers in the Middle East can make with little risk of failure.

Keywords Zero tillage · Direct drilling · Minimum tillage · Early sowing · West Asia · Farming systems

9.1 Introduction

This chapter examines the evolution of crop management practices in the Fertile Crescent, which is the center of origin for many of the world's crops, and the development of zero tillage (ZT) and conservation agriculture (CA) systems in the Middle East or West Asia. It focuses on a series of projects funded by the Australian Center for International Agricultural Research (ACIAR) and the Australian Agency for International Development (AusAID) being conducted by the International Center for Agricultural Research in Dry Areas (ICARDA) between 2005 and 2015 with the aim of promoting improving cropping systems in the rainfed areas of northern Iraq. Before these projects started, the area of ZT adoption in the Middle East was effectively zero. This project had and continues to have significant impact in promoting the adoption of ZT in northern Iraq with spillover effects in other countries, especially in Syria, where most of the research experiments were conducted at the ICARDA Tel Hadya headquarters near Aleppo.

Haddad et al. (2014a) recently reviewed CA in West Asia but this chapter differs in a number of respects. We take a long-term view of tillage, rotations, and other farming practices in this region, starting with the first likely crop management techniques within the Fertile Crescent, and examining how these changed over the millennia. We also explore the relatively recent changes in dryland farming systems of Australia and their relevance to the Middle East. Data from an extensive evaluation of ZT by Syrian farmers are presented, including over 500 comparisons of ZT plus early sowing with conventional crop management practices in neighboring fields. Up-to-date, figures of CA adoption are summarized for the important cropping countries in the Middle East, including the 2012/2013 season not covered by Haddad et al. (2014a), and the impact of the recent conflict in Syria on adoption is discussed.

9.2 Cultivation in the Fertile Crescent

About 12,000 years ago, inhabitants of the region now known as the Fertile Crescent, started gathering seeds of grasses and other edible plants to help overcome the threat of famine. Around 6,000 BC, they made the revolutionary step of purposefully planting seeds and managing crops, and at this point in history, agriculture, the active management of plants for food, feed, and fiber production, and human civilization began (Riehl et al. 2013). The Fertile Crescent stretches from the Persian Gulf, north along the Tigris and Euphrates Rivers restricted to the east by the Zagros Mountains which separate modern-day Iraq from Iran; east across northern Syria and to the south of the Taurus Mountains in southern Turkey; south down along the Mediterranean coast of what is now Lebanon, Israel, Palestine, and Jordan; and along the Nile valley in Egypt. This area was the source of some of the most productive and important crops grown around the world today, as people from the other continents (e.g., Europe, Africa, the Americas, Asia, and Australia) acquired, adapted, and successfully cultivated the crops from this region. In effect, these crops were a great gift from this region that enabled the agricultural development of many other countries.

The first farmers in the Fertile Crescent probably made holes in their soils with a stick during the wet winter season and in each hole planted a few seeds of the wild progenitors of many of our modern crops—e.g., wheat (emmer and einkorn), barley, flax, chickpea, field pea, lentil, or bitter vetch. Over thousands of seasons of trial and error and collective experience, they gradually improved the management of their crops and actively selected the types of plants that produced the greatest yield and quality of seeds. Likewise, they domesticated goats, sheep, cows, and pigs which they grazed mainly on the rich production of the wild grasses and forage legumes in the vast uncultivated parts of the landscape. And so, the Fertile Crescent developed into a food basket driving population growth in the Middle East and Mediterranean region.

9.2.1 Tillage

Crop management in the Fertile Crescent was dominated by minimal soil disturbance for the first few millennia (Huggins and Reganold 2008). Farmers, initially using human power and soon after with the help of animals, created furrows in which the seeds were spread and then backfilled with loose soil. About 3,500 BC, the Egyptians and Sumerians invented the plowshare, a wooden frame with an iron blade, to loosen the top soil, kill weeds, and facilitate seed placement. This plow technology and its more modern equivalents became the standard practice for seedbed preparation as agriculture spread to most parts of the world, but it was costly. Much of the fodder grown or grain harvested at the end of the season was required to feed the draft animals. It was not until the early 1900s that the development of farm tractors and cheap oil allowed farmers to plow the soil repeatedly and on large scales causing massive soil disturbance. This enabled farmers to increase the size of their fields and farms with minimal labor or animal costs. Three or four tillage operations before sowing with different types of cultivators and harrows (moldboard, disc, duckfoot, or chisel points) were common.

9.2.2 Improvements in Sowing

Seeding methods in the Middle East remained basic for many decades. The soil was cultivated once or twice using a plow or one-set duckfoot cultivator to loosen the soil, kill weeds, and initiate ridges and furrows on the soil surface. Fertilizer (when used) and seed were then spread into the furrows by hand, or top-dressed using a fertilizer spinner, or in more advanced cases, using a hopper with a simple metering device mounted on the plow. Finally, the furrows were backfilled with the use of harrows, spikes, or a heavy bar called “tabban” in Arabic (طبان). Alternatively, the ridges were split and filled the furrows using the same plow device, thereby covering the seed. This sowing technique, known as “broadcast over ridges” or in Arabic as “ayar and rdad” (عيار و رداد), is still used today in wheat- or barley-based systems in the less developed parts of the eastern Mediterranean region. It typically results in highly variable seed depth, and low and variable plant emergence.

Interestingly, another seeding practice called “skin planting” or “ziraat al jild” in Arabic (زراعة الجلد) was developed in the region when farmers were exceptionally late in planting and had no time for the normal tillage operations. The farmer simply broadcast his seeds and fertilizer directly onto untilled soil, and then covered it with an animal-drawn plow, duckfoot cultivator, or shallow moldboard plow. This was an early form of “direct drilling” but the resulting seed depth and emergence were extremely inconsistent.

Modern conventional seeders or seed drills were introduced to the region in the second half of the twentieth century. These were designed for sowing after the seedbed had been plowed and harrowed, typically using duckfoot points (or soil openers) which created high soil disturbance and killed any remaining weeds growing in the field. Even though disc-type seeders were common in other countries, tines were preferred over discs in the Middle East because of their lower cost and weight—this was also the case in Australia and Canada. Modern seed drills usually have accurate seed and fertilizer metering and placement systems, and can produce uniform and excellent crop establishment. Of course, the seeders must be well maintained, calibrated, and operated correctly, which is often not the case for poor illiterate farmers in the Middle East. Even the simple tine-type seeders are too expensive for many small, poor farmers which is why the traditional seeding systems described earlier still exist today in some districts.

9.2.3 Crop Sequences

Rotation of crops has probably been used for millennia in the Fertile Crescent, after the early farmers noticed the yields of cereals following legume crops were much improved compared to the continuous production of cereals year after year. By alternating crops, weed, insect, and disease problems were reduced and, as we know now, legumes fix nitrogen from the atmosphere which is partly carried over in the crop residues and within the soil for following crops. A common crop sequence practiced in Syria and other countries consisted of cereal (wheat or barley) followed by a legume (lentil or chickpea), and then in the 3rd year, a winter fallow was implemented followed by a summer crop (melon, sugar beet, etc.) grown on residual moisture from the winter rains. In many cases, village agricultural land was divided into three large communal blocks, one for each course of the rotation, and each family in the village owned a portion of land within each rotation block. Livestock collectively grazed the winter fallow blocks before they were moved to open rangeland areas in spring, and back then to the cereal and legume blocks after harvest to utilize the valuable crop residues and spilt grain. This collective approach to farming contributed to the understanding still present in many areas of the Middle East that crop residues are a common property available to everyone.

The practice of fallowing or "resting" the soil was and still is thought to improve soil fertility, and any weed growth can be utilized by livestock. In the 1900s, the availability of cheap fuel, tractors, and plows allowed farmers to kill weeds during the fallow period with tillage, and thereby conserve more moisture from one season to the next. Although farmers missed out on any production during the fallow year, it was hoped that this would be offset by the increased moisture and fertility, resulting in improved production in the following season. Hence, the barley–fallow rotation remains widespread in dry areas of the Middle East and is highly integrated with the production of small ruminants (Ryan et al. 2008).

9.2.4 Population Growth and Soil Degradation

In more recent decades, populations have rapidly grown, the numbers of sheep and goats have increased, and the pressure on the native rangelands and crop residues has escalated (Aw Hassan et al. 2010). In addition, the production of forage crops including annual legume species native to the region is not widespread (Ates et al. 2013). Feed resources for livestock are often insufficient, so supplementary feeding with barley or other feeds is required. Heavy grazing of crop residues often leaves the soil completely bare during the summer and autumn months, and highly prone to wind and water erosion, especially in dry seasons when feed is in short supply. Summer and autumn dust storms are common. The application of fertilizers rarely replaces the nutrients removed from the soil, and declining organic matter and poor structure caused by excessive tillage and wind and water erosion lead to reduced soil fertility. Although crop legumes (lentil and chickpea) had been grown for millennia in this region, they fell out of favor in many areas, partly because of an inability to harvest them with modern harvesters like cereals, problems with weeds, pests and diseases, and high wheat prices paid to farmers by governments who artificially inflated wheat's value in an attempt to boost production and food security. A collapse in soil fertility is thought to have been a major factor in the decline of many ancient civilizations in several parts of the world including those in the Middle East (Montgomery 2007).

The ongoing impacts of population growth, climate change, and unsustainable resource management exacerbate the constraints on land and food supply, and these are predicted to become increasingly evident in the Middle East and North Africa, where most countries rely heavily on imports to feed their growing populations (World Bank 2008). By the second half of the twentieth century, the Fertile Crescent had become just a glimmer of its former glory, and many areas could no longer be described as fertile, and it was not alone. Crop production in many parts of the world suffered a similar fate in a much shorter time frame during the first half of the century, including North America and Australia.

9.3 Australia's Example and Gift to the Middle East

The current agroecologies in the dryland areas of the Middle East have many similarities to those which prevailed prior to the 1970s in southern Australia. The edaphic constraints of both environments are alike. Both experience a Mediterranean-type environment with hot dry summers and cool wet winters, and in most areas, crop production is only possible during the winter and spring period because irrigation is not widely available. Crop rotations are dominated by wheat and barley, although in southern Australia, these were often grown in rotation with pastures based on subterranean clover, and fallow was widely utilized in low-rainfall areas to conserve soil moisture for the following winter season (Burvill 1979). Soils in both regions are typically infertile with poor structures and low amounts of organic matter. Alkaline, fine-textured soils are common to both regions, although parts of Australia also contain areas of acidic, coarse-textured soils, especially in Western Australia. Crop residues are heavily grazed by sheep especially in dry seasons, leading to water and wind erosion and dust storms. After the first autumn rains, two or three cultivations are often employed to kill weeds and this typically results in a 3–4-week delay before sowing can commence. As a result of the constraints of the climate and the crop management practices, the average grain yields of rainfed cereals are limited to around 1.0 t ha^{-1} in the Middle East, as was also the case in Australia in the 1960s.

Over the past 50 years, Australian farmers have changed their production systems dramatically. They have eliminated fallow phases, introduced new crops (e.g., grain legumes and canola), and embraced herbicides to kill weeds immediately before planting and/or selectively within the crop growth period (Anderson and Angus 2011). Herbicides enabled farmers to manage weeds without plowing and plant crops before or soon after the first autumn rains. During the last two or three decades, there has also been a dramatic shift away from plowing before sowing toward the adoption of ZT seeders (mostly tine-type) to sow seeds and fertilizers into undisturbed soil in narrow slots while most of the residues from the previous crop are left either standing or on the soil surface between the rows. The adoption of ZT in Australia has been driven by a combination of three main factors: high fuel and labor costs; the ability to conserve soil moisture, which enables early crop establishment particularly when autumn rains are marginal; and a desire to minimize the risk of soil erosion (D'Emden et al. 2008). The adoption of ZT practices is now widespread across Australia, and in many regions more than 85 % of all agricultural land is not cultivated (Llewellyn et al. 2012). Australia is now held up as an example of where the adoption of three key principles of CA, that is ZT, soil cover, and diverse rotations, has been a success (Kassam et al. 2012).

The similarities between the environments and cropping systems of the dryland areas of the West Asia and southern Australia gave collaborating Australian scientists confidence that CA practices, especially ZT and early sowing, could have a role to play in increasing crop productivity and improving farmer livelihoods in the Middle East. This led to the first phase of a project funded by ACIAR, which started in 2005. It was hoped that this project would provide a more advanced and sustainable cropping system for the Middle East, based on the one developed and used widely in southern Australia with crops originating from the Fertile Crescent. Australia had benefited greatly from the crops given by the Fertile Crescent. If elements of the Australian cropping system could be adapted to local conditions in the Middle East, it might in turn be a "gift" back to the Fertile Crescent that contributes to the restoration of the region as the food basket for its expanding populations who are much troubled by civil conflicts.

9.4 Zero-tillage Adoption in Iraq and Syria

Nineteen years before the Australian-funded project started, a long-term tillage experiment was established at ICARDA's headquarters at Tel Hadya, near Aleppo in northern Syria. The experiment compared conventional deep disc plowing and chisel cultivation, conservation tillage by a duckfoot cultivator, and direct seeding with ZT in two crop rotations: durum wheat–lentil–melon and bread wheat–chickpea–melon. All treatments were sown at the same time, well after the first autumn rains. Pala et al. (2000) reported no significant differences in the mean and range of grain yields and water-use efficiencies among the different tillage systems in both rotations over a 12-year period (1986–1997). Changes in weed populations were observed, and a higher level of weed management was required in the ZT plots. An economic analysis of the results was not conducted, but the ZT treatments would have provided cost savings associated with reduced fuel and labor inputs, and one could assume that these would produce higher profits than the conventional tillage (CT) treatments. However, no concerted effort was made to extend these results to farmers.

At the start of the ACIAR project, local researchers and extension specialists were skeptical whether crops could be grown in the region without plowing, partly because of the observations of increased weeds in ZT plots from the earlier tillage experiment. In response, the project initiated a series of research experiments commencing in 2005 to verify, adapt, and demonstrate ZT and other CA and improved crop management practices. These could not be done in northern Iraq (the target region of the project) because civil unrest and insurgency made it impossible for international staff to visit, undertake research, or conduct extension activities there. Instead, much of the research was conducted at Tel Hadya, where good facilities were available and international staff resided nearby. Early experiments confirmed that ZT cropping was indeed not only possible but also more profitable than CT systems, giving similar or better crop performance at lower cost. Other experiments and demonstrations were also conducted in Iraq by project collaborators, producing good results. These were instrumental in generating awareness and interest in ZT technology among other scientists and innovative farmers from Iraq and Syria inspecting this work and discussing the concepts of CA and ZT technology. The ICARDA adaptive research program also encouraged researchers, extensionists, and farmers to conduct similar experiments, demonstrations, and field evaluations in other parts of Syria, Iraq, and other neighboring countries.

To the best of our knowledge, no farmers were using ZT in Iraq or Syria when the project started in 2005. Since then, awareness and experience of ZT grew quickly, local ZT seeders were developed and became available commercially, and the technology was demonstrated and extended by participatory groups in both Iraq and Syria during the second phase of the project which started in 2008. The area and number of farmers adopting ZT increased steadily, undoubtedly as a direct result of the project, and with associated support from the national partners. In 2011/2012, measurements of adoption were around 30,000 ha by more than 500 farmers in Syria, and 7,800 ha by about 100 farmers in the Ninevah governorate in Iraq (Piggin et al. 2011). More recent surveys show further increases in 2012/2013 to more than 10,000 ha in Iraq; however, accurate figures for Syria were not available because of the ongoing conflict in that country (Figs. 9.1, 9.2, 9.3, and 9.4).

The civil unrest which commenced in Syria in 2011 prompted ICARDA to withdraw its international staff in the middle of 2012, and while its input into the promotion of ZT was greatly reduced, Syrian research and extension partners continued to support farmer groups where they were able. In the 2012/2013 season, ZT adoption appears to have increased because the conflict prompted more farmers to reconsider their crop management practices (Haddad et al. 2014b). The supply of fuel was often limited and prices increased by about four times in less than two years, so plowing rapidly became a lot more expensive. In 2012/2013, one farmer in the Kamishly

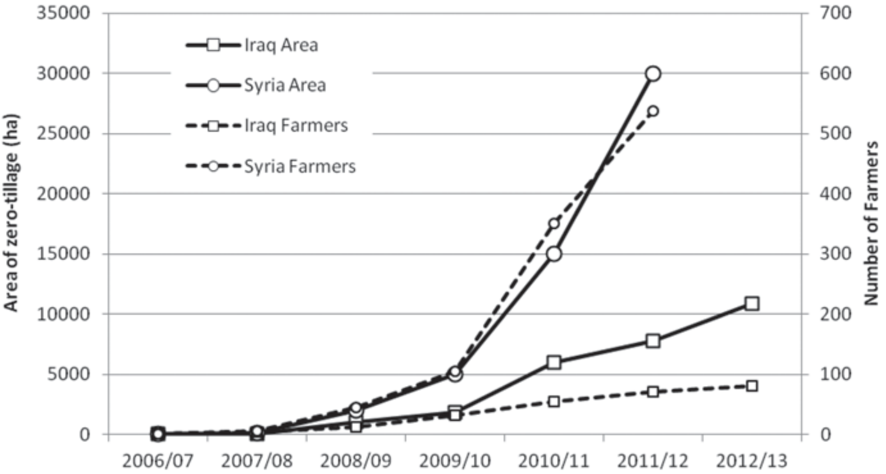


Fig. 9.1 Area and numbers of farmers that adopted zero tillage (*ZT*) in northern Iraq and Syria between 2006 and 2013

Fig. 9.2 Colin Piggin (Project Manager 2005–2011) explains to visitors one of the long-term experiments conducted at Tel Hadya, Syria, in 2008. (Photo: A. Haddad)

area, Mr. Ali Alewi, indicated that he was able to plant four times the area of crop using ZT because of the fuel and other savings compared to his previous intensive plowing practices. In addition, plowing during a civil conflict involved considerable personal risk, not only while working in the field but also during travel and the transport of machinery from village residences to sometimes distant fields along public roads, so this was another motivation to switch to ZT. Haddad et al. (2014b)

Fig. 9.3 A field workshop comparing the performance of various seeders at Tel Hadya, Syria, in 2009. (Photo: Y. Khalil)

Fig. 9.4 Syrian farmer, Ismail Jarrad, purchased an Ashbal zeo tillage (*ZT*) seeder made by Ibrahim Shibley at Qabbaseen, Syria, in 2011. (Photo: A. Haddad)

estimated that the area of ZT adoption in Syria in 2012/2013 may have reached as high as 50,000 ha, with plowed fields difficult to find in some northeastern districts.

There is little doubt that the project had a major impact in the adoption of ZT in Syria and Iraq in a relatively short period of time. The significant success of the project can be attributed to three critical strategies which we now explore:

1. Adaptive research to verify and fine-tune the technology for the region
2. Development of small, simple, and low-cost ZT seeders
3. Participatory extension campaigns that enabled farmers to test ZT seeders and develop CA packages on their own farms

9.5 Adaptive Research

During 2005–2012, more than 40 adaptive research experiments investigated the suitability of elements of the CA cropping systems used in southern Australia to northern Syria and northern Iraq. Other experiments were also conducted by the

General Commission for Scientific Agricultural Research in Syria and the University of Mosul in Iraq. A number of aspects of CA and improved crop management were investigated.

9.5.1 Crop Yields

Results in bread and durum wheat, barley, lentil, and chickpea showed that seeding without plowing resulted in similar or better crop growth and grain yields than the CT systems requiring two or three cultivations before sowing. The importance of the combination of ZT and early sowing was clearly apparent in the first few seasons. For example, in 2007–2008, lentil yield was 0.67 t/ha with the traditional farmer practice of CT and late sowing, and 1.23 t/ha with ZT and early sowing—a massive increase of 84 % (Piggin et al. 2011). The majority of the yield increase in the new cropping systems in northern Syria was attributed to the earlier sowing—in 2007/2008 and 2008/2009, early sowing accounted for 52–83 % of the yield response. As was the case in Australia, direct seeding into undisturbed soils enabled early sowing either before or immediately after the first effective autumn rains which often improved water-use efficiency and produced significant yield increase in the cereals and grain legumes, particularly when the growing season rainfall was below average (Piggin et al. 2014). The elimination of plowing, which reduces costs and in some cases increases crop yields, also permits early sowing, which subsequently increases yield in most seasons.

9.5.2 Soil Moisture and Fertility

In an analysis of a long-term experiment in 2009/2010 on the clay soil at Tel Hadya and using crop modeling with over 30 years of weather data, Sommer et al. (2012) suggest there is little benefit in retaining standing stubble in terms of soil water retention and yield at this site. Insignificant differences in crop growth, water use, and grain yields were measured between plots where 100 or 30 % of the crop residues were retained. This may be because of the "self-mulching" characteristic of this soil, which naturally prevents soil evaporation, however, they measured about 55 % of the seasonal precipitation was lost by unproductive soil evaporation in most years. Another factor in the lack of a measurable mulching effect may have been the fact that the residue treatments differed only in the amount of standing stubble left after harvest, while the amount of residues left laying on the soil surface were similar.

Improvements in soil fertility (organic carbon, available phosphorus, water-stable aggregates, and water infiltration) were measured in the experiments after 5–6 years (Loss et al. 2013). The carbon sequestration rate associated with increased soil organic matter was in the range of 0.27–0.30 Mg C/ha/year, and this rather modest increase was probably due to low to moderate crop productivity and a reasonable starting soil organic matter content of about 1.3 %. No effects of tillage or residue retention were measured on soil mineral N, microbial biomass, bulk density, or moisture retention.

9.5.3 Seed Rates and Varieties

Other experiments showed that seed rates could be reduced significantly because of the more accurate seed placement and metering with ZT seeders, resulting in improved plant establishment and early vigor, especially when crops were sown early. Traditional sowing practices with little control over seed placement (e.g., broadcast over ridges), poor quality seed, and the misperception that thick crops resulted in higher yields meant farmers typically used seed rates as high as 250–300 kg/ha for cereals. In contrast, the results from the field experiments indicated that seed rates of 70–100 kg ha^{-1} produced the most profitable outcomes over a range of seasons when sown early with accurate ZT seeders and good-quality seed.

In other experiments with a limited number of cereal and legume genotypes, results suggested that varieties which performed well under CT also performed well with ZT, and, therefore, breeders need not select varieties specifically for CA systems (Piggin et al. 2011). This requires further confirmation with a greater number of genotypes. Nonetheless, it is advisable that breeding programs switch to the new crop management practices to develop varieties best adapted to this system, given the rapid adoption of ZT, early sowing, and reduced seed rates in Syria and Iraq. There may be traits that make some varieties better adapted to particular aspects of the new cropping system; for example, cereals with long coleoptiles are better able to emerge through thick crop residues.

9.5.4 Weeds and Diseases

Plowing and removal of crop residue was widely justified as a technique to avoid the buildup of weeds and diseases. In a long-term tillage × time of sowing experiment conducted at Tel Hadya, the total weed population was increased in a cereal grain–legume rotation under ZT compared to CT after 6 years, however, the total weed biomass was less under ZT than CT (Khalil et al. 2013). The weed populations in the ZT plots were dominated by the legumes *Scorpiurus muricatus* L. (scorpion plant) and *Coronilla scorpioides* (L.) W. D. J. Koch (annual scorpion vetch) which tend to be small and are not very competitive with the crop, so their impact on crop growth was actually minimal. The weed spectrum changed with the adoption of ZT and it is likely that the weed seeds remaining on the soil surface in ZT were more prone to predation by insects and other animals, and their viability was reduced by greater exposure to the elements. Later observations in farmers' fields confirmed that the overall weed burdens under ZT were often not different or lower than CT. In many low- to medium-rainfall environments in the Middle East, there is no summer rainfall and weeds are unable to grow until the first autumn rains. In the majority of the experiments at Tel Hadya, when crops were sown before or immediately after the first rains, there was no noteworthy weed growth immediately before sowing and the use of a nonselective herbicide was not required. Surveys of fungal diseases and nematodes in a number of crops in ICARDA's long-term experiments showed no effect of ZT and crop residue retention, apart from Ascochyta blight in chickpea which was more widespread but not more severe in the ZT than CT plots, especially when sown early (Seid et al. 2012).

9.5.5 Growing Awareness

The adaptive experiments conducted by ICARDA, the General Commission for Scientific Agricultural Research, and the University of Mosul were instrumental in convincing skeptical scientists and technical staff that crops could be grown successfully without tillage. Some of these people had spent many decades believing that tillage was essential for weed control, good soil structure and water infiltration, low bulk density and favorable root growth, and disease and weed management, just as they had been taught many years earlier. But seeing the crop growth in the experiments first hand and the yield data after harvest played a critical role in changing their thinking.

Innovative farmers also visited the experiments at field days, and were given an introduction to the principles of the technology and how CA is implemented in other parts of the world. In many cases, the practice of tilling for land preparation was deeply ingrained and while many did not think ZT was viable, even after seeing the experimental results, they could see the benefits of reducing costs. Reluctant to abandon tillage completely, they often asked if reduced tillage might provide similar benefits. Consequently, there was an initial tendency to switch from the moldboard plow to using one pass of a chisel plow or duckfoot cultivator before sowing. However, early experimental results in Syria showed this was less preferable than going directly to ZT, partially because it did not allow early sowing or the same level of cost saving. Similar results with minimum tillage were obtained in Iraq (Alrijabo 2014).

Some progressive farmers inspecting the experiments immediately saw the potential benefits of ZT and were keen to test the new approach including early sowing, so a "conservation cropping package" was developed as a set of "best bet" recommendations for crop management (Table 9.1). As discussed later, the elimination of plowing and use of a ZT seeder were depicted as the most important elements, because these delivered immediate cost savings to farmers and in most cases yield increases. All other elements, including crop residue retention and rotation, were communicated as desirable options but farmers were not encouraged to adopt all parts of the package simultaneously.

9.6 Development of Zero Tillage Seeders

To implement the most critical part of the cropping package, i.e., eliminating plowing and direct drilling, farmers needed access to suitable ZT seeders. Most imported ZT seeders were heavy, expensive, complicated to use, and difficult to maintain and

Table 9.1 The elements of the recommended "conservation cropping package" derived from field experiments conducted in Syria and Iraq from 2005 to 2010

Stop plowing
Keep crop residue on the soil surface if possible—do not burn stubbles
Graze stubble if needed
If needed, kill weeds at sowing with a nonselective herbicide like glyphosate
Plant early before the autumn rains (October) or immediately after (November)
Use ZT seeders for all crops
Use good-quality seed of the best adapted varieties
Reduce seed rates: 50–100 kg/ha cereals; 100–150 kg/ha pulses
Sow consistently at a depth of 4–5 cm for cereals
Use best fertility and weed/disease/pest management practices
Include noncereals in rotations if possible

ZT zero tillage

repair, and therefore were not suitable for small farmers in developing countries. Several earlier research and development projects in other countries had demonstrated the advantages of ZT using imported seeders, but subsequent adoption was usually limited to large farmers who could afford to invest in imported machinery and derive a rapid and substantial return on their investment over the large areas of their farms. For example, in Morocco CA research started in the 1980s and demonstrated significant improvements in soil fertility and crop production (Mrabet 2007), but 30 years later adoption is still low. Similarly, the benefits of ZT were measured in various parts of Turkey two decades ago, but subsequent adoption by farmers was negligible (Gültekin et al. 2011). For most small farmers, the lack of suitable small ZT seeders or service providers using such equipment is a major barrier to adoption. Farmers in northern Syria and Iraq are relatively small (less than 20 ha), they lack the financial resources to invest in expensive machinery, and they can derive only a small benefit each year because of their limited cropping area. So the development of at least one supplier of small, simple, and affordable ZT seeders was considered essential if permanent and widespread adoption of ZT was to occur in the Middle East.

9.6.1 Syrian Manufacturing

In the Middle East, tined seeders with knifepoints were favored over disc machines because of their simplicity, robustness, and suitability to a wide range of soil types. A number of machinery workshops operated in Syria but their scale and quality was low by international standards. In 2007, machinery manufacturers near Aleppo were invited to inspect the field experiments at Tel Hadya and be introduced to CA technology. After seeing examples of ZT seeders and the impressive crop results in the field, several expressed interest in producing ZT prototypes. Their manufacturing capacity was enhanced with expertise from Australian agricultural engineers, and a number of prototype ZT seeders were manufactured commencing in 2008.

الرشيد 230 سم - الباب

الأشبال 230 سم - قباسين

العروس 230 سم - القامشلي

الرشيد 350 سم - الباب

الأشبال 380 سم - قباسين

العروس 350 سم - القامشلي

Fig. 9.5 Six of the simple zero tillage (*ZT*) seeders produced commercially by local village workshops in Syria in 2011. Prices varied from US$ 2000 to 7,000. (Photos: A. Haddad)

The flexible conservation cropping package promoted to farmers permitted grazing of crop residues before sowing, so the ability of the ZT seeders to sow into thick stubble was not essential, especially in rainfed fields where yields are often low. But in irrigated areas with intensive cropping, high yields, and low populations of grazing animals, there were some difficulties with heavy crop residues causing clumping and blockages of seed and fertilizer during sowing operations. These were overcome by widening the spacing between rows (typically from 15–17 to 20–25 cm), redistributing tines on three rather than two tool bars (or ranks), and lifting the seed and fertilizer boxes to allow the free flow of seed and fertilizer down the tubes to the furthest tines. Most had separate seed and fertilizer placement, but did not include press wheels to minimize the cost.

Many of the Syrian manufacturers benefited from a close association with their customers and they became promoters of the technology to a wider group of farmers inquiring about the purchase of machinery. Iterative improvements in seeder design and manufacture were assisted by the close links between the machinery workshops and farmer groups. In 2012, there were seven manufacturers of ZT seeders in Syria, mostly village based, and over 70 locally made seeders had been purchased by farmers for US$ 2000–7000 (see Fig. 9.5). Some seeders were also exported to other countries for CA development projects. The local manufacturing of ZT seeders created badly needed employment in rural areas and provided farmers with good access to advice, spare parts, and repairs when required.

During 2012, improvements in materials, design, and construction were ongoing when the escalation of the civil unrest disrupted manufacturing operations and workshops were unable to meet the increasing demand for ZT seeders. With the decline in the manufacture of seeders, Syrian farmers have recently turned more towards converting conventional seeders to ZT by simply replacing the traditional duckfoot points with locally made narrow knife-edge openers (Haddad et al. 2014b).

9.6.2 Iraqi Manufacturing

In northern Iraq, manufacturing capacity and availability of materials had been weakened by decades of conflicts and isolation of that country, so the initial focus of innovative farmers wanting to test ZT was to convert their existing conventional seeders using narrow knifepoints made locally and increasing row spacing from the common 17 to 22–30 cm (Jalili et al. 2011). Australian John Shearer seeders introduced by earlier Australian aid projects and Rama seeders made in Jordan were popular in Iraq, and proved cheap and easy to convert to ZT. Press wheels were considered an important part of the seeding systems by the Iraqi researchers and farmers, and these were also manufactured locally and fitted to converted seeders. In Iraq, more than 40 seeders were converted to ZT and several Iraqi farmer–manufacturer groups were involved in the development of locally made seeders, tines, and press wheels. The first Iraqi-manufactured ZT seeder prototype was completed in 2012, and several units were made in 2013/2014 (Jalili et al. 2014).

9.7 Participatory Extension Program

The “conservation cropping package” developed from the adaptive experimental program was initially evaluated by innovative farmers in Syria and Iraq in 2008/2009 when locally made ZT seeders first became available, and further fine-tuned to their local conditions in subsequent seasons. This package deliberately focused on eliminating tillage, adoption of ZT seeders, and sowing early with reduced rates of seed, because these changes provided the greatest immediate benefits to farmers through reduced costs (fuel, labor, and seed) and often increased yields (Table 9.1). In contrast to many other projects promoting CA around the world, little emphasis was given to the other two main principles of CA because it was recognized that maintaining soil cover with crop residues and diversifying crop rotations are more difficult changes for farmers in this region. For small farmers, many of whom are poor and illiterate, including all three aspects of CA simultaneously would have been too great a change in one step and the added complexity would have increased the likelihood that something would go wrong causing them to reject the whole package. Instead, adoption of CA was seen as a process, whereby farmers could take a step at a time when they felt ready, with ZT being the most important first step. Similar stepwise adoption of technological packages by farmers has been noted in Mexico (Byerlee and Hesse De Polanco 1986).

9.7.1 Participatory Approach

The approach of this development and extension program was based on experiences from Australia, where initial research showed direct drilling or ZT cropping without plowing was promising; farmers modified their seeders because of local unavailability of commercial ZT seeders; and farmers, researchers, and extensionists worked closely together in promoting ZT awareness, experience, and adoption in a participatory manner. Lessons were also learned from CA demonstration projects in other developing countries where activities had been less successful in generating real adoption. These projects often ran CA "farmer demonstrations" where government research, development, and extension staff conducted all operations from start to finish largely independently of the farmer; used large, complex, expensive, and imported ZT seeders; provided all the inputs for the farmers; and in some cases paid farmers for use of their land. These projects were less successful probably because a sound awareness and firsthand experience with ZT was not developed by the farmers who had low levels of ownership of the activity. With no simple access to small, affordable, and effective ZT seeders, it should have been no surprise that farmers went back to their CT and sowing methods at the end of the project.

Australian experts in participatory approaches were engaged to deliver training to extension specialists in Syria and Iraq. Farmer groups were established in Iraq and Syria to evaluate the conservation cropping package, and each group was provided with a simple and affordable ZT seeder, either manufactured or converted locally in the region (Haddad et al. 2014a). These groups involved not only farmers but also seeder manufacturers, local government employees, private and nongovernment organizations, researchers, and extension officers. Within each group, a ZT seeder was made available to farmers interested in testing it on their farm without providing any payment or inputs or other incentives to the farmer, other than use of the seeder free of charge. Some farmers were concerned about damaging the seeder, so it was guaranteed that they would not be held liable for any damage. Most groups elected a leader to coordinate the testing of the ZT seeder and arrange repairs if they were required during or after the sowing season. The fact that there were no payments for participating in the evaluation and the farmers were expected to provide all their own inputs (seed, fertilizer, fuel) was rarely questioned. This was not a constraint for innovative farmers who were keen to improve their profitability and could see the potential of the technology to increase production, reduce costs, and improve their soils.

Farmer-to-farmer communication and learning were supported and they willingly shared their experiences with other members of the group at field days and post-harvest meetings (Fig. 9.6). These activities proved popular with the members of the groups and highly effective in raising awareness and adoption, with the number of participants and comparisons growing exponentially as ZT was accepted more widely each year. Many participating farmers took much pride in presenting their results and discussing potential improvements at field days and meetings with everyone present, sometimes including national television coverage. The participatory

Fig. 9.6 Participants at a conservation agriculture (*CA*) field day at Al Shaikhan, Iraq, in 2013. (Photo: Z. Taha)

aspect of this program was critical to its success as it gave farmers ownership of the ZT demonstrations and direct experience with ZT seeder operation, early planting of crops, and reduced seed rates in their own fields.

As was the experience in Australia and many other parts of the world where CA has been successfully adopted (Kassam et al. 2012), farmers and farmer-led organizations are taking a lead in developing and promoting ZT technology in Syria and Iraq in collaboration with researchers and extension organizations, and local machinery manufacturers. In an encouraging development in both Iraq and Syria, some groups of farmers proud of their achievements and keen to spread the benefits of ZT technology have independently organized and funded their own field days. An important development in Iraq was the formation of the "Mosul Society of Conservative Agriculture," a group of farmers and scientists who encourage and support CA development and education in Ninevah.

9.7.2 Farmer Yields

Farmers were encouraged to compare the crop performance of their ZT field (mostly including early sowing at reduced seed rates) with CT crops in their own or nearby conventional fields, and keep good records of their management and yields. A preliminary analysis of the Syrian farmer evaluation data over three seasons is presented in Table 9.2—this includes a number of different crops (mainly barley, wheat, and lentil, but also chickpea, vetch, *Lathyrus,* and cumin), grown in a wide number of regions and rainfall conditions including some irrigated fields. Apart from ZT and early sowing (and in some cases reduced seed rate), the fields compared were managed similarly. In the vast majority of cases, crop growth and yields were equivalent or significantly better with ZT and early sowing compared to fields sown conventionally. Given this was the first time that many farmers had used the technology, it was surprising that CT fields outyielded ZT in only a handful of cases. On average, over all 3 years, the grain yield increases with ZT compared to

CT were 0.26 t/ha (15 %) for barley ($n=278$), 0.33 t/ha (19 %) for wheat ($n=264$), and 0.23 t/ha (21 %) for lentil ($n=88$).

The 2010/2011 season was especially dry in some parts of Syria, and among the 460 comparisons, there were 103 where crops grown with CT and late sowing could not be harvested (i.e., no yield was harvested) while nearby ZT fields with early sowing produced an average grain yield of 0.57 t/ha for both wheat and barley, and 0.48 t/ha for lentil. This evidence unmistakably confirms the benefit of ZT and early sowing in dry conditions, and the ability of this technology to increase the resilience of many crops to drought and climate change in the Middle East. In addition, under situations where yields were greater than 3.0 t/ha (some irrigated) the average yield increase with ZT and early sowing across all three seasons was 0.45 t/ha (13 %) for barley ($n=71$) and 0.35 t/ha (9 %) for wheat ($n=69$). So, contrary to studies in other regions, these data suggest CA technology is also highly suited to favorable environments (Farooq et al. 2011).

9.7.3 Experiences Under Irrigation

Some researchers and farmers in Iraq also tested the conservation cropping package under supplementary sprinkler irrigation and observed similar benefits (Alrijabo 2012). In irrigated areas where livestock numbers and the potential for grazing are low, such as the Kurdish region of northern Iraq, crop residue levels are usually large and farmers typically burn their stubbles before sowing. In some cases, excessive crop residues caused issues with direct drilling with a ZT seeder and poor crop establishment, and further improvements in the stubble-handling capacity of the seeders were required. Where crop establishment was good, farmers noted reduced irrigation water requirements and less tendency for the soils to become muddy and untrafficable, probably as a result of improved soil structure and water infiltration under ZT. As was the case for rainfed conditions, yields produced with ZT were usually similar or better than nearby CT fields. Improved timeliness of operations was also reported as an advantage of the ZT and early sowing technology, especially for farmers growing multiple crops each year. Many were able to harvest a crop one day and sow the next crop on the following day with the ZT seeder. While farmers in the region do not pay for water or face water quotas, they require fuel or electricity to run their irrigation pumps, so the ZT fields incurred lower costs associated with the pump use, in addition to the fuel savings with reduced tillage operations. Reduced need for irrigation will also increase the sustainability of local groundwater supplies.

The farmer evaluation campaign clearly demonstrated that the ZT seeder was widely applicable to all soils and seasons, and it was rare for a farmer to try a ZT seeder and not continue or expand their ZT plantings in subsequent years, by either borrowing the group's ZT seeder again or borrowing or renting from another farmer, or purchasing their own. Economic data were also collected and are currently being analyzed, but all farmers benefited through savings in fuel and labor because

Table 9.2 Summary of farmer yields comparing ZT plus early sowing with CT in nearby fields in three seasons in Syria for various crops (unpublished data)

	Crop	No fields	Mean yield ZT t/ha	SEM	Mean yield CT t/ha	SEM	Difference t/ha	SEM	Difference *P* value
2008/2009	Barley	19	2.72	0.326	2.25	0.292	0.46	0.125	<0.001
	Wheat	9	3.67	0.830	3.36	0.875	0.31	0.167	<0.002
	Lentil	7	1.78	0.269	1.43	0.160	0.35	0.171	0.04
	Chickpea	4	1.78	0.139	1.43	0.099	0.35	0.056	0.07
	Vetch and coriander	2	0.80	0.200	0.75	0.250	0.05	0.050	0.32
2009/2010	Barley	46	1.64	0.120	1.38	0.106	0.26	0.030	<0.001
	Wheat	79	1.82	0.101	1.56	0.090	0.26	0.028	<0.001
	Lentil	25	1.44	0.137	1.15	0.106	0.29	0.072	<0.001
	Chickpea	6	1.48	0.168	1.11	0.128	0.37	0.146	0.01
	Cumin	5	0.99	0.095	0.70	0.153	0.29	0.130	0.03
	Vetch and *Lathyrus*	2	0.71	0.210	0.43	0.075	0.29	0.135	0.03
2010/2011	Barley	213	2.00	0.101	1.76	0.095	0.24	0.031	<0.001
	Wheat	176	2.10	0.128	1.74	0.133	0.36	0.024	<0.001
	Lentil	56	1.26	0.081	1.10	0.091	0.17	0.039	<0.001
	Cumin	12	0.54	0.127	0.47	0.114	0.07	0.062	0.26
	Chickpea and vetch	3	1.83	0.467	1.97	0.504	-0.13	0.186	0.19
All years	Barley	278	1.99	0.084	1.73	0.078	0.26	0.026	<0.001
	Wheat	264	2.07	0.097	1.74	0.099	0.33	0.017	<0.001
	Lentil	88	1.36	0.069	1.12	0.067	0.24	0.035	<0.001
High Yields	Barley	71	3.98	0.065	3.54	0.070	0.45	0.062	<0.001
>3.0 t/ha	Wheat	69	4.23	0.136	3.88	0.141	0.35	0.037	<0.001

CT conventional tillage, *SEM* standard error of means, *ZT* zero tillage of the elimination of tillage operations, as well as reduced seed costs because of lower seed rates. In combination with the cost savings, increased yield also boosted overall profits significantly.

9.7.4 *Socioeconomics*

As part of the ACIAR project, several detailed socioeconomic surveys were conducted in Syria and Iraq to better quantify the impact of the extension program and patterns of adoption, and identify constraints and possible solutions. In 2011, a survey was conducted of 338 wheat farmers in Ninevah, of whom 35 used the conservation cropping package (Abdulradh et al. 2012). The average yield of wheat was increased significantly by adopting ZT and the mean level of technical efficiency between farming systems was 87 % for ZT farms compared to 75 % for those using CT. The cost of ZT seeder purchase or conversion was highlighted as an obstacle for adoption, especially by small poor farmers. It was suggested that adoption of CA would be enhanced further if government subsidies for inputs such as seed, fertilizer, and fuel which tend to promote their overuse were redirected towards reducing the cost of ZT seeders.

An analysis of a large survey conducted in 2011 of 820 households in 28 villages is presented by Yigezu et al. (2014) in Chap. 10 of this book. They found that the average Syrian farmer is able to increase their production efficiency by 86 % by adopting ZT, or produce the same levels of outputs as CT but with 22 % less inputs. By adopting ZT, the typical Syrian farmer was getting about 465 kg/ha (31 %) more yield than using CT, and net farm income increased by US$ 194/ha. Based on the Syrian poverty line of US$ 1.25 per capita per day, the adoption of ZT helped 57 % of farmers lift themselves out of poverty. The survey results also highlighted the effectiveness of field days and farmer testing to promote ZT.

9.8 Conservation Agriculture Adoption in Other Countries

9.8.1 *Turkey*

Since the late 1990s, various research projects have demonstrated the benefits of CA in Turkey’s dryland and irrigated farming systems. Fuel costs in Turkey are among the highest in the world, and reduced costs and similar yields make CA technologies more profitable compared to CT systems (Gültekin et al. 2011). In addition, significant benefits in soil fertility were measured and soil erosion which is a major issue in many parts of Turkey was reduced. Unlike other countries in the region, Turkey has a well-developed machinery manufacturing sector, and about seven companies currently manufacture reduced-tillage or ZT seeders, mostly disc type which are heavy, and complicated to use compared to tine-types. These ZT seeders attract government subsidies. Despite the favorable research results and local supply of relatively cheap ZT seeders, adoption of CA by farmers in Turkey is negligible apart from a few pilot CA demonstration areas. Barriers to adoption include the perceived cost and effectiveness of ZT seeders, the high value of crop residues for animal feed, although residues are often burned in irrigated areas, and the expectation that weeds will increase without tillage. Most importantly, a lack of knowledge and awareness about the practical implementation of ZT, and limited experience in residue handling under irrigated systems has discouraged any widespread attempts of implementing CA in Turkey to date.

9.8.2 Lebanon

In studies conducted in Lebanon during 2005–2007, Yau et al. (2010) compared the growth of barley, chickpea, and safflower under ZT, minimum tillage, and CT. They concluded that in contrast to most farmer opinions, there was no evidence showing that ZT yields less than CT, but also, little evidence that it would yield more. Other research in Lebanon showed that CA lowers production costs, thereby increasing farmers' profits, and reduces land degradation (Bachour et al. 2009), so there are net benefits with CA. Savings of US$ 2,000/ha were reported over three years in olive tree orchards interplanted with vetch using ZT by Jouni and Adada (2010), and adoption of this technology had expanded to more than 2,000 hectares in 2012. The perceived obstacles to adoption are lack of awareness among researchers, extensionists, and farmers; lack of suitable ZT seeders; crop residues creating a fire hazard in the summer season; and the need to use crop residues for animal feed. In addition, farm sizes in Lebanon are very small. About 70 % of farms are less than 1 ha, and farmers rely on local contractors to conduct most machinery operations, although this may not be a barrier to adoption if contractors embrace ZT and purchase ZT seeders.

9.8.3 Jordan

In Jordan, a CA demonstration program was established in 2009 by a joint project between the National Center for Agricultural Research and Extension and ICARDA. Syrian ZT seeders were imported and found to be less efficient than ZT seeders from Spain or Brazil which is not surprising given the Syrian seeders were four to ten times less expensive. Following the ICARDA evacuation of Syria, the ACIAR project was based in Amman, and it has worked with a local manufacturer (Rama Manufacturing) to design and produce affordable ZT seeder prototypes with considerable success. Further development and commercial availability of the Rama seeders will help promote adoption in Jordan and the region. Awareness of CA in Jordan is increasing but adoption currently remains low, which may be related to the facts that cropping is not a major enterprise in Jordan and, as in Lebanon, farm sizes are small and use of contractors is high.

9.8.4 Iran

Initial studies on irrigated wheat production in central and arid regions of Iran confirmed that ZT improved soil structural stability and, although crop productivity did not increase in the short term, costs were reduced (Hajabbasi and Hemmat 2000). Later work measured an improvement in crop productivity and water-use efficiency in continuous wheat, wheat/fallow, and wheat/chickpea rotations under rainfed conditions (Hemmat and Eskandari 2004a, b, 2006). As in Turkey, Iranian machinery manufacturing is relatively advanced and at least four companies have commenced producing small cost-effective ZT seeders, both disc and tine types. Reduced tillage (use of chisel plough rather than moldboard) is spreading and the Iranian government has plans to promote CA to Iran's vast dryland and irrigated agricultural areas.

9.8.5 Egypt

To the best of our knowledge, research into CA in Egypt is relatively new. This country has large areas of irrigation like central and southern Iraq, and crops are dominated by wheat–rice–cotton–forage and grain–legume rotations. Large amounts of crop residues are often burned if they cannot be harvested for hay or direct grazed. Initial studies in Egypt led by the Food and Agriculture Organization (FAO) have demonstrated significant benefits of CA and they can learn much about CA under irrigated conditions from central Asia (Nurbekov et al. 2013) and India (Lienhard et al. 2013).

9.8.6 Israel and Palestine

According to our information, there is no adoption of CA in either Israel or Palestine. Although these countries produce dryland cereals and other crops in almost identical conditions to Syria and Jordan, ZT seeders are yet to be introduced into these countries.

9.9 Challenges for Conservation Agriculture in the Middle East

There are several challenges for ongoing adoption of CA technology in the Middle East.

9.9.1 Soil Cover

Crop residues are highly valued in the integrated crop and livestock production systems common throughout central and West Asia and North Africa, and in dry years, the straw of crops can be more valuable as a stock feed than the harvested grain (Magnan et al. 2012). Where ZT has been adopted in the Middle East (mainly in Syria and Iraq), very little has changed in terms of crop residue retention or soil cover. In any case, the amount of crop residue produced in these dryland systems is relatively low and the benefits of crop residues may be relatively small (Sommer et al. 2012). This deserves further research in the region.

If farmers want to retain crop residues to benefit soil fertility and moisture retention, fields would need to be fenced because many livestock owners and shepherds do not recognize the farmer's ownership of the crop residue once the crop has been harvested. The high cost of fencing is a major obstacle for most farmers in the Middle East. However, one innovative farmer in Ninevah, Mr. Sinan Jalili, has started a fencing program to protect and allow effective management of his crop residues. If alternative feed sources were developed and adopted, and grazing better controlled, it is more likely that crop residues would be retained on the soil surface.

Many forage legumes or dual-purpose cereal crops (for both grazing and grain production) have potential, especially for farmers that produce both crops and livestock (Christiansen et al. 2000). The use of palatable perennial species like *Atriplex* spp. or cactus to form permanent alleys in combination with CA cropping in between the alleys could also provide another forage source, but grazing would need to be carefully managed to maintain soil cover between the alleys, and also avoid overgrazing of the alley species. The role and benefits of residues and alternative feed sources need more detailed study in the region, especially where rainfall is low and/or highly variable.

In irrigated areas where livestock numbers are relatively low, excessive crop residues can be an issue for effective crop establishment under ZT. Researchers and farmers in irrigated areas can learn much from experiences with CA in central Asia and India.

9.9.2 Diverse Rotations

Cropping systems in central Asia, West Asia, and North Africa continue to be dominated by cereals, especially in rainfed and risky environments. Development and promotion of productive and profitable alternative crop options to diversify rotations would be beneficial to the productivity and sustainability of the farming systems. Grain legume crops such as lentil, chickpea, and field pea should be reexamined and any promising varieties and technologies promoted widely, in addition to oilseed crops such as canola which is now grown extensively in medium-rainfall areas of Australia. Improved mechanical harvesting of lentil and chickpea should be a priority, as this is a major obstacle to their adoption.

Productive and persistent forage crops including legumes, once identified and verified, should be promoted widely. Both *Vicia* spp. and *Lathyrus* spp. have considerable potential to break the barley monoculture or replace fallow in the fallow–barley rotations common in dry areas (Ates et al. 2013). Government policy also has a role to play in regard to the production of alternative crops. Part of the dominance of wheat in some countries may be attributed to governments subsidizing wheat prices in an attempt at enhancing food security, in addition to low productivity and/or poorly developed markets for alternative crops.

9.9.3 Pest Management

While little change in the overall burden of weeds, insects, and diseases has been observed under ZT in Syria and Iraq, these could pose serious threats in localized areas, especially in high-rainfall zones where summer rainfall is more likely or under irrigation. In these cases, an integrated pest management system including crop rotation will help minimize their occurrence and impact. In general, spraying technology and practices are basic in the Middle East, and there may be greater reliance on the use of pesticides under ZT, so targeted training may be required to improve the efficiency of pesticide application within CA systems. Herbicide resistance has been a major issue in the CA systems of Australia requiring high levels of integrated weed management (Anderson and Angus 2011). However, the low level of herbicide use in the Middle East means this is not an immediate concern.

9.9.4 Farm Size

Another factor contributing to low adoption of ZT and other new agricultural technologies is that farm sizes have become very small (1–5 ha) after centuries of inheritance in countries like Jordan and Lebanon. In the absence of irrigation, these properties are often too small to generate a reasonable income for a family, and the owners have to seek employment in other enterprises to supplement their income. Often, these small farms are not a serious full-time endeavor but more a weekend activity or past time, in which case the efficiency and profitability of production are not always a high priority for the owner. By contrast, Australian farmers have increased their efficiency greatly by increasing their size and through increased mechanization improved their economy of scale. Small dryland properties in the Middle East are often planted to orchards or olives requiring low maintenance, but even in these cases, ZT and the use of forage legumes between trees can profitably replace tillage as reported by Jouni and Adada (2010). An important step in promoting adoption for small landholders in Lebanon, Jordan, and elsewhere will be working with machinery contractors who provide seeding services to these small farmers to develop their ZT awareness, knowledge, and skills.

9.10 Conclusions

Despite the challenges discussed above, many researchers, extensionists, and farmers are now convinced CA is a technology which is both profitable and sustainable for most cropping areas of the Middle East, and one of the few cropping methods capable of increasing the resilience of farming systems to annual weather variability associated with Mediterranean environments as well as any added stresses of climate change. With minor modifications and a modicum of flexibility, CA can be applied to a wide range of crops in diverse environments including irrigated conditions. ZT and early sowing deserve greater evaluation, promotion, and adoption across the dry areas of the world, particularly in developing countries. On the back of the success of the ACIAR project, other ICARDA projects have been recently funded to promote the adoption of CA in Morocco, Algeria, Tunisia, Egypt, Jordan, Lebanon, and Tajikistan, and there is also much interest from Iran, Palestine, Turkey, and Sudan. These and other CA projects will benefit from the lessons learned and the successful strategies used in Iraq and Syria. The three important elements of the success in Syria and Iraq were verifying and adapting the CA technologies to suit local conditions and farming systems, providing access to suitable ZT seeders, and facilitating and encouraging farmers to test the technology and promote it among themselves in a participatory approach.

While CA is a package of the three principles or pillars (ZT, soil cover, crop rotation), not all principles are equally important in all environments. In the dryland areas of the Middle East, as in southern Australia, ZT appears to be the most important pillar and farmers can reap significant benefits by adopting ZT, especially as this allows crops to be sown early. We recognize that ZT plus early sowing is not CA according to the rigid definition used by some authors, but it is a major step towards improving crop productivity, profitability, and sustainability, and one that many farmers can make with little risk of failure.

Acknowledgments The authors thank the Australian Centre for International Agricultural Research (ACIAR) and Australian Agency for International Development (AusAID) for support through the project CIM/2008/027 “Development of conservation cropping systems in the drylands of northern Iraq,” which funded much of this work since 2005. We gratefully acknowledge the support of our collaborating research and extension scientists, private consultants, agricultural companies, nongovernment organizations, seeder manufacturers, farmers, and ICARDA government liaison staff at Tel Hadya, for running of the extensive participatory extension programs in Iraq and Syria during 2006–2013. We thank Isam Bashour, Irfan Gültekin, and Yahya Shakhatreh for information on the CA situation in Turkey, Lebanon, and Jordan, respectively. We also want to recognize the many ICARDA farm operations staff that assisted in the extensive field experimental program at Tel Hadya—some are currently maintaining the long-term tillage experiments in Syria under difficult conditions.

References

Abdulradh MJ, Wegener MK, Shideed K (2012) Technical efficiency of wheat production under different cropping systems in Ninevah province, Iraq: a stochastic frontier production function analysis. Proceedings of 3rd international conference on conservation agriculture in southeast Asia, Hanoi Vietnam, 10–15 Dec 2012, pp 259–261

Alrijabo AS (2012) Effect of a new farming system (zero-tillage) on the growth, yield and its components of bread and durum wheat under supplementary irrigation area of Ninevah province. Proceedings of Minia international conference for agriculture and irrigation in the Nile Basin, pp 576–585

Alrijabo AS (2014) Effect of a new farming system (zero-tillage) on the growth, yield and its components of bread wheat, durum wheat and barley crops in the moderate rainfall area of Ninevah province. Mesop J Agric 42:1–16

Anderson WK, Angus JF (2011) Agronomy and cropping practices in semi-arid conditions in Australia. In: Bonjean AP, Angus WJ, van Ginkel M (eds) The world wheat book, vol 2. Lavoisier, Paris, pp 563–605

Ates S, Feindel D, El Moneim A, Ryan J (2013). Annual forage legumes in dryland agricultural systems of the West Asia and North Africa regions: research achievements and future perspective. Grass Forage Sci 69:17–31

Aw Hassan A, Shomo F, Iniguez L (2010) Trends in small ruminant meat production–consumption gaps in West Asia and North Africa implications for intra-regional trade. Outlook Agric 39:41–47

Bachour R, Jouni K, Estphan C, Skaff S, Hansmann B, Bashour I (2009) Field experiments on conservation agriculture in Lebanon. 10th international meeting on soils with Mediterranean type of climate, Beirut, 22–26 June 2009

Burvill GH (1979) Agriculture in Western Australia. University of WA Press, Leederville

Byerlee D, Hesse De Polanco E (1986) Farmers' stepwise adoption of technological packages: evidence from the Mexican Altiplano. Am J Agric Econ 68(3):519–527

Christiansen S, Bounejmate M, Bahhady F, Thompson E, Mawlawi B, Singh M (2000) On-farm experiments with forage legume-barley compared with fallow-barley rotations and continuous barley in north-west Syria. Exp Agric 36:195–204

D'Emden FH, Llewellyn RS, Burton MP (2008) Factors influencing adoption of conservation tillage in Australian cropping regions. Aust J Agric Resour Econ 52:169–182

Farooq M, Flower KC, Jabran K, Wahid A, Siddique KHM (2011) Crop yield and weed management in rainfed conservation agriculture. Soil Tillage Res 117:172–183

Gültekin İ, Arısoy RZ, Taner A, Kaya Y, Patigöç F, Aksoyak Ş (2011) Comparison of different soil tillage systems, under several crop rotations in wheat production at Central Anatolian Plateau in Turkey. Proceedings of 5th world congress on conservation agriculture, Brisbane, 26–29 Sep 2011, pp 98–99

Haddad N, Piggin C, Haddad A, Khalil Y (2014a) Conservation agriculture in West Asia. In: Jat RA, Sahrawat KL, Kassam A (eds) Conservation agriculture: global prospects and challenges. CAB International, Wallingford, pp 248–262

Haddad A, Loss S, Khalil K, Piggin C (2014b) Adoption of zero-tillage in the conflict zones of Syria. Proceedings of 6th world congress on conservation agriculture, Regina, Jun 2014 (in press)

Hajabbasi MA, Hemmat A (2000) Tillage impact on aggregate stability of a clay loam soil in central Iran. Soil Tillage Res 56:205–212

Hemmat A, Eskandari I (2004a) Conservation tillage practices for winter wheat–fallow farming in the temperate continental climate of north-western Iran. Field Crops Res 89:123–133

Hemmat A, Eskandari I (2004b) Tillage system effects upon productivity of a dryland winter wheat–chickpea rotation in the northwest region of Iran. Soil Tillage Res 78:69–81

Hemmat A, Eskandari I (2006) Dryland winter wheat response to conservation tillage in a continuous cropping system in north western Iran. Soil Tillage Res 86:99–109

Huggins DR, Reganold JP (2008) No-till: the quiet revolution. Sci Am 299:70–77

Jalili S, Fathi G, Fathi Y, AlRijabo AS, Piggin C, Desbiolles J (2011) Farmer innovation: seeder fabrication and uptake of zero tillage in Iraq. Proceedings of 5th world congress on conservation agriculture, Brisbane, 26–29 Sep 2011, pp 306–308

Jalili S, Fathi G, Fathi Y, Ahmed W, Al-Ghulami M, Kashmoula M (2014) Farmer adoption of zero-tillage in Mosul, Iraq. Proceedings of 6th world congress on conservation agriculture, Regina, June 2014 (in press)

Jouni K, Adada F (2010) Conservation agriculture in olive orchards in Lebanon. Poster presentation. The 4th Mediterranean meeting on conservation agriculture. Options Méditerranéennes, A no. 96, IV Rencontres Méditerranéennes du Semis Direct, Setif, 2010

Kassam A, Friedrich T, Derpsch R, Lahmar R, Mrabet R, Serraj R, Basch G, González-Sánchez EJ (2012) Conservation agriculture in the dry Mediterranean climate. Field Crop Res 132:7–17

Khalil A, Haddad A, Piggin C, Mona S (2013) Weed bank response to soil depth, tillage system and crop rotation. Res J Aleppo Uni 107:1–5

Lienhard P, Boulakia S, Legoupil JC, Gilar O, Seguy L (2013) Conservation agriculture in Southeast Asia. In: Jat RA, Sahrawat KL, Kassam A (eds) Conservation agriculture: global prospects and challenges. CAB International, Wallingford, pp 180–201

Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage systems in growing regions of Australia. Field Crop Res 132:204–212

Loss S, Feindel D, Sommer R, Haddad A, Khalil Y, Alrijabo AS, Piggin C (2013) The effect of conservation agriculture on soil fertility in northern Syria. Proceedings of American Society of Agronomy, Tampa Florida

Magnan M, Larson DM, Taylor JE (2012) Stuck on stubble? The non-market value of agricultural byproducts for diversified farmers in Morocco. Am J Agric Econ 94:1055–1069

Montgomery DR (2007) Dirt: the erosion of civilizations. University of California Press, Berkeley

Mrabet R (2007) Conservation agriculture in Morocco: a research review. In: Stewart BJ, Fares Asfary A, Belloum A, Steiner K, Friedrich T (eds) Proceedings of the international workshop on conservation agriculture for sustainable land management to improve the livelihood of people in dry areas. ACSAD and GTZ, Damascus, 7–9 May 2007, pp 183–208

Nurbekov A, Akramkhanov A, Lamers J, Kassam A, Friedrich T, Gupta R, Muminjanov H, Karabayev M, Sydyk D, Turok J, Bekenov M (2013) Conservation agriculture in Central Asia. In: Jat RA, Sahrawat KL, Kassam A (eds) Conservation agriculture: global prospects and challenges. CAB International, Wallingford, pp 223–247

Pala M, Harris HC, Ryan J, Makboul R, Dozom S (2000) Tillage systems and stubble management in a Mediterranean-type environment in relation to crop yield and soil moisture. Exp Agric 36:223–242

Piggin C, Haddad A, Khalil Y (2011) Development and promotion of zero tillage in Iraq and Syria. Proceedings of 5th World Congress on Conservation Agriculture, Brisbane, 26–29 Sep 2011, pp 304–305

Piggin C, Haddad A, Khalil Y, Loss S (2014) Evaluation of zero tillage for dryland cropping in northern Syria. Proceedings of 6th World Congress on Conservation Agriculture, Regina, Jun 2014 (in press)

Riehl S, Zeidi M, Conard NJ (2013) Emergence of agriculture in the foothills of the Zagros mountains of Iran. Science 341:65–67

Ryan J, Singh M, Pala M (2008) Long-term cereal-based rotation experiments in the Mediterranean region: implications for cropping sustainability. Adv Agron 97:273–318

Seid A, Piggin C, Haddad A, Kumar S, Khalil K, Geletu B (2012) Nematode and fungal diseases of food legumes under conservation cropping systems in northern Syria. Soil Tillage 121:68–73

Sommer R, Piggin C, Haddad A, Hajdibo A, Hayek P, Khalil Y (2012) Simulating the effects of minimum tillage and crop residue retention on water relations and yield of wheat under rainfed semi-arid Mediterranean conditions. Field Crop Res 132:40–52

World Bank (2008) World development report 2008: agriculture for development. World Bank, Washington, DC

Yau SK, Sidahmed M, Haidar M (2010) Conservation versus conventional tillage on performance of three different crops. Agron J 102:269–276

Yigezu Y, Mugera A, El-Shater T, Piggin C, Haddad A, Khalil Y, Loss S (2014) Explaining adoption and measuring impacts of conservation agriculture on productive efficiency, income, poverty and food security in Syria. In: Farooq M, Siddique KHM (eds) Conservation agriculture, chap. 10, Springer Science.

Chapter 10
Explaining Adoption and Measuring Impacts of Conservation Agriculture on Productive Efficiency, Income, Poverty, and Food Security in Syria

Y. A. Yigezu, A. Mugera, T. El-Shater, C. Piggin, A. Haddad, Y. Khalil and S. Loss

Abstract This study employs the Heckman selection model to identify factors affecting the adoption of zero tillage (ZT) and measure its yield, income, and consumption impacts among Syrian wheat producers. A stochastic production frontier model is also estimated to compare the productive efficiency of adopters and non-adopters. Model results show that participation in field days and hosting on-farm demonstration trials are among the most important variables that enhance adoption. ZT increases yield, consumption, and income and reduces income risk-lifting 57 % of the adopters out of poverty. A shift from conventional tillage (CT) to ZT would helps farmers to be more technically efficient in production and achieve current output levels with 22 % less inputs. Along with environmental benefits documented in existing literature, this study shows that ZT is one of the few technologies whose benefits can be justified on environmental, economic, and food security grounds. The policy implications of these results are that education and extension that encourage farmers to participate in field days and host demonstration trials on their own farms are essential in promoting ZT technology adoption. In-depth analysis of the trade-offs between crop residue retention and the resulting loss in livestock feed in mixed crop–livestock production systems is warranted.

Keywords Zero tillage · Conservation agriculture · Income · Efficiency · Food security · Stochastic frontier · Translog

---

Y. A. Yigezu (✉) · C. Piggin · A. Haddad · Y. Khalil · S. Loss
International Center for Agricultural Research in the Dry Areas (ICARDA),
P.O. Box 950764, Amman 11195, Jordan
e-mail: y.yigezu@cgiar.org

A. Mugera
The UWA Institute of Agriculture & School of Agricultural and Resource Economics,
The University of Western Australia Crawley, WA 6009, Australia

T. El-Shater
International Center for Agricultural Research in the Dry Areas (ICARDA), PO Box 5466,
Aleppo, Syria

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_10

10.1 Introduction

Severe land degradation and increasing scarcity of water raise concerns about the future of agriculture, especially crop production, in dryland areas of the Arab region. Conservation agriculture (CA), defined as cropping with minimal soil disturbance, stubble retention, and wide rotations (Friedrich et al. 2012), is believed to be a promising technology that can provide some solutions for these long-standing agricultural challenges in the region. However, CA is often looked upon with a high degree of skepticism mainly because of lack of information and evidence, particularly on its effectiveness and profitability relative to traditional tillage and other agronomic practices (Belloum 2014).

Globally, about 9 % of total cropland was estimated to be under CA in 2012 but not necessarily the entire CA "package" (Friedrich et al. 2012). Zero tillage (ZT), an important cropping technology in its own right, as well as a defined component of CA, has been widely adopted in North and South America and Australia (Fulton 2010; Horowitz et al. 2010; Llewellyn et al. 2012). However, with the exception of a few success stories in certain pockets, South Asia and Africa (Friedrich et al. 2012; Giller et al. 2009) and West Asia (Piggin et al. 2011) have not yet benefitted from the advances of CA technology in general and ZT in particular.

ZT is an agricultural practice or technology where seed and fertilizer are sown through remaining stubble from the previous crop into narrow slits in the soil, opened by special narrow points and tines on a ZT seeder, without any prior tillage. It is also known by various other names, including no-till (NT), direct seeding (DS), and minimum tillage (MT). Adoption of ZT conserves soil moisture and reduces fuel, labor, and machinery costs (Ribera et al. 2004). In addition, elimination of plowing and retention of roots and some stubble from previous crops can reduce wind and water erosion and provide significant environmental benefits. ZT can often lead to higher yields, increased net returns, and reduced yield and income variability. As in many high-income countries, CA can lead to benefits for resource-poor farmers and consumers, and improve rural and national economies in low- and middle-income countries in the Middle East, Asia, and Africa, especially those dryland regions (ICARDA 2012). ZT is thought to be the most important component of CA for the Middle East, providing immediate benefits to farmers (Chap. 9).

The aim of this study was to quantify the benefits of adopting ZT on rural household wheat production in Syria. In particular, we investigated the determinants of ZT technology adoption and the impact of adoption on area of land under ZT, yield, net income, and consumption. We also investigated the productive efficiency of ZT adopters and nonadopters under the assumption that ZT technology is available to all farmers.

In view of the tremendous skepticism about the efficacy and profitability of CA, especially in the context of mixed crop–livestock production systems, this chapter provides important empirical evidence of the technical and economic benefits of ZT. The results are also important for policy makers, researchers, extension offices, government and nongovernment development organizations, and development agents working in Syria and more widely in the Middle East and other areas with similar agroclimatic and production systems.

10.2 CA and ZT: Brief Synthesis of the Literature and Syrian Experience

10.2.1 Synthesis of the Literature

CA is a technology package that involves a range of interrelated practices such as ZT or NT for minimum soil disturbance, crop residue retention for soil cover (mulching), and diverse crop rotation, mainly between cereals and leguminous crops for nitrogen fixation and control of crop diseases and pests. These practices have been developed and promoted to farmers around the world as a response to food security, farm profitability, and land degradation concerns (Pannell et al. 2013). There is considerable literature on CA practices: Knowler and Bradshaw (2007) comprehensively reviewed and synthesized recent research on farmer adoption of CA and Pannell et al. (2013) synthesized farm-level economics of CA for resource-poor farmers. The general consensus emerging from those reviews was that there are few, if any, universally accepted determinants for the adoption of CA practices. This is partly due to heterogeneity between regions, farmers in a particular region, and institutional factors that influence technology adoption. The economic outcomes of CA tend to be specific to particular people, places, and situations. This highlights the importance of considering site-specific conditions in promoting and determining the financial and economic attractiveness of CA and, more specifically, ZT.

In general, factors that influence the adoption of CA practices and, more specifically, ZT can be broadly categorized into four groups: (1) farmer and farm household characteristics such as age, education, and experience; (2) farm biophysical characteristics such as farm size, area planted, and soil type; (3) farm financial and management characteristics such as use of hired labor, farm profitability, and expenditure on key inputs; and (4) exogenous factors such as input and output prices, and the use and availability of extension and technical assistance. The characteristics of the innovation (i.e., practices or components being adopted), especially its relative advantage over existing practices and trialability, are other key factors. Relative advantage is the degree to which an innovation is perceived as being better than the practice it supersedes, and trialability is the ease of physically establishing a trial and the factors that influence the ability to learn from a trial (Pannell et al. 2006). There is empirical evidence that adoption is also affected by risk-related issues, especially perceptions about the riskiness of the technology, attitudes toward risk, and the option value of delayed adoption (Greiner et al. 2009). From a theoretical perspective, it is assumed that farmers will only adopt a new innovation if they expect it will help them achieve their social, economic, or environmental goals.

Adoption of a new technology package (involving a single or several components) is a dynamic process that involves three interrelated decisions: (1) the choice of whether to adopt the technology components and in which sequence or combination, (2) the extent of adoption such as how much land to allocate to new and old technologies, and (3) the intensity of adoption such as the rate of fertilizer to apply per hectare (Jha et al. 1990; Smale et al. 1991). The combination of these three decisions comprises the technology adoption decision and, aggregated over farms to the national area, is the diffusion of the technology. Final adoption is defined as the degree of use of a new technology in the long-run equilibrium when there is full information about the technology and its potential (Feder et al. 1985).

This study focuses on ZT, which is the technology being verified and promoted in Syria, along with associated enhancements of early sowing and reduced (appropriate) seed rates (Piggin et al. 2011). There is empirical evidence that the main drivers of adoption of ZT (or at least reduced tillage) are reduced costs of production, increased yields, and increased net farm return. For example, Sidhu et al. (2010) estimated the economic benefits from reduced tillage in wheat production in Punjab, India, and found that profit increases were attributed to cost savings. Reduced costs come mainly because of labor savings in land preparation as well as in cases where herbicide use replaced manual weeding. A review of several studies on the economics of ZT in the Indo-Gangetic Plains consistently showed benefits of ZT adoption in terms of cost savings and increased yields (Erenstein and Laxmi 2008).

10.2.2 History of CA in Syria

The governments of Syria and Iraq began to introduce CA in general, and ZT and a few other components of CA in particular, around 2001 and 2005, respectively, using local resources and support and funding from international development organizations, including the Arab Agency for Agricultural International Development (AAAID), Arab Center for Studies of Arid Zones and Dry Lands (ACSAD), the Australian Center for International Research (ACIAR), and the Australian Agency for International Development (AusAID). ZT was a fairly recent introduction in Iraq, and its adoption and impacts are still relatively low. However, in Syria, given the awareness created through earlier efforts since 2001 by the government through funds from AAAID and ACSAD, and the major push to evaluate, develop, and promote ZT and associated crop management technologies in the ACIAR–AusAID project since 2005, ZT has been well received by a relatively large number of farmers over a fairly short duration. The success of the ACIAR–AusAID project at enhancing the adoption of ZT has been attributed to five main factors (Piggin et al. 2011):

1. Local research verification and adaption of ZT.
2. Development of local production of effective ZT seeders at affordable prices.
3. A major participatory extension program where local ZT seeders were made available to farmers without cost or incentive payment to test on their own farms.
4. A series of major on-farm field days and walks with local project partners to display and discuss the technology.
5. Flexibility in allowing demonstration farmers to choose the adoption of ZT alone or in combination with other improved crop management options, such as early sowing and low seed rates, and encouraging retention of as much residue as possible.

Survey results from Syria showed that ZT adoption is taking place rapidly (Piggin et al. 2011). However, it remains to be confirmed and quantified whether ZT is attractive in the Syrian context with clear social, economic, and environmental benefits.

From discussions and experiences with Syrian farmers, one of the major constraints for adoption of ZT technology was the lack of adapted and affordable ZT seeders. In response, the ACIAR–AusAID project discussed and demonstrated ZT seeding technologies and requirements with local seeder manufacturers in 2007/08. Various prototype ZT seeders were developed with modifications to suit local conditions, including wide (~4 m) trailed machines for extensive areas in eastern Syria and narrow (~2.5 m) three-point linkage machines with spring-loaded tines for rocky areas in the north and east. The efficacy of those machines was proven in studies at the International Center for Agricultural Research in the Dry Areas (ICARDA) research station in Tel Hadya Village in Aleppo Province and in farmer fields across the dryland cropping areas of the northern half of Syria. As a result, the total number of locally made ZT seeders has grown from 3 in 2007 to 105 in 2011, of which 23 were privately owned by farmers, with the rest owned by project implementers (ICARDA, Aga Khan Foundation (AGF), and Aleppo Agricultural Machinery Center) and private rental companies. A system was developed where farmers who did not own seeders either rented or borrowed from the project implementers, contractors, or seeder-owning farmers. By 2010/11, the total area under ZT had grown to about 15,000 ha, and it is estimated that the areas may have reached 50,000 ha in 2012/13.

10.3 Data

Data for this study come from a farm survey conducted by ICARDA scientists in 2011 in 28 villages distributed in 17 districts and 7 governorates in Syria. The cluster sampling procedure was used to collect data where different administrative units were used as clusters. Using power analysis (Cohen 1988), the minimum sample size required under the simple random sampling technique for ensuring 95 % confidence and 3 % precision levels in capturing up to 10 % adoption was determined to be 374. Accounting for the design effect, the minimum sample size under the cluster sampling technique required for ensuring the same levels of confidence, precision, and adoption levels was estimated to be 459, with an optimal cluster size of 17.44. The primary sampling units (PSUs) were the villages. Accordingly, a decision was made to take a random sample of 500 farmers uniformly distributed across all 28 sample villages (about 18 farmers in each village). To avoid the risk of not having adequate representation of ZT adopters, all 320 farmers known to be using the technology by the project were also purposively selected. These farmers had been incorporated into the project by ICARDA and local extension offices over the years; all had tried ZT technology at least once, and most were still using it. Therefore, the total sample was 820 households. Details of the sampling design are summarized in Table 10.1.

Table 10.1 Survey details. (Source: survey data)

Governorates included in the sample	Districts included in the survey						
	District name	Number of villages included in the sample	Total population in sample villages	Sample size from the district:			
				Whole sample		Randomly selected	
				Total	Wheat producers[a]	Total	Wheat producers
Aleppo	Al Bab	1	650	36	25	18	12
	Ein Al Arab	2	700	40	31	36	21
	Sama'an	2	800	26	19	36	22
	Sfiera	1	900	43	33	18	11
Al-haska	Kamshly	4	347	96	75	70	43
	Tel-Hamis	1	66	31	23	18	11
	Malkia	1	190	25	19	18	12
	Amoda	1	270	21	16	18	11
	Hasaka	1	700	62	49	18	12
	Ras-Alain	1	600	22	17	18	11
Edleb	Khan-Shikon	1	400	23	17	18	11
	Almara	4	3270	174	131	70	43
Hamah	Slmiah	3	2400	94	71	54	33
	Sabora	2	1200	50	38	36	22
Homs	Ksier	1	380	26	18	18	12
Deraa	Alshajra	1	410	25	19	18	10
Alswieda	Salked	1	800	26	20	18	11
Total		28	14,083	820	621	500	308

[a] Only 621 wheat producers out of a total of 800 sample farmers are included in this analysis

This study focuses on the impact of ZT on yield, income, consumption, and productive efficiency among Syrian wheat farms. From the 820 sample farms, 621 were wheat producers; hence, only observations that relate to those are included in the rest of the analysis.

10.4 Methods

10.4.1 *Explaining Adoption and Measuring Impacts*

ZT technology was popularized and promoted in Syria through the project with on-farm trials for the purpose of demonstration and also through a series of field days organized to achieve maximum exposure. However, not all farmers may have had an equal chance for exposure to the technology and adoption due to differences in access to information, knowledge, skills, and financial resources. Therefore, measuring the effect of adoption of ZT on outcomes of interest is not straightforward because it may be a combined result of an individual farmer's decision to adopt technology without any exposure through field trials, as a result of exposure, or a combination of both. We also expected selectivity bias in our data because only 500 households were randomly selected; the other 320 elite farmers were purposively included in the sample to minimize the chance of not having enough adopters. Therefore, sample selection correction methods were required to deal with those challenges (Greene 1997).

Supporting basic agricultural production and meeting food security needs in a sustainable manner are among the major benefits of ZT. Assuming farmers are profit maximizers and price-takers for their inputs and outputs (Nicholson 2005), many studies use yield as one of the most important indicators to investigate the impacts of ZT technology (Ribera et al. 2004; Endale et al. 2008; Smiley and Wilkins 1993; Wagger and Denton 1989) while others use net returns as the main driving factor (Bremer et al. 2001; Deen and Kataki 2003; Lankoski et al. 2004; Williams et al. 2009; Harper 1996). Given the importance of wheat in both consumption and income in the country, net farm income and consumption are used, in addition to yield improvements, as indicators for measuring food security and poverty impacts of ZT technology among Syrian wheat farms.

The Heckman two-step procedure was used in this study to evaluate the effect of various farm characteristics on the decision to adopt ZT technology and its outcome on the area of crop dedicated to ZT, expected yield, net income per hectare, and per capita consumption of wheat products (Heckman 1979). In the first stage, the probit model was used to estimate the selection equation that determines the effect of independent variables on the probability of a farmer choosing to adopt ZT technology or not:

$$\begin{aligned} &\text{Prob } (Z=1\,|\,W) = W_i\beta + u_i = \phi(W_i\beta) \\ &\text{Prob } (Z=0\,|\,W) = 1-\phi(W_i\beta), \end{aligned} \tag{10.1}$$

where Z is the observed behavior of a household with respect to ZT adoption, taking a value of 1 if adoption is observed and 0 otherwise; W is a vector of socioeconomic characteristics of households and their heads, including institutional variables and biophysical characteristics of the farm that are believed to explain adoption behaviors (see Table 10.2); and β is a vector of parameters to be estimated and Φ is the standard normal cumulative distribution function. As all farmers do not have equal exposure to the technologies, variables that imposed exclusion restriction were included to improve the performance of the model. The choice of such variables was made in such a way that they only affected the selection variable and not the outcome variables. To this effect, three binary variables which captured whether or not the farmers hosted demonstration trials, participated in field days, or participated in both demonstration trials and field days were included in the selection model as exclusion restrictions.

In the second stage, linear regression models were used to explain the effects of independent variables on area under ZT cultivation, yield, net income, and consumption. The probit model in stage 1 was used to selects observations in the samples to be estimated by the ordinary least squares (OLS) regression models. This implies that the outcomes of the decision on the area size allocated to ZT, yield, net income, and consumption are observed only when the farmer decides to adopt the

Table 10.2 Explanatory variables included in the models. (Source: survey data)

Variables		Average values for entire sample of 621 farmers			Average values for random sample of 308 farmers		
	Unit	Adopters	Nonadopters	Total	Adopters	Nonadopters	Total
Number of farmers	Number	249	372	621	15	293	308
Average farming experience of household head	Year	23.7	27.5	26.0	18.7	26.8	26.5
Average education level of household head	Year	4.2	3.0	3.5	3.9	2.8	2.9
Proportion of farmers with salinity affected soil	%	5.2	23.7	16.3	0	27.3	26
Average time since farmer started using ZT	Year	2.1	0	0.8	2	0	0.1
Proportion of farmers in zone 1[a]	%	33	36	34.8	85.7	72.3	73.4
Proportion of farmers who hosted demonstration trials	%	65.9	8.9	31.7	0	0	0
Proportion of farmers who participated in field days	%	5.2	11.6	9.0	0	0	0
Proportion of farmers who participated in field days and hosted trials	%	22.9	0.8	9.7	0	0	0
Total area cultivated (average)	ha	40	19.2	27.5	10.7	17.9	17.5
Total wheat area cultivated (average)	ha	20.8	8.7	13.6	8.7	7.6	7.7
Proportion of farmers who know ZT technology	%	100	59.4	75.5	100	50	52.6
Average distance to nearest input market (km)	km	13.8	15.4	14.7	13	18	17.7
Average value of total assets (million SL)	SL	1.56	1.59	1.58	1.92	1.59	1.58
Total number of plots	Number	2.39	1.9	2.1	2.1	1.8	1.83

Table 10.2 (continued)

Variables		Average values for entire sample of 621 farmers			Average values for random sample of 308 farmers		
	Unit	Adopters	Nonadopters	Total	Adopters	Nonadopters	Total
Average length of time since farmer first heard about ZT technology	Year	2.3	1	1.6	2.2	1	1.1
Average application rate of nitrogen fertilizers	kg ha^{-1}	70.9	96.5	86.2	72.9	93.5	91.8
Average application rate of phosphorus fertilizers	kg ha^{-1}	36.9	54.8	47.6	38.9	50.2	49.3
Average amount of labor used	h ha^{-1}	22.7	36.6	31	17	36	35
Average application rate of seed	kg ha^{-1}	110.7	145.1	131.3	119	145	143
Area under ZT	Ha	15.2	0	6.1	8.6	0	0
Proportion of area under ZT technology	%	73.4	0	32.4	95.2	0	8
Yield	kg ha^{-1}	1727.1	1242.5	1436.8	1740	1251.8	1275.5
Consumption	kg $year^{-1}$	79.6	48.6	61	101	48	50.7
Wheat net income	SL ha^{-1}	37,995	27,335	31,610	38,280	27,539	28,062
Total household income	SL	401,323	296,703	303,776	344,416	228,475	234,121

ZT zero tillage, *SL* Syrian Lira

[a] Syria is divided into five agroecological zones, where zone 1 represents the relatively wetter areas with average annual precipitation of about 350 mm but 33 % more likely to be less than 350 mm and zone 2 represents areas with average annual rainfall of about 250 mm with more than 33 % probability of falling below 250 mm

technology (i.e., *Z* takes a value of 1 in equation 10.1). The regression equations can be expressed as:

$$Y_i = \begin{cases} X_i\gamma + \varepsilon_i \text{ if } Z_i^* > 0 \\ 0 \text{ if } Z_i^* \le 0, \end{cases} \tag{10.2}$$

where Y_i is either one of the dependent variables of the outcome equations: total area under ZT, consumption per capita, yield or net income; X_i is a vector of covariates that is assumed to contain all the variables in the vector W_i plus some more variables, including the inverse Mills ratio (IMR) derived from the first-stage estimation which corrects for selectivity bias and endogeneity (Greene 1997); γ is a vector of parameters to be estimated. In the two equations, μ_i and ε_i are error terms that are assumed to be bivariate normal with mean zero and covariance matrix

$$\begin{bmatrix} \sigma_\varepsilon & \rho \\ \rho & 1 \end{bmatrix},$$

where σ_ε and ρ are standard deviation of ε_i and correlation between μ_i and ε_i. The two error terms are assumed to have a nonzero correlation.

Sample selection bias was tested by determining if the coefficient of IMR equals zero. Rejection of zero coefficients would confirm sample selection bias and therefore estimation of the regression with OLS without correcting for sample selection bias would produce inconsistent and biased estimates. Failure to reject the null hypothesis that the coefficient of IMR is zero would imply that the two error terms are not correlated and therefore OLS would produce consistent and unbiased estimates (Lennox et al. 2012). The R software and the sample selection package were used to estimate the models (Toomet and Henningsen 2008).

10.4.2 *Measuring Productive Efficiency*

A cross-sectional version of the stochastic production frontier (SPF) approach was used to investigate the effect of adoption of ZT on production efficiency and resource use of wheat farmers. The general model can be written as: $Y_i = X_i\beta + v_i - \mu_i$, where Y_i denotes the output of the *i*th farm; X_i is a vector of inputs and other input control variables; and β is a vector of unknown parameters to be estimated; v_i is a random error and μ_i is a nonnegative, independently distributed random error associated with the technical inefficiency of the *i*th farm. The random error term takes care of the stochastic nature of the production process and possible measurement errors of inputs and outputs (Bogetoft and Otto 2011). Following Battese and Coelli (1995), the inefficiency term is specified as follows:

$$u_i = Z_i\delta + \omega_i, \tag{10.3}$$

where Z_i is a vector of variables which explain technical inefficiency differentials among farmers; δ is a vector of the associated parameters to be estimated; and ω_i is a random variable defined by the truncation of the normal distribution with mean zero and variance σ^2, where the point of truncation is $-Z_i\delta$ such that $\omega \geq Z_i\delta$. Technical efficiency (TE_i) for each decision making can then be computed as:

$$TE_i = \exp(-u_i \mid v_i - u_i). \tag{10.4}$$

Technical efficiency (TE) scores for each farmer take values between 0 and 1. The closer the TE scores to 1, the higher the efficiency. In this specification, the stochastic production function and the technical inefficiency model are estimated simultaneously by the maximum likelihood method (Coelli 1992).

Estimation of SPF requires specification of the functional form of the production function. The Cobb–Douglas and translog functional forms are the most commonly used specifications in empirical analysis. However, the translog specification is often preferred over the Cobb–Douglas specification because it is more flexible and can be understood as a second-order Taylor's series approximation to any production frontier (Wilson et al. 2001; Liu and Juzhong 2000; Abdulai and Eberlin 2001).

The translog production function is used in this study to examine the relationship between output and inputs. The general form of the empirical model can be expressed as:

$$\ln\ Y_i = \beta_0 + \sum_i^4 \beta_i \ln X_i + 0.5\sum_i^4\sum_j^4 \beta_{ij} \ln X_i \ln X_j + \sum_i^3 \lambda_i D_i - \mu_i + v_i, \quad (10.5)$$

where Y_i is the value of output (yield) for farm *I*; X_i is the vector of inputs (seed, nitrogen, phosphorus, and labor) to the production process; D_i are binary variables (soil depth, soil salinity, and seed variety) used to control for land and seed quality; and $(-\mu_i + v_i)$ is the composite error term, which is composed of $-\mu_i$ (the technical inefficiency component) and v_i (the random error component). The technical inefficiency in production is often explained by farmer characteristics and management practices used. In this study, we use the following regression to capture this relationship:

$$u_i = \alpha_0 + \beta_{\text{ZT}} ZT_i + \beta_{\text{PD}} PD_i + \beta_{\text{CR}} CR_i + \beta_{\text{VR}} VR_i + \beta_{\text{EDU}} EDU_i + \beta_{\text{EX}} EX_i + \omega_i, \quad (10.6)$$

where *ZT* is a binary variable indicating whether or not ZT is adopted, *PD* is a binary variable indicating early or late planting, *CR* is a binary variable indicating if crop residue from the previous season was used for grazing, *VR* is a binary variable indicating whether improved or local seed variety was used, *EDU* is a continuous variable for years of schooling, and *EX* is a continuous variable indicating years of experience in farming. In this formulation, a negative sign of an element of estimated parameters indicates a variable with a positive influence of TE. However, because the translog parameters are not directly interpretable, the output elasticities with respect to the inputs are computed as:

$$\partial \ln Y_i / \partial \ln X_i = \beta_i + \sum_{j=1}^{n} \beta_{ij} \ln X_J \geq 0, \forall i. \quad (10.7)$$

The frontier package in R was used to estimate the SPF (Coelli and Henningsen 2011).

10.5 Results and Discussion

Results from the Heckman two-stage estimation are presented in Table 10.3. The coefficient estimates on the IMR included, as an explanatory variable in the second-stage estimation of the outcome equations on the area under ZT, net income, and yield variables (columns labeled R2–R4 in Table 10.3) are statistically significant, indicating the presence of selection bias and hence the need for a selection model. However, the coefficient on the IMR included in the consumption equation is insignificant, indicating that selection bias is not a problem and hence OLS would give consistent estimates (Lennox et al. 2012). We conjecture here that this is likely because consumption is affected by food preference issues that are independent of whether an individual was an adopter of ZT technology or not. The test of multicollinearity rejects any presence of collinearity between variables. The Breusch–Pagan test for constant error terms is rejected and the robust OLS method is used to estimate the equation.

10.5.1 Explaining the Decision and Intensity of Adoption of ZT

Coefficient estimates of the selection equation in the Heckman model (column R1 in Table 10.3) show that hosting a demonstration trial on a farmer's own land and participation in field days would positively and significantly increase the probability of adoption by 0.84 and 0.35, respectively. These results clearly indicate the importance of knowledge of the technology, and experience sharing in promoting the adoption of the new technology, which is consistent with theoretical expectation. Getting involved in both demonstration trials and field days would increase the probability of adoption by 0.77. This result is plausible, but the fact that the probability of a person involved in both demonstration trials and field days is less than the probability of one who is involved only in demonstration trials is counterintuitive. A possible but not very convincing explanation for this result is that if the farmer heard about a bad experience during their field days (even if it was only one among many success stories), it might erode their confidence and lead to a negative effect on their adoption decision.

A unit increase in yield and total wheat area would lead to an increase in the probability of adoption by 0.52 and 0.09, respectively. The fact that higher yields lead to increased probability of adoption suggests that farmers may be adopting ZT as a mitigation strategy against low yields. Moreover, the positive and significant probability of adoption due to ownership of larger wheat farms is consistent with theoretical expectation as farmers would be more willing to invest in ZT seeders if they can crop large areas and make more rapid savings in fuel and labor costs by eliminating tillage than smaller farmers.

A unit increase in years of experience and the presence of salinity in the soil reduced the probability of adoption by 0.19 and 0.18, respectively. The negative coefficient on the farmer experience variable might be an indication that younger farmers (who are relatively less experienced) might be the ones with the highest tendency to adopt the new technology. Several young farmers involved in the project anecdotally related that some older members of their families and/or villages were pessimistic about any positive outcomes during early efforts to test and adopt ZT.

Table 10.3 Coefficient estimates of the Heckman selection models

Variables	Robust OLS results		Outcome equations						Selection equation	
	R5		R4		R3		R2		R1	
	Consumption		Total yield (kg farm^{-1})		Net wheat income (SL farm^{-1})		Wheat area under ZT technology		Adoption dummy	
	Coef.	Std. Er.	Coef.	Std. Er.	Coef.	Std. Er.	Coef	Std. Er.	Coef.	Std. Er.
Education (year)	−0.0240	0.0448	0.0436	0.0543	0.0657	0.0578	0.0659	0.0803	0.1725	0.1880
Experience (year)	−0.0767	0.0386*	0.2032	0.0446***	0.1857	0.0477***	−0.2093	0.0672***	−0.5377	0.1537***
Distance to input market (km)	–	–	−0.0971	0.0464**	–	–	0.0597	0.0680	−0.1604	0.1354
Total Yield (kg farm^{-1})	–	–	Dependent variable		–	–	0.2930	0.0966***	1.4371	0.2572***
Net income (SL)	0.1888	0.0635***	–	–	Dependent variable		–	–	–	–
Demonstration trials (1=yes; 0=no)	–	–	–	–	–	–	–	–	2.8181	0.2123***
Field days (1=yes; 0=no)	–	–	–	–	–	–	–	–	0.9181	0.2618***
Both demons and field days (1=yes; 0=no)	–	–	–	–	–	–	–	–	3.3539	0.3613***
Value of total assets (SL)	−0.0213	0.0292	−0.0331	0.0338	−0.0462	0.0362	0.0745	0.0503	0.1392	0.1055
Total cultivated area (ha)	−0.0765	0.0220***	0.0531	0.0443	0.0539	0.0474	−0.3097	0.0632***	−0.0705	0.1380
Wheat area (ha)			0.6967	0.1208***	0.6871	0.0592***	0.7934	0.1068***	0.2525	0.1527*
Fertilizer (kg)	–	–	0.0531	0.0116***	–	–	–	–	–	–
Seed (kg)	–	–	0.1069	0.0761	–	–	–	–	–	–
Labor (h)	–	–	−0.0788	0.0580	–	–	–	–	–	–
Wheat area under ZT	0.2057	0.0194***	0.1419	0.0362***	0.1341	0.0379***	Dependent variable		–	–

Table 10.3 (continued)

Variables	Robust OLS results		Outcome equations						Selection equation	
	R5		R4		R3		R2		R1	
	Consumption		Total yield (kg farm^{-1})		Net wheat income (SL farm^{-1})		Wheat area under ZT technology		Adoption dummy	
	Coef.	Std. Er.	Coef.	Std. Er.	Coef.	Std. Er.	Coef	Std. Er.	Coef.	Std. Er.
Soil salinity (1 = yes; 0 = no)	–	–	0.1880	0.1109*	0.0656	0.1143	0.0052	0.1624	−0.5652	0.2830**
Zone (1 = zone 1; 0 = zone 2)	–	–	−0.1351	0.0566***	−0.1690	0.0590***	−0.0062	0.0836	−0.0761	0.1781
Total number of plots (number)	–	–	0.0394	0.0188**	0.0471	0.0193***	0.1107	0.0270***	−0.0841	0.0485*
Duration since starting using ZT (year)	–	–	0.1602	0.0816**	0.2615	0.0808***	0.0202	0.1174	–	
Inverse Mills ratio (λ)			−0.3866	0.0583***	−0.4031	0.0480***	0.4562	0.0761***	NA	
Constant	2.5451	0.7770***	6.7982	0.6457***	10.3297	0.5215***	−2.7170	1.0360***	−11.9203	2.4833***
Rho	NA		−0.9489		−0.9246	–	0.7709	–	–	–
Sigma	NA		0.4074		0.4360	–	0.5918	–	–	–

Description of dependent variables

Yield = natural logarithm of wheat yield (kg farm^{-1}); consumption = natural logarithm of per capita wheat consumption (kg year^{-1}); net income = natural logarithm of net income from wheat production *SL*; proportion of area under *ZT* (%) = % of wheat area under *ZT*; Adoption dummy = dummy variable for adoption of *ZT* (1 = yes and 0 = no)

NA not applicable, *OLS* ordinary least squares, *SL*

*significance at 0.1 level; **significance at 0.05 level; ***significance at 0.01 level

The negative coefficient on the salinity variable suggests that farmers with salinity problems are unlikely to adopt ZT technology relative to those without salinity problems. This could be because farmers with salinity problems use irrigation and have to cultivate and create furrows for supplying and draining water and hence ZT might not be appropriate. This subject needs further investigation.

The results show that in this Syrian case, there was no empirical evidence to support the hypothesis that farmers' formal education and wealth (as measured by value of total assets) have significant effects on the probability of adoption of ZT. The insignificant coefficient estimates may not necessarily be counterintuitive. While farmers with less knowledge of the technology might think otherwise, ZT sowing is not crop-, soil-, or scale-specific. For farmers already growing dryland crops, ZT can be a simple alternative to conventional cultivation, provided that there is access to personal, borrowed, or rented ZT seeders, with few changes required to other cropping operations.

In terms of intensity of adoption, factors that positively and significantly affected the area under ZT included yield, wheat area, and number of plots. These results are consistent with expectations that farmers with larger wheat areas and many fields are most attracted to ZT to simplify sowing operations and maximize profit. The positive and significant coefficient on the yield variable suggests that farmers would put more land under ZT as a mitigation measure against the risk of poor yields. On the other hand, increased years of experience in farming and total area cultivated lead to less land area dedicated to ZT cultivation. As with adoption, this may be because younger (and hence relatively less experienced) farmers might be less fixed on cultivation, understand the ZT technology better, and have a higher tendency to adopt. The fact that farmers with larger land areas tend to allocate less land for ZT is counterintuitive and needs further exploration.

10.5.2 Impacts of ZT on Yield, Production, and National Food Security

For ZT adopters, yield is positively and significantly affected by experience, area of land under ZT, area under wheat, number of plots, soil salinity, fertilizer, and duration of time since the farmer started using the ZT technology. While the main benefit of ZT, at least in the first few years, is in terms of fuel saving and yield advantage in most seasons—due to soil moisture conservation and early sowing because there is no cultivation—in the long run, it also leads to improved soil health, fertility, and moisture-retention capacity, all of which have a positive influence on yield. The positive and significant coefficient on wheat area shows that larger wheat farms are more productive per unit area than smaller farms. There is an age-old debate on this subject where this result is consistent with a number of studies, but others also argue otherwise (e.g., Barrett et al. 2010; Assunção and Braido 2007; Lamb 2003; De Janvry et al. 1991; Feder 1985; Carter 1984). The positive sign on the coefficient for soil salinity is counterintuitive, but one possible explanation is that areas where there is higher salinity (which would be positively correlated with the amount of irrigation water used) might have higher yields. The positive and significant coefficients on the duration since starting using ZT and number of plots point to the importance of the farmer having the "know-how" of ZT. Intuitively, it is likely that farmers who have been using ZT technology on many fields or plots over a longer duration and on a large area of land will have a better configuration of input combinations to achieve higher yields.

The marginal product of an input can be computed as the product of the estimated elasticity and the ratio of output to input. The yield elasticity of the proportion of area under ZT is 0.14. This translates into a yield gain of 465 kg ha^{-1} (31 % increase) by shifting from conventional tillage (CT) to ZT - quite an improvement in a region where average yield among users of CT is only 1317 kg ha^{-1}. Based on the random sample of 308 farms, ZT technologies are currently used on 5 % of the 1.52 million ha of wheat in the study region. Nationally, this represents a 2 % increase in total domestic wheat supply, which is very small. However, if ZT fully replaces CT, it has the potential to increase this figure by up to 31 %—a substantial gain in the overall effort toward national food security.

10.5.3 Impacts of ZT on Income, Poverty, and Wheat Consumption

10.5.3.1 Impact on Net Wheat Income

For adopters of ZT, the model results show that experience, area under ZT, wheat area, number of plots, and duration since starting using ZT all have positive and significant effects on net wheat income. These results suggest that experience in agriculture in general and duration of familiarity with ZT technologies are instrumental in taking full advantage of ZT, especially in cost savings. Larger wheat areas are likely to lead to higher net wheat income, showing the presence of scale economies. The coefficient estimate on the area under ZT shows that a 1 % increase in the area under ZT leads to a 0.13 % increase in net wheat income, which is equivalent to US$ 194 ha^{-1} or 29 % higher net wheat income than cultivation using CT. Therefore, the additional average household income generated by the adoption of ZT technology is about US$ 1180 year^{-1} or US$ 3.23 day^{-1}, which are 25 % higher than that of the nonadopters. This is equivalent to an income gain of about US$ 0.46 cents per capita day^{-1}. Considering the poverty line for the country, by adopting ZT, 57 % of adopter farm households (among the 308 randomly selected wheat producers) joined households above the poverty line.

The simple bivariate comparison (without correction for selection bias) also shows that ZT technology has increased the average income of adopter households living below the poverty line when compared to nonadopters in the same poverty category (Table 10.4). However, there is no evidence that the new technologies increased the average income of adopter households living above the poverty line relative to nonadopters in the same income group. While the results from the bivariate analysis show the potential of ZT technology in combating poverty, they need to be used with caution as no correction for selection bias was made. The stochastic

Table 10.4 Poverty status of farmers by adoption category. (Source: survey data)

Poverty status(US$ per capita day^{-1})	Adopters		Nonadopters		F-stat (sign.)	Total sample
	Average income ($)	%	Average income ($ PPP)	%		Average income($ PPP)
All income groups	1.71	33	1.31	67	11.1***	1.48
Above poverty line[a]	2.35	56.6	2.23	43.9	0.32	2.29
Below poverty line	0.87	43.4	0.59	56.1	105.49***	0.70

PPP purchasing power parity

*significance at 0.1 level of the K–S two-sided statistic; **significance at 0.05 level of the K–S two-sided statistic; ***significance at 0.01 level of the K–S two-sided statistic

[a] The poverty line for Syria is US$ 1.25 day^{-1} ($PPP) (http://iresearch.worldbank.org/PovcalNet/index.htm)

dominance criterion also shows that income of adopters of ZT first degree stochastically dominates that of nonadopters, suggesting that ZT technology reduces income risk.

10.5.3.2 Impact on Wheat Consumption

Among the variables included in the regression, area under ZT and net wheat income positively and significantly influenced wheat consumption. A 1 % increase in area under ZT and net income resulted in 0.2 and 0.19 % increases in wheat consumption. It is expected that farmers who devote larger areas to ZT and reduce their cost of production are likely to have better liquidity to ensure their household food security, especially during unfavorable seasons. Moreover, farmers who obtain higher wheat yields are more likely to have better access to more wheat for consumption, and perhaps in more varied forms, than those with lower productivity. Therefore, controlling for other factors, the adoption of ZT leads on average to about 13 % increase in family wheat consumption.

10.5.4 Impacts of ZT on Productive Efficiency

The likelihood ratio test was used to determine whether the Cobb–Douglas or the translog functional forms best fit the SPF of the typical Syrian wheat farm. The test rejected the Cobb–Douglas functional form in favor of the translog function. This suggests that yield can be best modeled by considering not only linear entries of individual inputs but also quadratic terms and interaction of inputs. The sigma squared and gamma parameters are statistically significant, affirming the correctness of the specified assumptions of the distribution of the composite error term and variation in yield per hectare that can be attributed to differences in technical inefficiency across the sample farms.

The coefficient estimates for the stochastic frontier production function and inefficiency model are presented in Table 10.5. Most of the inputs on the stochastic frontier are statistically significant and have the expected signs. Binary indicators of soil depth and salinity and seed variety were included in the production function to control the quality of inputs.

The hypothesis that there are no inefficiency effects in wheat production in the study area (gamma = 0) was rejected at 1 % level of significance. The gamma value indicates that 71.5 % of the total variation among Syrian farms can be explained by inefficiency and the remaining 28.5 % is random. This shows that a significant portion of the wheat farms are producing below the output-oriented technically efficient frontier with very high efficiency differential ranging from 28 to 95 %, with a mean of 75 % (Table 10.6). This indicates that there is wastage in resource use because, with the current technology, the average farmer can increase yield by 25 % only with efficient utilization of inputs. Particularly, the negative and significant coefficient on the ZT binary variable in the inefficiency model indicates that farms that use ZT have lower technical inefficiency in production relative to those that use CT, assuming that they all face the same best practice production frontier. The estimated mean output-oriented TE for ZT adopters is 88 % compared to nonadopters at 66 %, showing that the typical Syrian wheat farmer can increase output by 22 % simply by shifting from CT to ZT. There is also less variability in TE among adopters when compared to nonadopters. The positive and significant coefficient for the "planting date" variable indicates that late planting increases technical inefficiency relative to early planting. Likewise, the positive and significant coefficient for the "graze on crop residue" variable, which indicates whether or not the farmer has used or rented the crop residue for on-site grazing, indicates that allowing on-site animal grazing on crop residues leads to increased technical inefficiency relative to retaining or cutting and carrying away crop residues. Overall, the results suggest that besides adopting ZT technology, the adoption of other components of CA such as early sowing and residue retention or at least prevention of on-site grazing can lead to higher yields at current levels of inputs.

10.6 Conclusions

Farmers in many parts of the world are often skeptical about adoption of new innovations like ZT technology possibly due to lack of awareness or empirical evidence of its benefits over conventional practices. In this study, we develop and estimate econometric models in which the decision on how much area to put under ZT, and the outcomes related to area under ZT, yield, and net income are conditional on the decision whether or not to adopt the ZT technology. The Heckman two-step procedure was used to correct for selectivity bias in estimating the outcome variables of area under ZT, yield, and net wheat income. The difference in productive efficiency between adopters and nonadopters was investigated using the SPF approach, where TE of both adopters and nonadopters was estimated under the assumption that they both face the same production frontier.

Table 10.5 Parameter estimates of the translog stochastic frontier production and technical inefficiency model. (Source: model results)

Stochastic frontier parameters			Technical inefficiency parameters		
Parameter	Estimate	Std. error	Parameter	Estimate	Std. error
Intercept	4.300	(3.052)	Intercept	−0.207	(0.257)
Seed	0.351	(1.194)	Use ZT (0, 1)	−1.457	(0.414)***
Labor	1.048	(0.475)**	Plant date (0, 1)	0.721	(0.134)***
Phosphorus	−0.471	(0.167)***	Graze on crop residues (0, 1)	0.303	(0.102)***
Nitrogen	0.271	(0.152)*	Seed variety (0, 1)	0.160	(0.135)
Seed^2	0.043	(0.246)	Level of education	0.023	(0.014)
Labor^2	−0.192	(0.092)**	Experience (year)	−0.002	(0.003)
Phosphorus^2	0.096	(0.029)***			
Nitrogen^2	0.054	(0.022)***			
Seed × labor	−0.105	(0.092)			
Seed × phosphorus	0.075	(0.032)**			
Seed × nitrogen	−0.082	(0.029)***			
Labor × phosphorus	−0.026	(0.018)			
Labor × nitrogen	0.013	(0.179)			
Phosphorus × nitrogen	−0.005	(0.006)			
Soil depth (0, 1)	−0.140	(0.069)**			
Soil salinity (0, 1)	0.019	(0.045)			
Zone (0, 1)	0.001	(0.035)			
Variety (0, 1)	0.265	(0.048)***	Gamma	0.715	(0.075)***
			Sigma squared	0.216	(0.039)***
			Log (likelihood)	−190	

The dependent variable in the SPF function is yield (kg ha^{-1})

^2 represent the quadratic terms of the inputs in the translog SPF

*significance at 90 % confidence levels; **significance at 95 % confidence levels; ***significance at 99 % confidence levels

Table 10.6 Mean technical efficiency. (Source: survey data)

Zero tillage	Average	Std. Deviation
Nonadopters	0.66	0.17
Adopters	0.88	0.05
Total	0.75	0.17

Model results provided evidence that either or both participation in field days and hosting on-farm demonstration trials increase the likelihood of adoption. This evidence from our ZT experience in Syria reaffirms the importance of trialability, and visual and practical training and extension in promoting adoption of new agricultural technologies. Our results also show that increased yield is an important factor in a farmer's adoption decision.

Once farmers decide to adopt ZT, the key determinants of the land area to be dedicated to ZT are total wheat area and yield. The larger the wheat area farmed and the higher the yield, the more land will be dedicated to ZT. However, farmers with larger farmed areas tend to allocate less land to ZT which is counterintuitive and needs further investigation.

A farmer's farming experience in general and in using ZT in particular have a positive influence on yield obtained per unit area. These results point to the efficacy of training farmers using the "learning by doing" approach to enhance adoption of improved technologies. The amount of wheat area cultivated using ZT also had a positive and significant effect on yield. These results are consistent with the theoretical expectation that experienced farmers with a larger proportion of their land under ZT also have the technical know-how of using ZT, and therefore achieve higher yields.

By adopting ZT, the typical farmer in Syria gets about 465 kg ha^{-1} (or 31 %) higher yield than he/she gets using CT. At the current low adoption level of 5 %, ZT has led to a 2 % increase in total wheat supply in the study areas. Moreover, adoption of ZT increased net farm income by US$ 194 ha^{-1}, which translates into an increase in total family income of US$ 1180 $year^{-1}$ or per capita income by US$ 0.46 day^{-1}. Based on the poverty line of US$ 1.25 per capita day^{-1} for Syria, the adoption of ZT has helped 57 % of adopter farmers to raise themselves out of poverty.

Increased land under ZT and the associated increase in yield and net income were instrumental in improving per capita consumption of wheat. By adopting ZT technology, the typical Syrian farm household can increase its wheat consumption by 13 %. Adoption of ZT also improves farm production efficiency, and therefore the farmer's ability to make more efficient and sustainable use of resources without compromising their ability to feed their families. In particular, by shifting from CT to ZT, farmers can remove 22 % of the total production inefficiency which highlights the importance of ZT in improving productive efficiency. Other components of improved crop management such as early planting and prevention of on-site grazing of crop residues also improved TE. These results confirm that apart from the benefits documented in the literature in terms of enhancing sustainable management of land resources, ZT and related crop management improvements (e.g., early planting, retention of some stubble) are also associated with increased yields, household income, consumption, and food security. In our experience, and that of the Syrian farmers involved in our project, ZT is one of few technologies which can be justified on environmental, economic, and food security grounds, and hence has great potential for sizeable impacts in transforming the agricultural sector in the developing world.

From a policy perspective, this study points to the importance of training and extension that encourage farmers to participate in field days and host demonstration trials on their own farms to promote ZT technology. It is suggested that further work is needed (i) to investigate the effects of farmer perceptions of ZT technology and climate change on risk attitudes and behaviors and ultimately adoption decisions and (ii) to analyze the biophysical and economic trade-offs between crop residue retention and livestock production, and hence the net social and economic effects of adoption of ZT among mixed crop–livestock producers and the associated effect on the land resource and their policy implications.

Acknowledgments The authors are grateful to our Syrian partners in the ACIAR–AusAID Iraq project, who helped to implement the participatory extension program to promote ZT in Syria and, importantly in the context of this chapter, arranged for the survey questionnaire to be distributed, filled in, and collected under very difficult circumstances during 2011/12. These collaborators were scientists, extension officers, researchers, and support staff from many Syrian agricultural institutions, including the Ministry of Agriculture and Agrarian Reform (MAAR), Directorates of Extension, General Commission for Scientific and Agricultural Research (GCSAR), AGF, Aleppo Agricultural Machinery Training Center, the Syrian Libya Company (SYLICO), and private agricultural consultants and ZT seeder manufacturers. We are also grateful to ACIAR and AusAID for support and funding the project.

References

Abdulai A, Eberlin R (2001) Technical efficiency during economic reform in Nicaragua: evidence from farm household survey data. Econ Syst 25:113–125

Assunção JJ, Braido LHB (2007) Testing household-specific explanations for the inverse productivity relationship. Am J Agric Econ 89(4):980–990

Barrett CB, Bellemare MF, Hou JY (2010) Reconsidering conventional explanations of the inverse productivity–size relationship. World Dev 38(1):88–97

Battese GE, Coelli TJ (1995) A model for technical inefficiency effects in a stochastic frontier production function for panel data. Empirical Econ 20:325–332

Belloum A (2014) Conservation agriculture in the Arab World between concept and application. In: Stewart BI, Asfary AF, Belloum A, Steiner K, Friedrich T (eds). Conservation agriculture for sustainable land management to improve the livelihood of people in dry areas. http://www.fao.org/ag/ca/doc/CA%20Workshop%20procedding%2008–08-08.pdf. Accessed 17 Jan 2014

Bogetoft P, Otto L (2011) Benchmarking with DEA, SFA and R. Springer, New York

Bremer J, Livingston S, Parker R, Stichler C (2001) Conservation tillage applications. Texas Coop. Ext., Texas A & M University, College Station

Carter MR (1984) Identification of the inverse relationship between farm size and productivity: an empirical analysis of peasant agricultural production. Oxf Econ Pap 36:131–145

Coelli TJ (1992) A computer program for frontier production function estimation: frontier, version 2.0. Econ Lett 39:29–32

Coelli T, Henningsen A (2011) Frontier: stochastic frontier analysis. R package version 0.997–14. http://CRAN.R-project.org/package=frontier. Accessed 15 Jan 2013

Cohen J (1988) Statistical power analysis for the behavioral sciences, 2nd edn. Lawrence Erlbaum, Hillsdale

Deen W, Kataki PK (2003) Carbon sequestration in a long-term conventional versus conservation tillage experiment. Soil Tillage Res 74(2):143–150

De Janvry A, Fafchamps M, Sadoulet E (1991) Peasant household behavior with missing markets: some paradoxes explained. Econ J 101:1400–1417

Endale D, Schomberg H, Fisher D, Jenkins M, Sharpe R, Cabrera M (2008) No-till corn productivity in a Southeastern United States ultisol amended with poultry litter. Agron J 100:1401–1408

Erenstein O, Laxmi V (2008) Zero tillage impacts in India's rice-wheat systems: a review. Soil Tillage Res 100(1–2):1–14

Feder G (1985) The relation between farm size and farm productivity: the role of family labor, supervision and credit constraints. J Dev Econ 18(2–3):297–313

Feder G, Richard EJ, David Z (1985) Adoption of agricultural innovations in developing countries: a survey. Econ Dev Cult Chang 33:255–298

Friedrich T, Derpsch R, Kassam A (2012) Overview of the global spread of conservation agriculture. J Field Actions 6. Field Actions Science Reports Special. http://factsreports.revues.org/1941. Accessed 13 Dec 2013

Fulton M (2010) Foreword. In: Lindwall C, Sonntag B (eds) Landscapes transformed: the history of conservation tillage and direct seeding. knowledge impact in society. Saskatoon, Saskatchewan, pp 9–14. http://www.kis. sk.ca/ZeroTill/LandscapesTransformed_HistoryofCT_Book.pdf. Accessed 13 Dec 2013

Giller KE, Witter E, Corbeels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crops Res 114(1):23–34

Greene W (1997) Econometric analysis, 3rd edn. Prentice Hall, Englewood Cliffs

Greiner R, Patterson L, Miller O (2009) Motivations, risk perceptions and adoption of conservation practices by farmers. Agric Syst 99:86–104

Harper J (1996) Economics of conservation tillage. Conservation Tillage Series. No. 6. Penn State College of Agricultural Sciences

Heckman JJ (1979) Sample selection bias as a error specification bias. Econometrica 47(1):153–161

Horowitz J, Ebel R, Ueda K (2010) No-till farming is a growing practice. Economic Information Bulletin, No.70. Economic Research Service, USDA, Washington. http://www.ers.usda.gov/publications/eib-economic-information-bulletin/eib70.aspx. Accessed 13 Dec 2013

International Center for Agricultural Research in the Dry Areas (ICARDA) (2012) Conservation agriculture: opportunities for intensified farming and environmental conservation in dry areas. ICARDA Research to Action 2. http://www.icarda.org/sites/default/files/conv-agree.pdf. Accessed 17 Jan 2014

Jha D, Hojjati B, Vosti S (1990) The use of improved agricultural technology in Eastern Province. In: Celis R, Milimo JT, Wanmali S (eds) Adopting improved farm technology: a study of smallholder farmers in eastern province, Zambia. University of Zambia, Government of the Republic of Zambia, and IFRPI, Washington, DC

Knowler D, Bradshaw B (2007) Farmers' adoption of conservation agriculture: a review and synthesis of recent research. Food Pol 32:25–48

Lamb RL (2003) Inverse productivity: land quality, labor markets, and measurement error. J Dev Econ 71(1):71–95

Lankoski J, Ollikainen M, Uusitalo P (2004) No-till technology: benefits to farmers and the environment? Discussion paper 1, Helsinki, Finland, University of Helsinki, March 2004

Lennox C, Francis J, Wang Z (2012) Selection models in accounting research. Account Rev 87(2):589–616

Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. Field Crops Res 132:204–212

Liu Z, Juzhong Z (2000) Determinants of technical efficiency in post-collective Chinese agriculture: evidence from farm-level data. J Comp Econ 28:545–564

Nicholson W (2005) Microeconomic theory: basic principles and extensions. Thomson, Mason

Pannell DJ, Marshall GR, Barr N, Curtis A, Vanclay F, Wilkinson R (2006) Understanding and promoting adoption of conservation technologies by rural landholders. Aust J Exp Agric 46(11):1407–1424

Pannell DJ, Llewellyn RS, Corbeels M (2013) The farm-level economics of conservation agriculture for resource-poor farmers. Agriculture, Ecosystems and Environment (in press). http://dx.doi.org/10.1016/j.agee. 2013.10.014

Piggin C, Haddad A, Khalil Y (2011) Development and promotion of zero tillage in Iraq and Syria. In: Proceedings of the 5th World Congress on Conservation Agriculture, Brisbane. 26–29 September 2011, Australia, pp 304–305

Ribera L, Hons F, Richardson J (2004) An economic comparison between conventional and no-tillage farming systems in Burleson County, Texas. Agron J 96:415–424

Sidhu RS, Kamal V, Dhaliwal HS (2010) Conservation agriculture in Punjab: economic implications of technologies and practices. Indian J Agric Econ 53(3):1413–1427

Smale M, Kaunda ZHW, Makina HL, Mkandawire MMMK, Msowoya MNS, Mwale DJEK, Heisey PW (1991) Chimanga Cha Makolo, hybrids and composites: an analysis of farmers' adoption of maize technologies in Malawi, 1989–91. CIMMYT Economics Working Paper 91/04, Mexico, D.F

Smiley R, Wilkins D (1993) Annual spring barley growth, yield and root rot in high- and low-residue tillage systems. J Prod Agric 6:270–275

Toomet O, Henningsen A (2008) Sample selection models in R: package sample selection. J Stat Softw 27(7):1–23. http://www.jstatsoft.org/v27/i07/. Accessed 12 Dec 2013

Wagger M, Denton H (1989) Tillage effects on grain yields in a wheat double-crop soybean, and corn rotation. Agron J 81:493–498

Williams J, Pendel D, Llewelyn R, Peterson D, Nelson R (2009) Returns to tillage systems under changing input and output market conditions. J ASFMRA 78–93 . http://www.asfmra.org/wp-content/uploads/2014/06/301_Williams.pdf

Wilson P, Hadley D, Ashby C (2001) The influence of management characteristics on the technical efficiency of wheat farmers in Eastern England. Agricu Econ 24:329–338

Chapter 11
Conservation Agriculture in South Asia

Hafeez-ur-Rehman, Ahmad Nawaz, Abdul Wakeel, Yashpal Singh Saharawat and Muhammad Farooq

Abstract Conventional agriculture has put forth soil and crop sustainability to substantial soil degradation resulting in a concomitant decrease in the productivity of these systems. Conservation agriculture (CA) including minimum soil disturbance, permanent soil cover, and diversified crop rotations aimed to decrease and/or revert the effects of conventional farming practices like soil organic matter decline, soil erosion, soil physical degradation, and fuel use. However, in South Asia, the area under CA is very small compared to the rest of the world. The history of CA in South Asia starts when wheat plantation with zero tillage was first introduced in Indian and Pakistani Punjab in the 1980s. Currently, conservation tillage is being practiced on more than 5 M ha in Indo-Gangetic plains of South Asia. Conservation tillage reduced greenhouse gas emission and the production cost, and improved the soil health and crop yields. However, challenges like cultural and economic entrenchment of tillage agriculture in this region, weeds, insect pests, diseases, crop residue management, and reduced availability of suitable seeding and planting equipment are hindering its uptake. In this scenario, problem-oriented research and training, provision of conservation machinery at specific sites at proper time at affordable rates, and aggressive extension campaigns may help to boost up the uptake of CA in South Asia.

Keywords Zero tillage · Crop residues · Production costs · Indo-Gangetic plains · Mindset

---

H.-ur-Rehman (✉)
Department of Crop Physiology, University of Agriculture, Faisalabad 38040, Pakistan
e-mail: hafeezcp@gmail.com

A. Nawaz · M. Farooq
Department of Agronomy, University of Agriculture, Faisalabad 38040, Pakistan

Abdul Wakeel
Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

Y. S. Saharawat
The Indian Agricultural Research Institute, New Delhi, India

M. Farooq
The UWA Institute of Agriculture, The University of Western Australia, Crawley, WA 6009, Australia

College of Food and Agricultural Sciences, King Saud University, Riyadh 11451, Saudi Arabia

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_11

11.1 Introduction

South Asia (the southern region of the Asian continent) consists of the sub-Himalayan countries, but a few scientists also include the neighboring countries adjoining to the west and the east of these sub-Himalayan countries in South Asia (Chauhan et al. 2012). Southern Asia comprises Pakistan, Afghanistan, India, Bangladesh, Iran, Nepal, Sri Lanka, Bhutan, and Maldives (millenniumindicators.un.org.). However, the South Asian Studies Program of Brandeis University declares Myanmar and Tibet as a part of South Asia (http://www.brandeis.edu//bulletin/index.html), but the South Asian Studies Program of Columbia University excludes Afghanistan and the Maldives from South Asia but includes Tibet (http://www.sai.columbia.edu/).

South Asia has a fairly good economic growth rate but the region is suffering from extreme poverty, malnutrition, and the deterioration of natural resources (Joshi 2012). The challenges of rapidly rising economic growth and increasing population are putting great pressure on the agriculture sector to fulfill the present and future food and nutritional demands of the South Asian people (Joshi 2012). Intensive agriculture is helpful to feed the growing population but often leaves several negative impacts on soil systems including soil organic matter (SOM) loss, wind/water erosion, physical and biological degradation, groundwater pollution, declining water tables, poor nutrient-use efficiency, waterlogging, salinization, and greenhouse gas (GHG) emissions (Hobbs et al. 2006). These factors also result in global warming, loss of biodiversity, air pollution, and decline in factor productivity (Hobbs et al. 2006).

A major breakthrough in enhancing the agricultural productivity in South Asia took place with the introduction of wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) cultivars with dwarf genes and responsive to nutrient inputs especially nitrogen. In the past 40 years, the rice-wheat system has emerged as the predominant livelihood support cropping system for millions of farmers in South Asia. The use of high-yielding varieties under irrigated condition along with the nutrients input indeed led to a highly productive and intensified cropping system. Improved natural resources management significantly enhanced the system productivity. It contributed to food security through increased food production and decrease in food prices, and also demonstrated that agricultural development provides an effective means for accelerating economic growth and reducing poverty (Balasubramanian et al. 2012).

In South Asia, conservation agriculture (CA) views the farm as a factory to harness maximum outputs with maximum inputs of seed, fertilizer, biocides, and fuel. Over time, conventional crop production technologies have introduced intensive tillage to prepare fine seed- and rootbeds for sowing to ensure proper germination and early vigor, improve moisture conservation, control weeds and other pests, and mixing of fertilizers and organic manures. Monocropping systems for higher income and productivity gains led to soil health degradation, insect-pest buildup, high nutrient depletion, and the removal or burning of crop residues. This led to organic matter and nutrient depletion, moisture loss, and environmental hazards. In addition, indiscriminate use of pesticides and imbalanced use of chemical fertilizers have declined input-use efficiency, and pollution of natural resources especially surface and ground water. While energy- and labor-intensive usage has increased inputs with an ever-escalating production cost (Duxbury et al. 2000; Ladha et al. 2003; Saharawat et al. 2012), and the current production systems are posing a threat to food security and livelihood of farmers, especially to poor and underprivileged farmers. Therefore, the conventional practices need improved management practices for (i) production of more food at higher income levels and reduced risk; (ii) more efficient use of land, labor, water, nutrients, and pesticides than at present; (iii) improving the natural resource base; (iv) mitigating climatic change; and (v) adapting to the climatic variability (Saharawat et al. 2010).

CA, a suit of technologies including minimal soil disturbance, permanent soil cover, diversified crop rotation, and integrated weed management, offers a paradigm shift in crop production to sustain yields and have positive environment foot print (Farooq et al. 2011). Efforts to accelerate the farm-level impact of CA have been increased since the introduction of zero tillage (ZT) in wheat in South Asia. The faster adoption of CA in South Asia is an integrated effort of several drivers including (i) availability of new farm machinery; (ii) availability of improved herbicides or biocides for efficient weed, insect, pest, and disease control; (iii) ever-decreasing labor force and increasing labor cost; (iv) increasing production costs, energy shortages, erosion losses, pollution hazards, and escalating fuel cost; and (v) residue burning have accelerated change in the thinking of the researcher, policy maker, and farmer to adopt modified methods for cultivation of crops aimed at improving productivity and resource-use efficiency (Jat et al. 2011b).

In this chapter, we discuss the CA-based resource conservation technologies (RCTs) including ZT wheat and direct-seeded rice (DSR) in South Asia; dissemination, adoption, and potential impact of CA to improve the crop productivity and mitigate the climate change effects for sustainable crop production are also covered. A brief history and present status, experiences, challenges, and prospects of CA for its upscaling are also discussed.

11.2 History of CA in South Asia

The history of CA in South Asia is inextricably linked with the wheat production constraints in the rice-wheat system, which is one of the dominant cropping systems (Ladha et al. 2003). Wheat, the staple cereal crop of South Asia, showed declining yield trends in the 1980s due to late planting, poor plant stand, less seed replacement, inefficient fertilizer and irrigation system, weed competition, deterioration in soil health, and menace of little seed canary grass (*Phalaris minor* Retz.) (Malik et al. 2002). The productivity and sustainability threat to the rice-wheat further intensified because of the inefficient production practices, overexploitation of resources, especially water, energy, and labor, climate change, and socioeconomic changes. The rice-wheat cropping system in South Asia, therefore, suffers from conflicts in the economic, social, climatic, ecological, and production-related issues. In the Indo-Gangetic plains (IGP), with the rice-wheat system across this region, cotton (*Gossypium hirsutum* L.)-wheat, rice-maize (*Zea mays* L.), and sugarcane (*Saccharum officinarum* L.)-wheat systems are also prominent. However, associated with yield potential, the rice-wheat system in IGP is defind into two broad categories i.e. irrigated environment favorable for rice and wheat exists in the western part of the IGP including Pakistan and northwest Indian Punjab and Haryana states, with western Uttar Pradesh and the eastern part of the IGP which includes the districts favorable for rainfed rice or irrigated or rainfed wheat consisting of Bangladesh, West Bengal, the northern parts of Bihar and eastern Uttar Pradesh, and the Terai region of central Nepal. Two new technologies of the 1960s, that is, invention of new herbicides and the development of the ZT machine enabled farmers to practice no-till farming on a commercial scale. ZT was attempted in the IGP of South Asia in the late 1970s but the technology missed the mark for several reasons.

ZT technology in wheat was introduced in the early 1980s in South Asia by using a New Zealand-imported seed drill for the first time in Punjab, Pakistan. In 1996, when the ZT was again attempted, what really helped the technology was timing and the way it was evaluated at farmers' fields. The International Maize and Wheat Improvement Center (CIMMYT)'s call through Rice-Wheat Consortium (RWC) and collaboration from Australian Centre of International Agriculture Research (ACIAR), International Rice Research Institute (IRRI), and National Agriculture Research Institutes helped in planning and executing RCTs. The RWC, through its collaborators, planned for the introduction of second-generation machinery from 2002 onwards. The change towards CA perceived a fundamental shift from the age-old practice of excessive plowing to a new paradigm shift, whose best exponent is RCTs, based on "no-till/ZT" (minimal soil disturbance and compaction), innovative cropping systems, and management of crop residues rather burning.

The development, testing, and refinement of RCT practices were based on an innovative low-cost seed-cum-fertilizer drill (costing US $ 400–500), which can plant crops with minimal of disturbance to soil. With the commissioning of the RWC in 1994, ZT and reduced-till practices spread very rapidly, increasing from just few thousand hectares in 1997–1998 to more than 2.18 million ha in 2004–2005 and 2.6 million ha in 2010–2011 (data compiled by YS Saharawat and ML Jat). With the advancement of CA, second-generation drill or planters were developed in South Asia for seeding in the presence of anchored and loose residue. In the past few years, major emphasis has been put toward developing CA-based small machinery keeping in view the small farmer's needs. The success of CA's spread in South Asia is attributed to a multi-stakeholder approach and low-priced drills which increased the demand in other countries and across regions too.

Based on the success and formative nature of framework for promotion of RCTs, to both small- and large-scale farmers from service providers, use of farmer-participatory approach with on-farm demonstration trial with involvement of local manufacturer and their national partners has made available cheap, affordable, and effective ZT drills. Nonetheless, the alarming threat of climate change and reduced water availability in the region indicate there exists potential for further increase

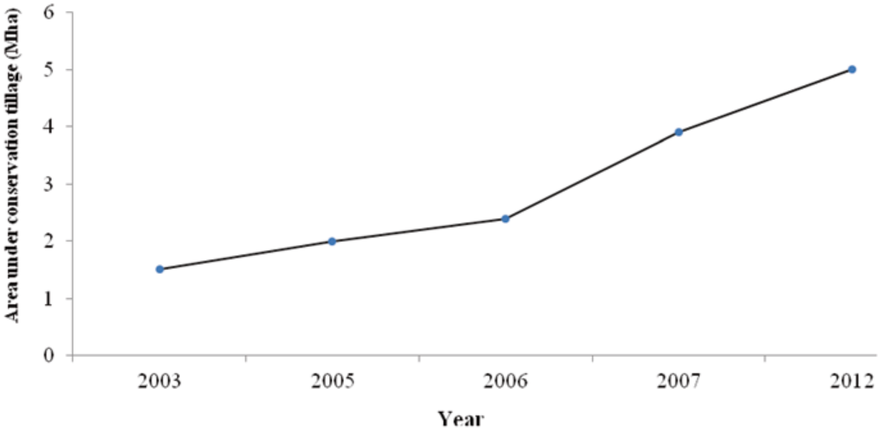


Fig. 11.1 Area increase under conservation tillage in South Asia. (Adapted from Friedrich et al. 2012)

in cereal system profitability, if CA-based RCTs in the IGP of South Asia are promoted (Krishna et al. 2012). Based on the efforts of RWC and survey-based data collected from villages and different aspects of cropping systems followed in the IGP, the Cereal Systems Initiative for South Asia (CSISA) project was implemented in 2009 to enhance the short- and long-term cereal production growth in South Asia. The project has been developed following a hub approach through involvement of public–private partnership for dissemination of RCTs in the region. The first phase was established with nine hubs: five in India, two in Bangladesh, and one each in Nepal and Pakistan. The main focus of the project is to improve livelihoods of small farmers through increased farm incomes by considering socioeconomic constraints for rapid growth and adoption of RCTs in intensive cereal systems (Krishna et al. 2012). Considering socioeconomic conditions and potential to enhance farm productivity, ZT in wheat, direct seeding in rice, and precision leveling using laser land leveler (LLL), special consideration is given to these technologies in these hubs during the initial phase. Nonetheless, efforts are not stopped here and are on with start of second phase. In order to characterize the cereal production systems in this region, village surveys were conducted by CIMMYT and IRRI with technical support of International Livestock Research Institute (ILRI) and International Food Policy Research Institute (IFPRI). Farmers have adopted ZT wheat quickly after changing their mind-sets regarding tillage and experimenting with the technology in their own fields. As earlier planting of wheat ensures yield, the low cost of production adds to their incomes. However, in the IGP, CA is mainly practiced in the rice-wheat cropping system and in other cropping systems including permanent no-till systems, its uptake is marginal (Friedrich et al. 2012).

Currently, conservation tillage in the rice-wheat cropping system is being followed on an area of about 5.0 million ha in South Asia (Friedrich et al. 2012; Fig. 11.1). In India, wheat cultivation through conservation tillage is being practiced in the wheat-rice double cropping system on a large area (Friedrich et al. 2012) and promoted in the northwestern states like Punjab, Haryana, Bihar, and Uttar Pradesh (Jaipal et al. 2005) and is rapidly growing popular among farmers, because farmers have realized that conventional tillage practices are time consuming, resulting in delayed seeding and yield loss of the wheat crop after rice (Hobbs and Gupta 2003; Hobbs et al. 2008).

CA is a revolutionary process of developing suitable and easily accessible CA implements, and crop cultivars, etc. under the changing scenario of limiting resources, urbanization, and climatic conditions to improve the profitability and sustainability of the rice-wheat system. Presently, we are halfway through evaluation and accelerating the adoption of double no till is the immediate step towards CA as double ZT with crop residue retention has resulted in higher system productivity than conventionally tilled systems in the IGP (Jat et al. 2005, 2006).

11.3 Experiences with CA in South Asia

Since the 1980s with development of ZT wheat, the area under RCTs in South Asia, through interventions of RWC and CSISA, is rapidly spreading and being adopted. This section underpins the developments in machinery and with its adoption-associated impact on crop performance, soil quality, changes in nutrient availability, coincidence in shift of weeds dynamics and diseases, insect pests, and efficient use of resources. Further integrated effects of these RCTs on the environment in terms of GHG emission and their mitigation have been elaborated.

11.3.1 CA and Machinery Development

Field machinery is the prerequisite for the adoption and success of CA. Since the 1990s, in South Asia, several site-specific modifications were made in the ZT machinery (Fig. 11.2). Ultimately, the widespread manufacturing and sales of locally adapted and improved versions of ZT drill were the cornerstone to kick-start the ZT initiative in South Asia. The ZT technology showed an average early seeding by 2–3 weeks, lesser weed infestation, and 15–25 % higher productivity. But ZT drills were not able to seed in the residue-retained condition and therefore were not able to address the natural resource management problems. Therefore, the second-generation machines were introduced from 2002 onwards in South Asia. Different kinds of machines including double-disk coulters, the star wheel punch planters, the rotary disc drill with a powered fluted or straight edge disc in front of double disks, turbo seeder and the combo happy seeder have been and are being tested as part of second-generation machine to facilitate residue retention as an integral part of CA.

The new planter also helps to foster development of more innovative intercropping systems particularly suitable for flood- and drought-prone environments. These technologies benefit farmers and help in practicing irrigated agriculture. However, with some fine-tuning, it can be easily transferred to many rainfed areas in the hills

Fig. 11.2 Prototypes of different conservation agriculture-based drills, planters, and seed metering system

and plains because it reduces the cost of cultivation, minimizes soil disturbance, and provides soil covers to reduce soil erosion and promote efficient nutrient and water use. The CA-based production technologies have emerged as clear winners! It is being adapted, and is divisible, reliable, and spreading faster than projected. Now CA-based no-till transplanted rice is being successfully demonstrated in the northwestern and central IGP using a paddy transplanter. The CA-based technologies are being widely adopted in South Asia in rice-, wheat-, maize-, sorghum-, and barley-based systems. With the development of "second generation" drill prototypes, crops can be planted in the presence of anchored and loose straws, which increase soil carbon, improve soil fertility, and provide a niche for beneficial soil microbes.

The IGP are the hub of CA mechanization and its package development in South Asia. Here, the farmer groups including the landless farmers have benefited from it through custom-hiring basis. With more and more farmer experimentation, the CA practices are "coevolving" with agents of change (public research and extension systems, champion farmers, drill manufacturers, custom service providers, and private agri-input dealers). Whereas there were just 2 drill manufacturing units in the private sector, in the year 2000, the popularity of the technology has swelled to the number close to 134 units spread all over the IGP including Pakistan, India, Nepal, and Bangladesh. Other significant contributions due to machinery development include the spread of raised bed technology in cereal-based systems, use of narrow tires to avoid compaction, and drip and sprinkler irrigation in raised bed mulch vegetable systems. The conservation of resources has to be tagged with value addition and that is why in sugarcane- and maize-based cropping systems bed planting has been accepted by farmers. Through a grassroot-level collaboration from researchers to farmers, the CA-based drill has undergone several modifications from the time of its introduction (Fig. 11.2).

11.3.2 Crop Performance

Crop performance in terms of growth and yield is variable in conventional and conservation tillage systems. As no preparatory tillage is carried out in CA,crop growth rate is lower than conventional tillage due to root penetration resistance. For instance, a recent study reported poor wheat growth in ZT wheat compared to conventional tillage wheat (Nawaz 2012), but at booting stage, a rapid increase in the growth of ZT wheat was observed (Nawaz 2012). Interestingly, productive tillers in ZT wheat were much more than the zero tillage due to root penetration resistance by compact soil in zero tillage (Nawaz 2012), which ultimately improved the yield of ZT wheat. Several reports in rice-wheat areas of India, Nepal, and Pakistan indicated that rice yields are not reduced in DSR compared to transplanted rice and wheat yields are higher under ZT after aerobic DSR (Hobbs et al. 2001; Farooq and Nawaz 2014). In addition, timely plantation of both rice and wheat in conservation systems results in reduced weed infestation, irrigation water saving (up to 15–20 %), better yields and enhanced input-use efficiency due to better crop stands and better seed and fertilizer placement (Gupta and Sayre 2007; Gupta and Seth 2007; Saharawat et al. 2010).

Crop cultivars also vary in their response under conservation tillage and early vigor can help to discriminate cultivars for their performance in no-till systems with retention of crop residues. For example, Noorka and Shahid (2013) compared the performance of a diverse set of four cultivars in conventional and conservational tillage without removal of rice crop stubbles. The cultivars varied in their response to different tillage; wheat genotypes with early vigor under conservational tillage produced higher grain yield than conventional tillage when rice residues were retained.

Retention of crop residues helps to maintain the soil temperature and moisture (Green and Lafond 1999). Crop residue retention also helps to regulate canopy temperature in wheat by reducing soil evaporation and conserving soil moisture avoiding crop from terminal heat stress effects (Jat et al. 2009a). Thus, retention of crop residue and ZT can help in adaptation to high temperature in late-sown wheat by timely planting, thus improving productivity of the rice-wheat system (Gupta et al. 2010). Along with the surface retention of crop residue, the full benefits of ZT can be harvested in the rice-wheat cropping system, if both crops are grown with a double ZT system. For instance, Jat et al. (2009a) evaluated the effect of tillage and crop establishment methods when integrated with conservation and precision agriculture-based RCTs as a double-ZT system in rice-wheat. Crops grown with precision land leveling improved system productivity (7.4 %), water saving up to

12–14 % in rice, and 10–13 % in wheat, and profitability by US $ 113–175 compared to traditional planted crops. The adoption of CA-based RCTs produced an additional 0.5 million tons of wheat and saved US $ 80 million through reduced fuel consumption in tillage and irrigation operations. In the short period of its introduction, farmers across the IGP have quickly adopted the CA-based RCTs. The total benefits to the farmers from ZT are astounding. ZT has reduced the cost of cultivation by US $ 55 ha^{-1} and burning of fossil fuel by 50–60 L diesel ha^{-1} (Gathala et al. 2011).

Four tillage systems including conventional tillage, deep tillage, ZT, and happy seeder at different rates of nitrogen in wheat were evaluated for 2 years in Punjab, Pakistan. Maximum grain yield was found for deep-tilled wheat and happy seeder followed by other tillage systems. However, improved yield in deep-tilled system was associated with an increase in leaf area index and crop growth rate while use of happy seeder increased economic benefits by cutting down the production cost (Qamar et al. 2013). In Nepal, wheat grain yield was high in ZT compared to permanent bed planting and conventional tillage. In another study in Nepal, the maize (*Zea mays* L.) crop had longer duration to reach silking with maintenance of previous crop residues than the plots with removal of residue. Moreover, significant reduction in production cost was observed in CA-based practices compared to conventional practices (BK et al. 2013). Nonetheless, for sustainable productivity of the rice-wheat system, RCTs with integration of laser land leveling and precision agriculture can be a more pragmatic and viable alternative, if long-term effects of these technologies are studied in different agroecologies of the South Asia.

Akter and Gathala (2014) reported that CA in rice-maize rotation can produce equivalent or higher yields than conventional tillage systems. In another 2-year study to compare the yield levels of wheat in conventional tillage, deep tillage, ZT (zone disc tiller or happy seeder), significantly higher growth rates, and grain yields were found in deep tillage followed by ZT with happy seeder (Qamar et al. 2013). However, yield response in no-till systems varies with soil type, agroecological regions, to some extent on machinery used and integrated crop management practices, such as residue management, weed management, and cultivar type used.

Further, with CSISA efforts to introduce new Boro dry season rice varieties for saline soils and short-duration Aman varieties into the rice-wheat cropping system has allowed farmers to grow mustard as third crop for system intensification. Likely, in eastern India, rice-maize + potato (*Solanum tuberosum* L.)-relay cowpea (*Vigna unguiculata* L. Walp.) cropping system seems to be profitable but is quite labor intensive. CSISA is also facilitating and accelerating mechanized farming in women farmers by upscaling of appropriate machinery such as two-wheel tractors and rice-wheat harvesting machines through ICT-based extension tools. Similar efforts are continued in Nepal to assess the effects of improved management practices on lentil and spring maize hybrids, line sowing DSR, and optimum fertilizers practices including upscaling of machinery to women farmers (Mathys and McDonald 2013).

Continuous ZT resulted in a significantly higher yield of the rice-wheat system compared to continuous conventional tillage (Mishra and Singh 2012). Wheat

Table 11.1 Yield levels of conventional and conservation wheat production systems

Grain yield (t ha^{-1})		Change (%)	Soil type	Country	References
Conventionally tilled wheat	Zero-tilled (ZT) wheat				
3.97	4.61	16	–	Pakistan	Latif et al. (2013)
3.05	3.27	7	–	Pakistan	Bakhsh et al. (2005)
5.30	5.80	9	Sandy clay loam	Pakistan	Qamar et al. (2013)
3.50	4.50	29	Sandy clay loam	Pakistan	Qamar et al. (2013)
3.50	3.80	9	Sandy clay loam	Pakistan	Qamar et al. (2013)
3.90	4.20	8	Sandy loam	Pakistan	Farooq and Nawaz (2014)
5.37	5.47	2	Silty clay loam	India	Tripathi et al. (2013)
4.00	3.67	–8	Sandy clay loam	India	Singh et al. (2001)
4.96	5.17	4		India	Sapkota et al. (2014)
4.93	5.27	7	Sandy loam	India	Saharawat et al. (2012)
4.60	4.84	5	Sandy loam soil	India	Rautaray (2005)
4.19	4.49	7	–	India	Erenstein and Laxmi (2008)
3.78	3.81	1	–	India	Erenstein et al. (2008)
2.04	2.83	39	–	Nepal	Tripathi (2010)
2.49	2.77	11	–	Nepal	Sah et al. (2013)

yields were similar under ZT with rice residues and conventionally tilled crop. System productivity and net returns were comparable under DSR with brown manuring followed by ZT wheat with rice residues and conventional practice. However, the highest productivity was recorded under DSR followed by ZT wheat-green gram (*Vigna radiata* L. Millsp) cropping system. DSR required about 30–40 % less water and had three times less global warming potential compared with the transplanted rice crop (Sharma et al. 2012). DSR with brown manuring of *Sesbania*, followed by ZT wheat with rice residues and ZT green gram during summer, is a better option for higher productivity, profitability, and environmental sustainability in the northwestern parts of IGPs.

CA thus offers the opportunity to the farmer community to enhance their crop yields, produce more food than their need for subsistence, and grow new crops which can be more profitable. However, yield trends in CA in South Asia are variable. In wheat, many researchers reported higher yields in ZT wheat than conventional tillage (Table 11.1), which possibly may be due to timely sowing of wheat.

11.3.3 Soil Quality

Soil quality is the ability of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Chiurazzi 2008). Planting methods significantly influence the physical, chemical, and biological properties of soil. In conventional production systems, extensive plowing and crop residue removal results in removal of soil organic carbon (SOC) and soil fertility (Lal 2004). However, CA practices improve the soil quality. ZT improves soil fertility, as well as soil physical and biological properties (Chauhan et al. 2002; Mohanty et al. 2007). Improvement in soil structure by ZT may be due to continuous buildup of organic matter with better water infiltration, retention, and overall reduced water use (Erenstein 2002; Govaerts et al. 2005; Hobbs 2007). Bazaya et al. (2009) found increased soil moisture content and organic carbon in ZT seeding plots compared to conventional seeding and had the highest microbial population. Recently, Das et al. (2013) found that ZT with bed planting or flat sowing increases 26–28 % SOC compared to conventional tillage and bed planting in the 0–5 and 5–15 cm soil layer in western IGPs after 4 years of cropping. The sandy loam soil of the Indian Himalayas possessed more soil carbon contents when soil was zero tilled compared to the extensive tillage in the rice-wheat cropping system (Bhattacharyya et al. 2008, 2012). Promotion of DSR may be useful to improve the soil physical environment for post-rice winter cereals by facilitating the root penetration. In a recent study, we found that root penetration resistance was reduced after DSR (Nawaz and Farooq 2013).

11.3.4 Nutrient Use and Dynamics

In the last five decades, in the IGP, especially in India, fertilizer use has increased by 1573 %, total food grain production by 145 % with an increase in area of 3.5 % and average yield increase of 125 %. Therefore, the input-use efficiency is decreasing at a fast pace, posing a threat of food insecurity and rapidly engulfing the poor and underprivileged population leading to increased poverty, which will be exacerbated further by the projected threats to agriculture due to consequences natural resource degradation and projected climate change effects.

SOC in most cultivated soils of India is less than 5 g kg^{-1} compared with 15–20 g kg^{-1} in uncultivated virgin soils. Low SOC concentration is attributed to plowing, removal of crop residue and other biosolids, and mining of soil fertility (Lal 2007). Large acreages of cultivated land show fertility fatigue and deficiency of micronutrients in many intensively cropped areas. This adds to our challenge of making farming more profitable. On a macroscale, N:P:K ratio of 4:2:1 has come to be known as an ideal ratio, and a deviation in NPK consumption pattern would suggest imbalanced fertilizers use—the greater the departure, the more the imbalance. But on the farmer usage level, this is not entirely true as there is hardly any basis for the suggested single valued ideal N:P:K ratio. The ratio will be further widening with mismatch in the demand and supply of major nutrients across IGPs. The NPK ratio is likely to vary with crops, cropping systems, CA practices, soils, and their reactions. It appears that there is a need to work out new N:P:K ratios for basing fertilizer allocations for different regions. In the demand and supply of fertilizer nutrients, use of organics in agriculture seems inevitable, particularly for correcting the N:K imbalances. From the plant nutrition point of view, the importance of the concept of balanced fertilizer use lies in adjusting the level of fertilizer use, taking into account available soil nutrients, crops requirement for targeted production levels under specific soil-water-crop management practices. New information seems to strengthen our understanding that CA has a distinct influence on soil quality and nutrient dynamics in soil as compared with the traditional agriculture-based intensively tilled systems. The current nutrient recommendations are age-old, area general not site specific, designed for the component crops of the cropping system, and better suited to tilled agriculture. Therefore, the focus should be "*feed the soil and let the soil feed the plant*" (Derpsch 2008). Under the changing scenario of natural resources and management practices, the production variables are dynamic. Hence, when everything is changing—how will nutrient recommendations designed for different situations work. It is only prudent that new fertilizer recommendations should be able to mimic significant effects of residue retention vis-à-vis incorporation of organics having differential soil moisture and thermal regimes. Therefore, the paradigm shift from tilled to no-till CA systems require a serious thrust on nutrient management research to improve soil and crop productivity and environmental quality.

Soil bulk density, soil moisture contents, and SOC are usually higher in ZT than CT (Bazaya et al. 2009). A no-till system significantly enhances the soil microbial biomass, total carbon, total nitrogen, active carbon, basal respiration, sand-free particulate organic matter, and aggregate stability, while carbon catabolism over time is decreased. Moreover, soil physical, chemical, and biological quality and soil quality index are improved under no-till system (Aziz et al. 2013). Rotation of crops with different rooting patterns can promote more extensive network of root channels and macropores in the ZT soil, which improves the water infiltration with a simultaneous increase in soil microbial diversity and decrease in pests and disease outbreaks from pathogenic organisms (Hobbs 2006). Incorporation of legumes in crop rotation as cover crops may help to fix the atmospheric nitrogen and add the soil carbon which may be utilized by the subsequent crop, thus improving the soil quality (Lu et al. 2000). Conservation tillage practices increase the fertility of the soil by carbon sequestration (Al-Kaisi and Yin 2005). Improved soil structure with conservation tillage decreases the GHG emission, pesticide use, eutrophication, and production cost and increases the nutrient recycling (Holland 2004). The incorporation of no till and inclusion of other RCTs into the rice phase of the rice-wheat system may further increase long-term profitability of this system due to reduced soil cultivation and may decrease soil sickness associated with mono-cropping in aerobic rice systems (Chauhan et al. 2012). Surface retention of crop residues in ZT systems may improve soil health (Sharma et al. 2008). Maintenance of crop residues as soil mulches increases the SOC pool (Sharma and Acharya 2000), modifies soil moisture and temperature regimes, and has a positive impact on soil fauna (Akter and Gathala 2014). In addition, retention of crop residues on the soil surface reduces the soil runoff and erosion by 52.5 and 80.2 %, respectively, compared to intensive tillage (Yan et al. 2000). However, adoption of conservation tillage may reduce the organic acid mineralization resulting in slow nutrient release (Benech-Arnold et al. 2000) and nutrient availability. Thus, appropriate integrated nutrient management with conservation tillage is required for site-specific nutrient management and long-term sustainability of the rice-wheat system.

11.3.5 *Weeds, Diseases, and Insect Pests*

Weed flora, pest population, and disease incidence are changed from a shift towards CA. Weed density is substantially higher in conservation tillage and is posing a severe threat for harvesting better yields in no-till systems (Gangwar et al. 2006). However, several studies have reported that adaptation of ZT in wheat of IGPs has minimized the weed flora in wheat compared to CT (Malik et al. 2004; Franke et al. 2007). Little seed canary grass is a noxious weed of wheat in the IGP but reduced soil disturbance with ZT fields has reduced its infestation in wheat (Mehta and Singh 2005). Farmers at various locations in India, for instance, report less infestation of little seed canary grass in ZT fields (Kumar et al. 2005). With ZT, undisturbed soil in a noncropped area delays the weed emergence due to which weed–crop competition is reduced (Erenstein and Laxmi 2008). On the other hand, some reports showed an increased incidence of broadleaf weeds in ZT wheat (Malik et al. 1998; Laxmi et al. 2007b). For example, Sharma et al. (2004) and Chhokar et al. (2007) reported that dicot weeds dominate in ZT while monocot weeds dominate in furrow irrigated raised bed sowing and conventional tillage. In our previous study in Punjab, Pakistan, we found more weed growth in ZT compared to other methods of wheat establishment (Nawaz 2012; Nawaz and Farooq 2013). However, little seed canary grass density in ZT was higher than in conventional tilled wheat (CTW) (Nawaz 2012). Similarly, surface retention of crop residues suppressed the weeds by altering the microclimatic soil environment (Robinson 1998). The presence of crop residues on the soil surface decreases the possibility of weed seed contact with the soil (Peigné et al. 2007), which inhibits the seed germination rate of weeds (Bond and Grundy 2001).

In addition to weed shift towards conservation tillage system, occurrence of the pest and disease is also changed (Chauhan et al. 2002; Laxmi et al. 2003; Jaipal et al. 2005). Rodent attack in ZT has been reported due to residue retention (Laxmi et al. 2007b). Increase in nematode population has also been reported in the rice-wheat region due to adoption of ZT and it enhances the predator density and diversity (Duveiller et al. 2004). Neurotropic pathogens and *Fusarium* head blight may be the possible threats to ZT adaptation (Duveiller et al. 2007). Increase in the incidence of rice stem borer in Pakistan (Inayatullah et al. 1989; Gill 2006) and pink stem borer in India has been reported in rice after wheat. Minimum-tilled or ZT fields hold the seeds of weeds near the soil surface that expose weed seeds to predators, viz. aphid (*Sonchus* spp.; Gallagher et al. 1999), and prevent the spread of weeds. Nonetheless, conservation tillage reduces the population of weeds by creating unfavorable conditions for weed seed germination (Benech-Arnold et al. 2000). Therefore, in CA systems, focus should be to control weeds, pests, and diseases through residue retention, use of cover crops, and crop rotations (Govaerts et al. 2009; Mader and Berner 2012).

Tillage affects weeds by uprooting, dismembering, and burying them deep enough to prevent emergence, by moving their seeds both vertically and horizontally, and by changing the soil environment and so promoting or inhibiting weed seed germination and emergence. Any reduction in tillage intensity or frequency may, therefore, have an influence on weed management. As the density of certain annual and perennial weeds may change under CA, effective weed control techniques are required to manage weeds successfully. Crop yield losses in CA due to weeds may vary depending on weed dynamics and intensity. However, studies by Mahajan et al. (2002) and Kumar et al. (2008) indicated that with the development of postemergence broad-spectrum herbicides, weeds can be effectively controlled in CA-based systems without affecting the crop productivity. Jung et al. (2004) reported evidence of allelopathic properties in some cereal residues to inhibit weed germination, overall suggesting that cropping system/pattern plays an important role in influencing weed flora in CA systems. In CA systems, weeds can be effectively managed during the harvest of cover crop in the systems by the use of different herbicide molecules. Higher microbial populations in CA-based farming practices also help in weed suppression. Various approaches, including the use of preventive measures, minimizing soil disturbance to avoid breaking dormancy of weed seeds, crop residue as mulches, intercropping, competitive crop cultivars, herbicide-tolerant cultivars, and eventually herbicides are needed to manage weeds effectively in a CA system. Among the preventive measures, weed-free crop seeds integrated with cultural and mechanical measures need to be adopted. The stale seedbed practice can be a valuable way of reducing weed pressure. This practice has been found very effective in ZT wheat in the northwestern IGPs (Mahajan et al. 2002; Saharawat et al. 2009). Studies have suggested a small difference in weed populations between conventional and ZT fields, and in some cases, few weeds have been observed in ZT conditions (Hobbs and Gupta 2003; Malik et al. 2002).

One of the pillars of CA is ground cover with dead or live mulch, which leaves less time for weeds to establish during fallow or a turnaround period. The crop residues not only improve soil health and moisture conservation but also pose a problem for weed seed germination by obstructing sunlight. Crop residues, when uniformly and densely present under CA, could suppress weed seedling emergence, delay the time of emergence, and allow the crop to gain an initial advantage in terms of early vigor over weeds. Cover crops, such as *Sesbania*, can produce green biomass of up to 30 t ha^{-1} within 60 days and control most of the weeds. In addition to reducing weed emergence, high amounts of residue may prolong or delay emergence, which may have implications for weed management in CA. Brown manuring involving growing of *Sesbania* along with DSR or maize as inter- or mixed-crop for 25–30 days and then killing *Sesbania* by 2,4-D spray or mechanical means has been found to be a highly beneficial resource conserving technology for soil and water conservation, weed control, and nutrient supplementation (Sharma et al. 2010).

Ramakrishna and Sharma (1998) reported that ZT increases the number and diversity of beneficial soil microbes, which can compete with the harmful soil organisms and increase the yield of crops. Moreover, a higher number of microbial diversities in conservation tillage systems reduce the population of parasitic nematodes (*Pratylenchus thornei*; Govaerts et al. 2007). Nonetheless, burning of crop residues during land preparation is common in South Asia to prepare a good seedbed, and has the advantage to control soil-borne pests and diseases (Aulakh et al. 2001).

The compilation of several CA and diversification studies across the IGP showed that CA-based practices not only help in improving the productivity in current cropping systems but also help in their diversification. The gains in the productivity were almost two times higher in the central and eastern IGP through CA-based practices in current cropping systems; however, when CA was intergraded with diversification, the gains were much higher (around four times) in the central and eastern IGP.

11.3.6 Energy-Use Efficiency

The current intensively cultivated production system is energy and input intensive and relies on the use of fossil fuels for tillage, transportation, harvesting, threshing, grain drying, and manufacturing of fertilizers, pesticides, and equipment used to apply agricultural inputs. The tillage and crop establishment operation accounts for 25–30 % of the wheat production cost in the rice-wheat system of South Asia. Farm mechanization plays a vital role for the success of CA-based technologies and their sustainability. Various studies under different CA-based practices show that CA-based ZT improves the operation field capacity by 81 % and grain yield by 6 % compared to the conventional practice in the rice-wheat system. The CA-based practices with reduced-/no till ensures timeliness, precision, and quality of field operations; reduces production cost; saves labor; reduces weather risk in these changing climatic scenarios; improves productivity, environmental quality, and sustainability; and generates rural employment on on-farm and off-farm activities (Barclay 2006, Ladha et al. 2009, Saharawat et al. 2010). Adopting CA techniques is a holistic approach for management of soil and water resources, and improving efficiency and productivity per unit of carbon-based energy consumed. Mishra and Singh (2012) reported that the intensively tilled conventional rice-wheat systems require maximum energy (38,187 MJ ha^{-1}), due to intensive field preparations, whereas CA-based ZT systems require least energy and have higher energy output to input ratio as well as higher system productivity. At Modipuram, higher energy output: to input ratio in ZT wheat after rice has been reported by Kumar et al. (2013). Mishra and Singh (2012) also reported higher cost of cultivation in the conventional tillage rice-wheat system as well as higher net returns and benefit to cost ratio in ZT rice-wheat systems. Similarly, in the ZT maize-wheat cropping system, low cost of cultivation, minimum energy usage, higher water productivity, higher net returns and enhanced energy input to output ratio were also reported (Ram et al. 2010).

11.3.7 Environmental Impacts of CA

The rice-wheat cropping system of IGP is considered to be the main source of atmospheric CO_2, N_2O, and CH_4 due to the large area and huge frequency of agricultural inputs use (Bhaatia et al. 2005) especially intensive use of nitrogen fertilizers (Cole et al. 1997; Pathak et al. 2002; Zou et al. 2007; Van-Groenigen et al. 2010) and alternate aerobic–anaerobic cycles during transition from wheat to growing rice (Malla et al. 2005). Flooded conditions cause anaerobic decomposition of organic matter and methane is the end product of this anaerobic decomposition of organic matter in the soil (Verburg et al. 2006). Rice fields contribute to 5–20 % of total methane emission throughout the world (Scheehle and Kruger 2006; IPCC 2007; Xu et al. 2007). However, conservation tillage practices are eco-friendly. In direct seeding, the rice crop is directly drilled into the field without standing water and can be grown like an upland crop such as wheat. Rice growing by this method may mitigate the risk of methane emission but emission of potent anthropogenic nitrous oxide is reported. Similarly, wheat crop sown after extensive tillage in post-rice fields can be source of atmospheric CO_2 when octane-rich fuel is used for preparatory tillage before wheat sowing. Adaptation of ZT in IGPs can save the environment through reduction in green house emissions (Erenstein and Laxmi 2008) by decreasing the tillage operations. Use of conservation tillage reduces the energy consumption and emission of carbon oxide emissions (Holland 2004). Subash et al. (2014) argued that by using appropriate integrated nutrient management practices, the negative footprints of extreme climatic conditions can be minimized.

The intensive tillage practices fragment the soil, trigger the release of soil nutrients, kill weeds, and modify soil aeration and also accelerate soil C loss and enhance GHG emission, which have an adverse impact on environment, whereas in CA systems, avoiding tillage operations helps in sequestering soil carbon, reducing gaseous emissions, reducing global carbon footprints, and sustaining environmental health. Since CO_2 is the final decomposition product of SOM, intensive tillage, particularly the mold board plough, releases large amounts of CO_2 as a result of physical disruption and enhanced biological oxidation (Reicosky et al. 1995). In CA systems, the crop residue cover on the surface helps to reduce soil erosion, enhance soil physical and microbial properties, increase nutrient availability, and control the conversion of plant C to SOM and humus. Duxbury et al. (2000) estimated that agriculture has contributed to 25 % of the historical human-made emissions of CO_2 during the past two centuries. However, a significant portion of this C can be stored or sequestered by soils managed with no tillage and other low-soil disturbance techniques. Improved tillage management techniques have shown that scientific agriculture can also be a solution to environmental issues in general, and specifically to mitigate the greenhouse effect (Lal et al. 2007). In the long-term adoption of CA practices, enhanced C sequestration and buildup in SOM constitute a practical strategy to mitigate GHG emissions and imparting greater resilience to production systems to climate change-related aberrations (Saharawat et al. 2012).

11.3.8 Economic Aspects of CA

Conservation tillage practices are economically feasible for small as well large landholders. CA involves the use of modern machinery and sometimes socioeconomic constraints limit the access of small-scale farmers to this machinery. However, experiments have revealed that the benefits of ZT are scale-neutral and the smallholders as well large-sized farms are getting the same benefits (Thakur et al. 2004; Malik et al. 2005). Small landholders with limited access to purchase the CA machinery often obtain from the rent services, similar to other conventional tillage implements. In IGPs, on-farm experiments of ZT wheat in the rice-wheat zone have reported reduced production cost combined with potential yield increases (Aslam et al. 1989; Hobbs and Gupta 2003; Malik et al. 2002, 2005; Laxmi et al. 2007a). ZT significantly reduces the cost of energy by decreasing the tractor costs associated with conventional tillage methods. Moreover, studies show that irrigation requirement of ZT wheat is reduced compared to cultivation with conventional tillage method (Gupta et al. 2002; Hobbs and Gupta 2003), thus reducing the energy costs associated with pumping underground water.

Promotion of DSR in the rice-wheat system of the IGP has great potential of saving water and labor resources, cutting down the production costs with simultaneous increase in net returns. High net income in zero-tilled direct-seeded rice (ZTDSR) was reported compared to conventionally tilled direct-seeded rice (CTDSR). Maximum net profit was achieved with zero-tilled direct-seeded crop sown in double no-till practices integrated with laser leveled. Further, wheat profitability was also higher with residue retention than residue removal. However, on system basis, maximum net returns were achieved in ZTDSR-ZTW followed by CTDSR-ZTW and lowest in puddled transplanted rice and conventional wheat system (TPR-CTW). Similarly, in rice, water saving on beds with a laser-leveled plot was 32.8 % more than TPR, while in wheat, permanent beds saved more water than other tillage practices (Naresh et al. 2013).

A survey in Punjab, Pakistan, regarding the use of agriculture inputs and outputs of RCTs showed that these interventions have improved the crop yield and net income of farmers with simultaneous reduction in water use. ZT, bed furrow, and laser land leveling saved 49, 40, and 31 % irrigated water per hectare, respectively, in the study areas. Higher water productivity and fertilizer-use efficiency (FUE) was recorded for ZT farms followed by bed-furrow and laser land-leveled farms (Latif et al. 2013). In India, a study undertaken to compare the economics of ZTW and CTW showed higher net income in ZT method than conventional one (Tripathi et al. 2013). Recently, Krishna and Veettil (2014) collected primary data to evaluate the on-farm impacts of ZT wheat and found significant cost savings (14 %) in ZT wheat. Productivity and technical production efficiency were also increased due to ZT sowing. Nonetheless, most of these studies report the agronomic and economic benefits related to ZT technology on researcher-managed fields and the impact of these interventions under a farmer's field needs clear understanding of socioeconomic factors.

11.4 Farmers' Participatory Approach in CA

The wide diffusion of technology rather than its invention is more important and is the only way to bring the maximum benefit. Technologies evolved are made visible for the farmers. Farmers see the technological product, own it, comment on the product, and finally accept or reject. In rural areas, the decrease in landholding and lack of interest of rural youth in agriculture is causing ever-rising unemployment. There is also a growing inequality between rural and urban population. Although information technology and other technological changes have created more jobs, benefits of these changes are being harnessed by better-educated urban youths rather than the rural youth. The common message behind all such developments is that changing the face of the South Asian economy calls for nothing less than a new economic paradigm for rural youth by creating jobs through agriculture-related subsidiary occupations where the rural youth have a comparative advantage. Such types of farming system approaches represent a significant shift both in the way scientists think about their field and how they investigate it. Merely listing the individual component does not really serve the purpose. A complete understanding of the farming system and then putting the bits together again is more important. While evolving technologies, participation of farmers at every stage of technology development starting from conceiving the idea, articulating the way it will be accepted, inviting the partners who can help outsource technical inputs, demonstrating the technology, and marketing at the same time is very important. Squeezing many components in any candidate technology at a farmer's field is not easy. Technologies leading to CA have been/are being coevolved with agents for change, the farmers. Therefore, evolution of CA rests as much on farmers as on the scientists. Experience has shown that farmers just love new technologies and try new things. It is, therefore, necessary to develop technologies which are in demand. Instead of perfecting a technology within the four walls of research stations, it is therefore more prudent that CA are perfected on farmers' fields together with them for greater adoption of the new CA practices. This process adopted by researchers in South Asia has not only made it easy for the CA to coevolve and accept CA in India but also helped transferring this technology across borders including Pakistan, Bangladesh, and Nepal.

11.5 Challenges for CA in South Asia

In spite of encouraging experiences, CA in South Asia is confronted with several challenges on cultural and economic fronts, crop residues and pest management, and availability of suitable planting equipment. An overview of these challenges is given in the following sections.

11.5.1 Cultural and Economic Entrenchment of Tillage Agriculture

CA may be difficult for the farmers to adopt as it goes against their cherished beliefs, cultural norms, and sometimes economics. The main factor behind the slow uptake of RCTs in the South Asia is the mind-set of the farming community related to conventional tillage. The farmer does not know how much profit can be achieved with RCTs. Farmers are interested about the outlook of their crop in terms of growth and their minds have been made up that more tillage yields more. Cultural and economic entrenchment of tillage agriculture is considered as one of the main barriers to the adoption of CA practices (Friedrich and Kassam 2009). The main hindrance is to change the mind-set of farmers that extensive plowing operations deteriorate the soil and aerial environment. Once they realize the story, they will be willing to try something novel. Farmers adaption to CA depend on their participation in each steps of operations from practicing to harvesting rather than just by observation. Few inventions are compulsory and the techniques suited to local environment are also a prerequisite.

CA necessarily involves a positive shift in attitudes, which can be only achieved by encouraging the farmers to investigate the potential impacts of these technologies on their own farm, and providing with more relevant information about these tillage practices through networking. For the CA to be successful, besides change in farmers' attitudes, this will require new skills for selecting crops for better marketing, sorting, grading, marketing, and postharvest processing of their produce. Farmers with large landholdings and earning some income from some nonfarm sources are likely to adopt CA. Moreover, the likelihood of adoption differs between various climatic conditions, cropping patterns, and irrigation access. The probability of adoption of CA is inhibited by rental market, while the adoption intensity is constrained by soil type (Akter and Gathala 2014).

11.5.2 Crop Residues and Management

Crop residues are also the one of main hindrances in the adaptation of RCTs in IGPs of South Asia, especially in the rice-wheat cropping system. In this system, rice harvesting is usually completed with combine harvester and the rice residues are left in the field. After drying, these residues are burnt in the field and then wheat is sown after pulverizing the soil. Burning of crop residues is not an environment-friendly way of crop residue management (Gupta and Seth 2007). Farmers need to be encouraged to stop burning their loose residues after combine harvesting. However, in IGPs, a lack of seeding implements for planting into loose residue also seems one of the main limitations at the moment, but local engineers and manufacturers are working together to solve this issue.

During harvesting with a combine harvester, the crop residues are chopped inside the combine and spread on the field after leaving the combine. Moreover, the recently designed inverted-T openers are not affected by anchored straw and there will be minimum clogging when straw has been cut into small pieces and spread uniformly (Naresh et al. 2013). Nowadays, trash removers, cutting disks, and other systems used in the USA and Europe are being practiced in South Asia, but these implements need more horsepower for operation and are costly. Similarly, strip-till systems possessing the rotary blade are also being tested to manage residues as they cut the residue and make a narrow strip placement of seed and fertilizer (Naresh et al. 2013). In Pakistan, happy seeder is being used for wheat sowing after heavy rice residues as it cuts and lifts up the cut loose straw ahead of the planter, and blows it out behind the planter and places the seed through inverter into the soil which is free from crop residues. These chopped crop residues which fall behind the planter serve as mulch (Naresh et al. 2013). Sidhu et al. (2007) reported that the use of tine-type openers for management of crop residues in no-till systems is not feasible, nonetheless new-generation planters, viz. rotary-disk drill, happy seeder, punch planter, and double-disk drill may be useful for management of crop residues resulting in wider adoption of CA in the region.

11.5.3 Weed, Insect-Pest, and Disease Challenges

CA practices may influence species diversity, weed status, biology and carryover of insects, diseases and beneficial pests due to significant change in crop environment and ecology. Several reports indicate that ZT has negative impact on soil texture, weed dynamics, and carryover of insect pest on post rice crop, especially rice stem borer (Singh and Meena 2013). Weeds in CA are posing a severe threat for harvesting better yields (Gangwar et al. 2006), an increase in broad-leaved weeds in ZT systems is observed quite often (Malik et al. 1998; Laxmi et al. 2007b; Nawaz and Farooq 2013). Besides weeds, insect pests and diseases decrease crop yields significantly depending on their prevailing population in crops (Chauhan et al. 2002; Laxmi et al. 2003; Jaipal et al. 2005).

Conservation tillage systems influence the insect-pest population densities which become reduced with tillage (Jaipal et al. 2005). Shift in weed biota when switching from conventional to conservation tillage may influence several insect-pest species developed during fallow periods. As the conservation tillage reduces the fallow period between crops, a change in sowing period of the following crop may alter certain insect's incidence. For example, in conservation rice-wheat system, the rice stem borers overwinter in the rice stubbles and affect the preceding crop's performance (Jaipal et al. 2005). The larvae of striped stem borer (*Chilo suppressalis*), yellow stem borer (*Scirpophaga incertulas*), and white stem borer (*S. innotata*) may undergo hibernation and stay there unnoticed, while the pink stem borer (*Sesamia inferens*) may damage the wheat (*Triticum aestivum* L.) until maturity in subtropical semiarid region (Jaipal et al. 2005). Rodents attack due to residue retention (Laxmi et al. 2007b), and increase in nematode population has also been observed in conservation rice-wheat systems of IGPs (Duveiller et al. 2004). Moreover, neurotropic pathogens and Fusarium head blight are the leading threats to adoption of conservation systems in South Asia (Duveiller et al. 2007). In case of dry DSR, weed and nutrient management are severe challenges for successful crop production (Chauhan et al. 2012), which need to be addressed. Recently, under CSISA in Bihar, India, on-farm demonstration trial on DSR indicated that mixing of bispyribac with 2,4-D improves weed control and paddy yields were 4.2 t ha^{-1} compared to 3.8 t ha^{-1} with bispyribac alone and corresponding yield with manually transplanted rice were 5.3 and 4.3 t ha^{-1} with same weed management practices.

11.5.4 Availability of Suitable Seeding and Planting Equipment and Inputs

Unavailability of suitable seeding and planting equipment, inputs in many parts of South Asia, is one of the main hindrances to the wide adoption of CA (Friedrich and Kassam 2009). Practicing CA requires a different set of tools and equipment to complete different operations and a variety of tools and equipment have been developed to suit different farm sizes, conditions, and operations, but still many equipment necessary for CA are too expensive or not appropriate for specific localities. Most of the CA equipment designed are still not widely available in local markets and some are still being used on trial basis. There is a "chicken-and-egg" situation as the manufacturers/dealers are not willing to manufacture or stock inputs and equipment unless assured demand from growers. At the same time, if these implements and inputs will not be available in the market, the farmers cannot buy them. Under such conditions, the local manufactures can adapt the existing designs or make their own. Major efforts for development and dissemination of RCTs practices have been under RWC of IGPs with ZT cum fertilizer drill for sowing wheat crop in the rice-wheat system through involvement of National Agricultural Research Systems of India, Pakistan, Bangladesh, and Nepal. Other interventions being tested and promoted include raised-bed planting system, laser-aided land-leveling equipment, residue management alternatives, and alternatives to the rice-wheat cropping system in relation to RCT technologies (Singh and Meena 2013)

Managing the crop residues during combine harvesting must essentially build a mechanism in the combine to chop and evenly spread the straw on the field after removal from the combine. There is a need to evaluate other systems of planting besides the inverted-T opener-like cutting disks, trash removers, and other systems used in Europe and the USA but their operation costs are high and need heavy and bigger tractors.

There is need to develop and mass produce the prototype which is locally suitable for low-horsepower used in Asia for farm operations. Heavy equipment like disk openers have been tried and unfortunately fail to get much popularity as inverted-T opener and other pragmatic options being promoted. Equipment designed for small-scale farm operations used in South America can be more suitable to the power systems in Asia. The cultivation and use of cover crops has not been tried much yet since rice residue leaves considerable biomass (Naresh et al. 2013).

Fine-tuning the ZT of wheat and DSR under farmers' conditions to get maximum benefit is also very important (Chauhan et al. 2012). Recently, in South Asia, laser leveling is being adopted over 1.5 M ha (Jat et al. 2009a, b; 2011b). The turbo seeder (drill) places the straw between rows and thus proved very effective in controlling weeds. Therefore, for sustainable intensification, the machines need to be more user-friendly to develop the interest of private manufacturers for investing in the machine (Akter and Gathala 2014).

Nonetheless, many appropriate mechanical CT implements from manual to large-scale levels are commercially available for the farmers. For example, manually animal-driven simple precision crop planters such as no-till seeder with 3–5 row, boom sprayers, and knife roller weed in India, and for no-till sowing, single axle reduced cost tractors for direct seeding of small grains into soil with residue left, precision planters and strip till cum seeder are also available in Bangladesh (Table 11.2). In South Asia, multiple-purpose tractors (single axle) with no-till seed drills have been manufactured with the collaboration of CIMMYT. For bed plantation, bed planters with single-axle tractor are also available. Chisel-type no-till planters relatively of low cost and for small-size tractors are available but have limitations for residue handling during wheat planting into heavy maize or rice straw stubbles. Similarly, for strip tilling with narrow rotary harrows through happy seeder to facilitate penetration through residue or for pickup of residue are available commercially in Pakistan and India. For harvesting under CA, two-step harvests with stationary threshing at field side or on the farm yard or combine harvester to facilitate the retention, return, and spreading crop residues for mobile pick up threshing are also available. Nonetheless, high management skills required in conservation tillage may not be economically feasible and are one of the constraints for the farmers.

Nonetheless, development and refinement of machinery for various soil types and cropping systems will be central for promotion of conservation tillage systems in South Asia (Friedrich et al. 2012). The detail of CA machinery available in some South Asian countries is given in Table 11.2.

11.5.5 Problem-Oriented Research and Training

Instead of promising benefits of RCTs, farmers are unable to adopt it unless problems associated with ZT wheat and DSR are solved. There is also need to fine-tune the RCTs to suit the farmer conditions (Chauhan et al. 2012). Continuous cropping can interact negatively with conservation tillage systems by shifting the weed flora towards a troublesome composition. Rotating crops having distinct morphologies and divergent growth habits, life cycles, different cultural practices, and water and nutrient needs can all potentially affect the community composition and distribution of weeds.

Sequential inclusion of certain crops in the intercropping system has been found to decrease water and nutrient requirements and substantially reduce the population of some obnoxious weeds. Thereby herbicide application could be reduced to a great extent in areas of alarming population of these weeds. Nitrate leaching into the lower profile can be reduced by insertion of legume crops in cropping systems and play an important role in conserving soil and groundwater water. Farmers are not interested to cultivate pulses, in spite of much demand, because of their sensitivity to biotic and abiotic stresses resulting in low yield as compared to wheat and rice. Sunflower (*Helianthus annuus* L.) or maize cultivation holds some promise during spring but can replace only wheat rather than rice. For the diversification of rice-wheat system, consistent efforts are needed to attract farmers with better price support, profit, and removing marketing bottlenecks for the alternative crops. The situation cannot be changed unless high-yielding cultivars of pulses and oilseeds are developed. Raised-bed planting technology is a pragmatic opportunity

Table 11.2 Conservation agriculture machinery available in South Asia

Country	Conservation machinery available	Functions
Pakistan	Bed planter	Bed and furrow making plus seed drilling
	Laser land leveler	Leveling of uneven land for water saving
	Happy seeder	Residue management and seed sowing in rice-wheat cropping system
	Zone disk tiller	Sowing of wheat in rice residues
	Turbo seeder	Sowing of wheat in rice residue in residual moisture
	Direct-seeded rice drill	Drilling of rice seed after seedbed preparation
India	Raised bed planter	Bed making and sowing on the tip of the bed is done in single operation
	Zero tillage drill	Sowing of seeds in the stubbles of previous crop
	Strip tillage drill	Cultivate a targeted area and leaving the crop residue on the surface between the tilled strips, retaining moisture and organic matter to improve the soil structure and fertility
	Happy seeder	Residue management and seed sowing in rice-wheat cropping systems
	Direct-seeded rice drill	Drilling of rice seed after seedbed preparation
Bangladesh	Power tiller-operated minimum tillage seeder	Timely sowing of wheat
	Power tiller-operated bed planter	Creates a trapezoidal raised bed and can perform seeding operations on the top of the bed simultaneously
	Power tiller-operated zero-tillage seeder	Sowing of wheat and maize in residues of previous crop
	Power tiller-operated strip tillage seeder	Cultivate a targeted area and leaving the crop residue on the surface between the tilled strips utilize residual soil moisture for crop establishment
Nepal	Power tiller rototiller	Soil cultivation, aeration, weeding, fertilizer application, and flower seedbed preparation
	Strip till drill	Cultivate a targeted area and leaving the crop residue on the surface between the tilled strips, retaining moisture and organic matter to improve the soil structure and fertility
	Zero till drill	Sowing of seeds in the stubbles of previous crop
	Jab seeder	Hole-making and seed-dropping are done simultaneously, and there is no bending or squatting
	Power tiller seed drill	Seed sowing

for diversification through intensification and saving water (Jat et al. 2005). Crop diversification within the RW system can be achieved by replacing rice area under rice with basmati types and bread-wheat with durum-wheat (Gill et al. 2008).

There is need to develop weeds competitive and pest-resistant inbred lines or hybrids most suitable to conservation tillage. Evidences for nutrient deficiency such as iron deficiency in DSR indicate research efforts to improve nutrient-use efficiency and total factor productivity of conservation tillage or ZT systems by improving soil health, crop residue management, and improving water-use efficiency integrated with different crop and soil management practices. With the rising cost and nonavailability of labor, mechanization will become even more important in the future. Further experiments are necessary with improved machinery keeping in view that private business find it demanding more than the existing power tiller which constraints adoption of RCTs (Akter and Gathala 2014). The impact assessment of ZT has been primarily limited to wheat and needs extensive study on subsequent rice crop. Although there has been rapid uptake of ZT technologies in these regions, no convincing data are available for their role in household food and nutrition security.

11.6 Prospects for Upscaling CA in South Asia

11.6.1 Effects of Climate Change

South Asia, due to its large population, limited resources, and predominance in agriculture, is more vulnerable to global environment change (GEC). Serious concern about the vulnerability of food systems in the IGPs and the development of robust adapting strategies are priorities of the policy makers (Aggarwal et al. 2004). Burning of crop residues results in the emission of GHGs causing global warming and CA practices can reduce the carbon emissions and sequester it in the soil. Minimal disturbance of soil by ZT reduces the oxidation of organic matter, thus lowering CO_2 emissions compared to tilled soils.

Under conservation tillage, reduced use of diesel minimizes CO_2 emission to the atmosphere and can increase the carbon sequestration in the soil (Erenstein et al. 2008; Hobbs and Govaerts 2010). Gupta et al. (2004) reported that the use of ZT drill can reduce the CO_2 emission in the range of 13–14 t ha^{-1}. The data from Haryana, India, and Punjab, Pakistan showed that ZT saved approximately 35 L of diesel and reduced CO_2 emission (Erenstein et al. 2008). Gupta and Seth (2007) argued that avoiding the crop residues burning on an area of 5 million ha can minimize carbon dioxide emissions by 43.3 million tons. Grace et al. (2003) and Gupta et al. (2004) reported that ZT can eliminate the carbon dioxide emission by 156 kg ha^{-1} annually. However, more extensive research is needed, especially in the tropical areas where good quantitative information about the emission of these gases is lacking. Traditionally, farmers remove crop residues for feeding animals, or plough them through tillage or in high-production areas, mostly burnt which releases huge quantity of GHGs and pollutants to the atmosphere (Hobbs and Govaerts 2010). Reduction in the intensity of tillage could help to reduce the adverse effects of cultivation on soil CH_4 uptake (Hütsch 1998).

As studies are limited, the impact of tillage on the methane flux in a crop production system is still unclear (Jacinthe and Lal 2004). However, ZT in rice cultivation could minimize CH_4 emissions by avoiding puddling and encourage more water percolation through the soil profile and help in soil aeration. This effect would be more visible in bed-planted rice production system since aeration is greater. However, large reductions in rice yields will hinder adaptation of ZT use by farmers; hence, future research is needed to develop new crop management systems for conservation tillage on different soils and water regimes. These management practices include development of aerobic crop varieties, better weed control measures, good nutrient applications, and proper seeding equipment (Hobbs and Govaerts 2010).

11.6.2 Soil and Crop Management-Related Policies

Improved soil and crop management-related policies have considerable positive environmental and socioeconomic feedback. For example, irrigation pricing would be an important effort to increase the water-use efficiency in the western IGPs with improvement in associated environmental impacts but it will have considerable sociopolitical resistance to implement due to adverse affects on farmers' income in the rice-wheat system. Policy makers, planners, and civil society need to be made aware of the long-term benefits of RCTs to ensure sustainable development in the IGP (Aggarwal et al. 2004). The government should make durable efforts to persuade farmers to diversify rice-wheat monoculture with other crops (Chauhan et al. 2012). In Indian Punjab, experts have proposed to reduce rice area by about 1 M ha (Hira 2009), by introducing the other crops like maize, Bt-cotton (*Gossypium hirsutum* L.), groundnut (*Arachis hypogaea* L.), and soybean (*Glycine max* (L.) Merr.) as viable alternatives to rice by saving plenty of water (Kaur et al. 2010).

A model study using ORYZA2000 and hybrid corn models predicted very high yield potential of post-rice winter corn in four South Asian countries, viz. Pakistan, India, Nepal, and Bangladesh (Timsina et al. 2010, 2011). In Indian Punjab, 0.5 million ha of rice area can be switched to maize, soybean, or pigeon pea (*Cajanus cajan* L. Millsp.) in less irrigated upland areas. Because of environmental pollution by straw burning, it may be banned. In spite of better understanding and scientific knowledge of climate change and its implications, there is a lack of functional partnership between scientists, the private sector, policy planners, and farmers in order to move beyond rhetoric to real actions. To adapt to climate change, use of RCTs can buffer soil and canopy temperatures. Farmers' participatory field trials have been conducted across the IGPs to develop, define, and validate the innovative solutions to combat with terminal heat stress in wheat production. No tilling should also be uplifted. Only then does it become possible for all stakeholders to operate in a converging and complementary manner for transforming the prevailing tillage-based production systems to conservation tillage-based systems as the basis for sustainable production and intensification.

11.6.3 Evolution of Production Costs and Commodity Prices

Agricultural policies should focus on improving access to market, input and credit input supplies, and rural infrastructure. They should support the development of farmers' groups. Incentives should encourage diversification and RCTs, especially during the transition phase from conventional farming to conservation practices. Appropriate product pricing can raise productivity per unit land and reduce pressure on marginal regions. Inadequate policies and subsidies that support conventional practices might discourage farmers from adopting conservation tillage. Land use and customary rights must also be taken into account. Subsidies and other incentives can also support the spread of RCTs. Policies may guarantee farmers' long-term rights to the land they cultivate and in case of insecure tenure, their willingness to invest in improvements to the land through conservation tillage will be reduced (Singh et al. 2007).

11.6.4 Regional Differences Affecting Uptake

The learning process for the adaptability of site-specific RCTs can be accelerated by promoting and developing the information-sharing network among scientists, farmers, and other stakeholders. It is extremely necessary because RCTs are site specific and a technology showing success on one site may fail on another one (Singh and Meena 2013). Manufacturers' base to prepare and provide services for access to equipment, cost of tillage drills, institutional policy framework, and landholding size are major drivers for awareness, uptake, and spread of RCTs among farmers' cooperatives. Access to equipment can be increased through service providers and quality of planting can also be increased, if service providers are trained about the technology. For instance, in northwest India and central Nepal, growers are associated with farmers' club and cooperatives and participation through household cooperatives is high in northwest Bangladesh. Large landholders in these cooperatives provide services to their neighbor cooperatives by providing machinery on rent basis and land on lease to nonfarming or small landholders. Due to very common differences of small or large landholdings in northwest India, these cooperatives and farmers club can play role in designing the strategies for diffusion of ZT. Adoption surveys indicate that 60% of farmers adopting ZT drill in Haryana, India, do not have their own drills and depend on service providers having hands-on experience and self-interest to promote the technology and this model is successful only in this region of South Asia (Erenstein et al. 2007b; Erenstein and Laxmi 2008). Similarly, in Punjab, Pakistan, where the agroecological conditions and system instability are same, successful experimentation favored the adoption of ZT drill in the 1990s but later the uptake had been slow due to less demand, smaller manufacturer base, and machine cost including institutional controversy (Aslam et al. 1993; Erenstein et al. 2007a).

Political instability and lack of manufacturer base has also hampered the spread of technology in Nepal and this increased the import of costly machinery from India. In Bangladesh, use of two-wheel tractors and least developed local manufacture base has largely bypassed the adoption of ZT drill; however, now research and development efforts are going to adapt two-wheel tractor-based RCTs (Tripathi et al. 2006; Erenstein et al. 2007a). RWC had played a critical role in the spread of conservation technologies through public-private partnership with involvement of national and international sources and efforts are underway to accelerate the profitability and dissemination of RCTs in South Asia through CSISA project. Nonetheless, with the involvement of several local manufacturers, at comparable costs guaranteed repair services and access to good quality machines can play a role in uptake of these technologies. Development of close linkage of private sector with researchers and farmers for easy access to machines in nearby villages for on-farm experiments can play a role in the spread of technologies with feedback for further refinement. Encouraging support from local government and extension officials, and provision of tillage machines at subsidized rates to initiate extensive on-farm demonstration trials can be conclusive to change the mind-set and accelerate adoption rate of CA practices. Further, there is need to look for the true indicators to robust the uptake and diffusion of these technologies on ground basis.

11.7 Conclusion and Future Thrusts

CA in South Asia provides a pragmatic option to reduce the production cost, energy use, and improve the soil resource base, soil health, and net benefits at farmer field on sustainable basis. However, its spread is very low due to farmers' mind-sets about conventional tillage, noninvolvement of international organizations like CSISA, CIMMYT, IRRI, and RWC, nonavailability of suitable planting implements, and increased incidence of pests and diseases.

The future CA research thrusts for South Asia are listed below:

- Spread can be promoted rapidly by developing a strong collaborative network among scientists, farmers, international organizations, implement manufacturers, and other stakeholders
- There is an urgent need for basic, strategic, and adaptive research in CA-based systems in contrasting soils with different edaphic and crop requirements. Emphasized breeding programs to develop crop varieties for CA systems are needed
- In-depth understanding and modeling of crop behavior, physiology, and adaptation to drought stress and other limiting abiotic factors is required
- There is need to develop integrated weed, disease, insect, and pest management strategies for CA systems with profound integration in different microclimates
- Integrating genetic enhancement (biotic and abiotic stresses) traits with relevant CA-based technology to help the resource poor farmers to produce more and high-value crops
- Integrating crop-livestock commodities with CA-based land and water management research
- Lot of progress has been made in cover crops, diversification especially in maize-based cropping system, permanent bed planting with residue cover, introduction of intercropping, laser land leveling, DSR, ZT transplanted rice, dual purpose wheat, and crop-livestock interface and this need to be distilled to the rainfed environments
- The better foresight and projections will help to minimize the uncertainty about decision and impact of CA-based technologies in different agroecologies and cropping systems of South Asia.

References

Aggarwal PK, Joshi PK, Ingram JSI, Gupta RK (2004) Adapting food systems of the Indo-Gangetic plains to global environmental change: key information needs to improve policy formulation. Environ Sci Policy 7:487–498

Akter S, Gathala MK (2014) Adoption of conservation agriculture technology in diversified systems and impact on productivity: evidence from three districts in Bangladesh. Contributed paper prepared for presentation at the 88th annual conference of the agricultural economics society, AgroParisTech, Paris, France, 9–11 April, p 24

Al-Kaisi MM, Yin XH (2005) Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn-soybean rotations. J Environ Qual 34:437–445

Aslam M, Majid A, Hobbs PR, Hashim NI, Byerlee D (1989) Wheat in the rice-wheat cropping system of the Punjab: a synthesis of on-farm research results 1984–1989. PARC/CIMMYT paper No. 89–93. CIMMYT, Mexico

Aslam M, Majid A, Hashmi NI, Hobbs PR (1993) Improving wheat yield in the rice-wheat cropping system of the Punjab through zero tillage. Pak J Agric Res 14:8–11

Aulakh MS, Khera TS, Doran JW, Bronson KF (2001) Managing crop residue with green manure, urea, and tillage in rice-wheat rotation. Soil Sci Soc Am J 65:820–827

Aziz I, Mahmood T, Islam KR (2013) Effect of long term no-till and conventional tillage practices on soil quality. Soil Till Res 131:28–35

Bakhsh K, Hassan I, Maqbool A (2005) Impact assessment of zero-tillage technology in rice-wheat system: a case study from Pakistani Punjab. Electron J Environ Agric Food Chem 4:1132–1137

Balasubramanian V, Adhya TK, Ladha JK (2012) Enhancing eco-efficiency in the intensive cereal-based systems of the Indo-Gangetic Plains. In: Hershey CH, Neate P (eds) Issues in tropical agriculture eco-efficiency: from vision to reality. CIAT, Cali, pp 99–115

Barclay A (2006) The direct approach: a return to the ways of their forefathers has seen Indian and Bangladeshi rice farmers reduce their cost for water and address the growing problem of labor shortages. Rice Today 5:12–18

Bazaya BR, Sen A, Srivastava VK (2009) Planting methods and nitrogen effects on crop yield and soil quality under direct seeded rice in the Indo-Gangetic plains of eastern India. Soil Till Res 105:27–32

Benech-Arnold RL, Sánchez RA, Forcella F, Kruk BC, Ghersa CM (2000) Environmental control of dormancy in weed seed banks in soil. Field Crops Res 67:105–122

Bhaatia A, Pathakb H, Jaina N, Singha PK, Singh AK (2005) Global warming potential of manure amended soils under rice-wheat system in the Indo-Gangetic plains. Atmos Environ 39:6976–6984

Bhattacharyya R, Kundu S, Pandey SC, Singh KP, Gupta HS (2008) Tillage and irrigation effects on crop yields and soil properties under rice-wheat system of the Indian Himalayas. Agric Water Manage 95:993–1002

Bhattacharyya R, Toti MD, Kundu S, Bisht JK, Bhatt JC (2012) Conservation tillage impacts on soil aggregation and carbon pools in a sandy clay loam soil of the Indian Himalayas. Soil Sci Soc Am J 76:1–11

BK SB, Srivastav SB, Gurung SB, Ferrara GO, Shrestha J (2013) Effect of conservation agriculture on growth and productivity of maize in Terai Region of Nepal. Merit Res J Agric Sci Soil Sci 1:66–77

Bond W, Grundy AC (2001) Non-chemical weed management in organic farming systems. Weed Res 41:383–405

Chauhan BS, Yadav A, Malik RK (2002) Zero tillage and its impact on soil properties: a brief review. In: Malik RK, Balyan RS, Yadav A, Pahwa SK (eds) Herbicide resistance management and zero tillage in rice-wheat cropping system. CCSHAU, Hisar, pp 109–114

Chauhan BS, Mahajan G, Sardana V, Timsina J, Jat ML (2012) Productivity and sustainability of the rice-wheat cropping system in the Indo-Gangetic plains of the Indian subcontinent: problems, opportunities, and strategies. Adv Agron 117:315–369

Chhokar RS, Sharma RK, Jat GR, Pundir AK, Gathala MK (2007) Effect of tillage and herbicides on weeds and productivity of wheat under rice-wheat growing system. Crop Prot 26:1689–1696

Chiurazzi M (2008) Microbial diversity as soil quality indicator in agricultural soils. http://www.fedoa.unina.it/2040/. Accessed 01 May 2014

Cole CV, Duxbury J, Freney J (1997) Global estimates of potential mitigation of greenhouse gas emissions by agriculture. Nutr Cycl Agroecosyst 49:221–228

Das TK, Bhattacharyya R, Sharma AR, Das S, Saad AA, Pathak H (2013) Impacts of conservation agriculture on total soil organic carbon retention potential under an irrigated agro-ecosystem of the western Indo-Gangetic plains. Eur J Agron 51:34–42

Derpsch R (2008) No-tillage and conservation agriculture: a progress report. In: Goddard T, Zoebisch MA, Gan YT, Ellis W, Watson A, Sombatpanit S (eds) No-tillage farming systems. Special Publication No. 3. World Association of Soil and Water Conservation (WASWC), Bangkok, pp 7–39

Duveiller E, Bridge J, Rutherford M, Keeling S (2004) Soil health and sustainability of the rice-wheat systems of the Indo-Gangetic plains. Rice-Wheat Consortium Paper Series 16. RWC, New Delhi

Duveiller E, Singh R, Nicol J (2007) The challenges of maintaining wheat productivity: pests, diseases, and potential epidemics. Euphytica 157:417–430

Duxbury JM, Abrol IP, Gupta RK, Bronson KF (2000) Analysis of long-term fertility experiments with rice-wheat rotations in South Asia. In: Abrol IP, Bronson KF, Duxbury JM, Gupta RK (eds) Long-term soil fertility experiments in rice-wheat cropping systems. Rice-Wheat Consortium Paper Series 6. RWC, New Delhi, pp 7–22

Erenstein O (2002) Crop residue mulching in tropical and semi-tropical countries: an evaluation of residue availability and other technological implications. Soil Tillage Res 67:115–133

Erenstein O, Laxmi V (2008) Zero tillage impacts in India's rice-wheat systems: a review. Soil Tillage Res 100:1–14

Erenstein O, Farooq U, Malik RK, Sharif M (2007a) Adoption and impacts of zero tillage as a resource conserving technology in the irrigated plains of South Asia: comprehensive assessment of water management in agriculture. Research Report 19, International Water Management Institute, Colombo, Sri Lanka

Erenstein O, Malik RK, Singh S (2007b) Adoption and impacts of zero tillage in the irrigated rice-wheat systems of Haryana, India. Research report New Delhi. International Maize and Wheat Improvement Center and Rice-Wheat Consortium

Erenstein O, Sayer K, Wall P, Dixon J, Hellin J (2008) Adapting no-tillage agriculture to the smallholder maize and wheat farmers in the tropics and sub-tropics. In: Goddard T, Zoebisch MA, Gan YT, Ellis W, Watson A, Sombatpanit S (eds) No-tillage farming systems. Special Publication No. 3. World Association of Soil and Water Conservation (WASWC), Bangkok, pp 253–277

Farooq M, Nawaz A (2014) Weed dynamics and productivity of wheat in conventional and conservation rice-based cropping systems. Soil Till Res 141:1–9

Farooq M, Flower K, Jabran K, Wahid A, Siddique K (2011) Crop yield and weed management in rainfed conservation agriculture. Soil Tillage Res 117:172–83

Franke AC, Singh S, McRoberts N, Nehra AS, Godara S, Malik RK, Marshall G (2007) *Phalaris minor* seed-bank studies: longevity, seedling emergence and seed production as affected by tillage regime. Weed Res 47:73–83

Friedrich T, Kassam AH (2009) Adoption of conservation agriculture technologies: constraints and opportunities. Invited paper at the IV world congress on conservation agriculture, 4–7 February 2009, New Delhi, India

Friedrich T, Derpsch R, Kassam A (2012) Overview of the global spread of the conservation agriculture. Field Actions Sci 6:1–7

Gallagher R, Fernandes E, Mccallie E (1999) Weed management through short-term improved fallows in tropical agroecosystems. Agrofor Syst 47:197–221

Gangwar KS, Singh KK, Sharma SK, Tomar OK (2006) Alternative tillage and crop residue management in wheat after rice in sandy loam of Indo-Gangetic plains. Soil Till Res 88:242–252

Gathala MK, Ladha JK, Kumar V, Saharawat YS, Kumar V, Sharma PK, Sharma S, Pathak H (2011) Tillage and crop establishment affects sustainability of South Asian rice-wheat system. Agron J 103:961–971

Gill MA (2006) Zero tillage wheat in rice-wheat cropping system-evidence from farmers' fields. Pak J Agric Res 19:1–6

Gill MS, Pal SS, Ahlawat IPS (2008) Approaches for sustainability of rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system in Indo-Gangetic plains of India: a review. Indian J Agron 53:81–96

Govaerts B, Sayre KD, Deckers J (2005) Stable high yields with zero tillage and permanent bed planting? Field Crop Res 94:33–42

Govaerts B, Mezzalama M, Unno Y, Sayre K, Luna-Guido M, Vanherck M, Dendooven L, Deckers J (2007) Influence of tillage, residue management, and crop rotation on soil microbial biomass and catabolic diversity. Appl Soil Ecol 37:18–30

Govaerts B, Verhulst N, Castellanos-Navarrete A, Sayre KD, Dixon J, Dendooven L (2009) Conservation agriculture and soil carbon sequestration: between myth and farmer reality. Crit Rev Plant Sci 28:97–122

Grace PR, Jain MC, Harrington L, Robertson GP (2003) The long-term sustainability of tropical and sub-tropical rice and wheat systems: an environmental perspective. In: Ladha JK, Hill JE, Duxbury JM, Gupta RK, Buresh RJ (eds) Improving the productivity and sustainability of rice-wheat systems: issues and impacts. ASA special publication 65. ASA, Madison, pp 27–43

Green B, Lafond G (1999) Farm facts: soil temperature and crop emergence under conventional and direct seeding. Department of Agriculture and Food, Saskatchewan Government, p 4

Gupta R, Sayre K (2007) Conservation agriculture in South Asia. J Agric Sci 145:207–214

Gupta R, Seth A (2007) A review of resource conserving technologies for sustainable management of the rice-wheat cropping systems of the Indo-Gangetic plains (IGP). Crop Prot 26:436–447

Gupta RK, Naresh RK, Hobbs PR, Ladha JK (2002) Adopting conservation agriculture in the rice-wheat system of the Indo-Gangetic plains: new opportunities for saving water. In: Bouman BAM, Hengsdijk H, Hardy B, Bindraban PS, Tuong TP, Ladha JK (eds) Water wise rice production. Proceedings of the international workshop on water wise rice production, April 8–11. International Rice Research Institute, Los Banos, pp 207–222

Gupta P, Sahai S, Singh N, Dixit C, Singh D, Sharma C, Tiwari M, Gupta R, Garg S (2004) Residue burning in rice-wheat cropping system: causes and implications. Curr Sci 87:1713–1717

Gupta R, Gopal R, Jat ML, Jat RK, Sidhu HS, Minhas PS, Malik RK (2010) Wheat productivity in Indo-Gangetic plains of India during 2010: terminal heat effects and mitigation strategies. PACA Newslett 14:1–11

Hira GS (2009) Water management in northern states and the food security of India. J. Crop Improv 23:136–157

Hobbs PR (2006) Conservation agriculture: what is it and why is it important for future sustainable food production? Paper presented at international workshop on increasing wheat yield potential, CIMMYT, Mexico

Hobbs PR (2007) Conservation agriculture: what is it and why is it important for future sustainable food production? J Agric Sci 145:127–137

Hobbs PR, Gupta R (2003) Resource-conserving technologies for wheat in the rice-wheat systems. In: Ladha JK, Hill JE, Duxbury JM, Gupta RK, Buresh RJ (eds) Improving the productivity and sustainability of rice-wheat systems: issues and impacts. ASA Special Publication Number 65. ASA-CSSA-SSSA, Madison, pp 149–172

Hobbs PR, Govaerts B (2010) How conservation agriculture can contribute to buffering climate change. In: Reynolds M (ed) Climate change and crop production. CABI Climate Change Series, vol 1. CABI, Cambridge, pp 177–199

Hobbs P, Singh Y, Giri GS, Lauren JG, Duxbury JM (2001) Direct seeding and reduced tillage options in the rice-wheat systems of the Indo-Gangetic plains of South Asia. In: Pandey S, Mortimer M, Wade L, Toung TP, Lopez K, Hardy B (eds) Proceedings of the Workshop on Direct Seeding in Asian Rice Systems. IRRI, Los Banos

Hobbs P, Gupta R, Meisner C (2006) Conservation agriculture and its applications in South Asia. In: Uphoff N (ed) Biological approaches to sustainable soil systems. CRC, United States, pp 357–571

Hobbs P, Sayre K, Gupta R (2008) The role of conservation agriculture in sustainable agriculture. Phil Trans R Soc B 363:543–555

Holland JM (2004) The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric Ecosys Environ 103:1–25

Hütsch BW (1998) Tillage and land use effects on methane oxidation rates and their vertical profiles in soil. Biol Fertil Soils 27:284–292

Inayatullah C, Ehsan-ul-Haq, Ata-ul-Mohsin, Rehman A, Hobbs PR (1989) Management of rice stem borer and the feasibility of adopting no-tillage in wheat. Entomological Research Laboratories, National Agricultural Research Centre, Pakistan Agricultural Research Council, Islamabad, p 64

IPCC (2007) Summary for policymakers. In: Parry ML, Canziani OF, Palutikof JP, Linden PJV, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 7–22

Jacinthe PA, Lal R (2004) Effects of soil cover and land-use on the relations flux-concentration of trace gases. Soil Sci 169:243–259

Jaipal S, Malik RK, Hobbs P, Yadav A, Singh S (2005) Conservation agriculture—IPM issues. In: Abrol IP, Gupta RK, Malik RK (eds) Conservation agriculture status and prospects. Centre for Advancement of Sustainable Agriculture, New Delhi, p 242

Jat ML, Singh S, Rai HK, Chhokar RS, Sharma SK, Gupta R (2005) Furrow Irrigated raised bed planting technique for diversification of rice-wheat system of Indo-Gangetic plains. J Jpn Assoc Int Coop Agric For 28:25–42

Jat ML, Chandana P, Sharma SK, Gill MA, Gupta RK (2006) Laser land leveling—a precursor technology for resource conservation. Rice-Wheat Consortium Technical Bulletin Series 7. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, p 48

Jat ML, Gathala MK, Ladha JK, Saharawat YS, Jat AS, Kumar V, Sharma SK, Kumar V, Gupta R (2009a) Evaluation of precision land leveling and double zero-till systems in the rice-wheat rotation: water use, productivity, profitability and soil physical properties. Soil Till Res 105:112–121

Jat ML, Ramasundaram P, Gathala MK, Sidhu HS, Singh S, Singh RG, Saharawat YS, Kumar V, Chandna P, Ladha JK (2009b) Laser-assisted precision land leveling: a potential technology for resource conservation in irrigated intensive production systems of Indo-Gangetic plains. In: Ladha JK Yadvinder-Singh, Erenstein O, Hardy B (eds) Integrated crop and resource management in the rice-wheat system of South Asia. International Rice Research Institute, Los Baños, pp 223–238

Jat ML, Saharawat YS, Gupta RK, Khosla R (2011a). Layering precision land leveling and furrow irrigated raised bed planting: productivity and input use efficiency of irrigated bread wheat in Indo-Gangetic plains. Am J Plant Sci 2:578–588

Jat ML, Saharawat YS, Gupta RK (2011b) Conservation agriculture in cereal systems of South Asia: nutrient management perspectives. Karnataka J Agric Sci 24:100–105

Joshi PK (2012) Greening agriculture in South Asia. http://www.ifpri.org/blog/greening-agriculture-south-asia. Accessed 15 May 2014

Jung WS, Kim KH, Ahn JK, Hahn SH, Chung IM (2004) Allelopathic potential of rice (*Oryza sativa* L.) residues against *Echinochloa crusgalli*. Crop Prot 23:211–218

Kaur B, Sidhu RS, Vatta K (2010) Optimal crop plans for sustainable water use in Punjab. Agric Econ Res Rev 23:273–284

Krishna V, Mehrotra MB, Teufel N, Bishnoi DK (2012) Characterizing the cereal systems and identifying the potential of conservation agriculture in South Asia. Socio-Economics Program Working Paper 5. CIMMYT, Mexico, D.F

Krishna VV, Veettil PC (2014) Productivity and efficiency impacts of conservation tillage in northwest Indo-Gangetic plains. Agric Syst 127:126–138

Kumar S, Kukreja K, Suneja S, Kundu BS, Malik RK (2005) Tillage effect on wheat (*Triticum aestivum* L.) rhizosphere microbiol cummunities and their activity. Project workshop proceeding on "Accelerating the Adoption of Resource Conservation Technologies in Rice-wheat Systems of the Indo-Gangetic Plains" held on June 1–2, at Hisar (Haryana), India, pp 54–60

Kumar V, Bellinder RR, Gupta RK, Malik RK, Brainard DC (2008) Role of herbicide resistant rice in promoting resource conservation technologies in rice-wheat cropping systems of India: a review. Crop Prot 27:290–301

Kumar V, Saharawat YS, Gathala MK, Jat AS, Singh SK, Chaudhary N, Jat ML (2013) Effect of different tillage and seeding methods on energy use efficiency and productivity of wheat in Indo-Gangetic plains. Field Crop Res 142:1–8

Ladha JK, Pathak D, Yadav RL (2003) How extensive are yield declines in long term rice wheat experiments in Asia? Field Crop Res 81:159–180

Ladha JK, Kumar V, Alam MM, Sharma S, Gathala MK, Chandna P, Saharawat YS, Balasubramanian V (2009) Integrating crop and resource management technologies for enhanced productivity, profitability and sustainability of the rice-wheat system in South Asia. In: Ladha JK Yadvinder-Singh, Erenstein O, Hardy B (eds) Integrated crop and resource management in the rice-wheat system of South Asia. IRRI, Los Banos, pp 69–108

Lal R (2004) Soil carbon sequestration in India. Clim Change 65:277–296

Lal R (2007) Constraints to adopting no-till farming in developing countries. Soil Till Res 94:1–3

Lal R, Reicosky DC, Hanson GD (2007) Evolution of plow over 1000 years and rationale for no tillage farming. Soil Tillage Res 93:1–12

Latif A, Shakir AS, Rashid MU (2013) Appraisal of economic impact of zero tillage, laser land leveling and bed-furrow interventions in Punjab, Pakistan. Pak J Eng Appl Sci 13:65–81

Laxmi V, Gupta RK, Swarnalatha A, Perwaz S (2003) Environmental impact of improved technology—farm level survey and farmers' perception on zero tillage (case study). In: Paper Presented at Roles of Agriculture Workshop October 20–22, Rome, Italy. Indira Gandhi Institute of Development Research, Mumbai

Laxmi V, Erenstein O, Gupta RK (2007a) Assessing the impact of NRM research: the case of zero tillage in India's rice-wheat systems. In: Zilberman D, Waibel H (eds) The impact of NRM research in the CGIAR. CABI, Wallingford, pp 68–90

Laxmi V, Erenstein O, Gupta RK (2007b) Impact of zero tillage in India's rice-wheat systems. CIMMYT and Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi

Lu YC, Watkins KB, Teasdale JR, Abdul-Baki AA (2000) Cover crops in sustainable food production. Food Rev Int 16:121–157

Mader P, Berner A (2012) Development of reduced tillage systems in organic farming in Europe. Renew Agric Food Syst 27:7–11

Mahajan G, Brar LS, Walia US (2002) *Phalaris minor* response in wheat in relation to planting dates, tillage and herbicides. Indian J Weed Sci 34:213–215

Malik RK, Gill G, Hobbs PR (1998) Herbicide resistance: a major issue for sustaining wheat productivity in rice-wheat cropping systems in the Indo-Gangetic plains. Rice-Wheat Consortium Paper Series 3, New Delhi

Malik RK, Gupta RK, Singh CM, Brar SS, Singh SS, Sinha RK, Singh AK, Singh R, Naresh RK, Singh KP, Thakur TC (2004) Accelerating the adoption of resource conservation technologies for farm level impact on sustainability of rice–wheat system of the Indo-Gangetic plains. NATP Progress Report. CCSHAU, Haryana, India

Malik RK, Yadav A, Singh S, Malik RS, Balyan RS, Banga RS, Sardana PK, Jaipal S, Hobbs PR, Gill G, Singh S, Gupta RK, Bellinder R (2002) Herbicide resistance management and evolution of zero tillage—a success story. Research Bulletin, CCS Haryana Agricultural University, Hisar, p 37

Malik RK, Yadav A, Singh S (2005) Resource conservation technologies in rice-wheat cropping system of Indo-Gangetic plain. In: Abrol LP, Gupta RK, Malik RK (eds) Conservation agriculture: status and prospects. Centre for Advancement of Sustainable Agriculture, New Delhi, pp 13–22

Malla G, Bhatia A, Pathak H, Prasad S, Jain N, Singh J (2005) Mitigating nitrous oxide and methane emissions from soil in rice-wheat system of the Indo-Gangetic plain with nitrification and urease inhibitors. Chemosphere 58:141–147

Mathys C, McDonald A (2013) Cereal Systems Initiative for South Asia (CSISA) Phase II. International Maize and Wheat Improvement Center (CIMMYT). Annual Report, November 15

Mehta AK, Singh R (2005) Transfer of resource conserving technologies through Krishi Vigyan Kendras. In: Abrol IP, Gupta RK, Malik RK (eds) Conservation agriculture: status and prospects. Centre for Advancement of Sustainable Agriculture, New Delhi, pp 128–134

Mishra JS, Singh VP (2012) Tillage and weed control effects on productivity of a dry seeded rice-wheat system on a vertisol in central India. Soil Tillage Res 123:11–20

Mohanty M, Painuli DK, Misra AK, Ghosh PK (2007) Soil quality effects of tillage and residue under rice-wheat cropping on a Vertisol in India. Soil Tillage Res 92:243–250

Naresh RK, Singh SP, Tomar SS, Purushottam (2013) Role of conservation agriculture for enhancing productivity, sustainability of Rice-wheat systems in climate change scenario of North West India. Int J Res Biomed Biotechnol 3:21–29

Nawaz (2012) Studying the resource use efficiency and productivity of wheat in conventional and conservation rice based cropping systems. M. Sc. (Hons.) Thesis, Department of Agronomy, University of Agriculture, Faisalabad, Pakistan

Nawaz A, Farooq M (2013) Weed dynamics and soil physical properties in conventional and conservation rice-wheat cropping systems. In: Farooq M, Hussain M, Lee DL (eds) Proceedings of 3rd international conference 'Frontiers in Agriculture' 3–5 October 2012. Dankook International Cooperation on Agriculture, Dankook University, Cheonansi, pp 1–4

Noorka IR, Shahid SA (2013) Use of conservation tillage system in semiarid region to ensure wheat food security in Pakistan. In: Shahid SA, Abdelfattah MA, Taha FK (eds) Developments in soil salinity assessment and reclamation. Springer, Netherlands, pp 769–782

Pathak H, Bhatia A, Prasad S, Jain MC, Kumar S, Singh S, Kumar U (2002) Emission of nitrous oxide from soil in rice-wheat systems of Indo-Gangetic plains of India. Environ Monit Asses 77:163–178

Peigné J, Ball BC, Roger-Estrade J, David C (2007) Is conservation tillage suitable for organic farming? A review. Soil Use Manage 23:129–144

Qamar R, Ehsanullah, Rehman A, Ali A, Ghaffar A, Mahmood A, Javeed HMR, Aziz M (2013) Growth and economic assessment of wheat under tillage and nitrogen levels in rice-wheat system. Am J Plant Sci 4:2083–2091

Ram H, Kler DS, Singh Y, Kumar K (2010) Productivity of maize (*Zea mays*)-wheat (*Triticum aestivum*) system under different tillage and crop establishment practices. Indian J Agron 55:185–190

Ramakrishna A, Sharma SB (1998) Cultural practices in rice- wheat-legume cropping systems: effect on nematode community. In: Sharma SB, Johansen C, Midha SK (eds) Nematode pests in rice-wheat-legume cropping systems: proceedings of a regional training course, CCS Haryana Agricultural University, Hisar, Haryana, India, 1–5 September 1997. Rice-Wheat Consortium Paper Series 4. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, pp 73–79

Rautaray SK (2005) Machinery for conservation agriculture: progress and needs. In: Abrol IP, Gupta RK, Malik RK (eds) Conservation agriculture—status and prospects. Centre for Advancement of Sustainable Agriculture, New Delhi, pp 43–49

Reicosky DC, Kemper WD, Langdale GW, Douglas CL, Junior CW, Rasmussen PE (1995) Soil organic matter changes resulting from tillage and biomass production. J Soil Water Conser 50:253–261

Robinson DW (1998) Mulches and herbicides in ornamental plantings. Hort Sci 23:547–552

Sah G, Shah SC, Sah SK, Thapa RB, McDonald A, Sidhu HS, Gupta RK, Wall P (2013) Productivity and soil attributes as influenced by resource conservation technologies under rice-wheat system in Nepal. Agron J Nepal 3:64–72

Saharawat YS, Gathala M, Ladha JK, Malik RK, Singh S, Jat ML, Gupta R, Pathak H, Singh K (2009) Evaluation and promotion of integrated crop and resource management in rice-wheat system in North West India. In: Ladha JK, Yadvinder-Singh, Erenstein O, Hardy B (eds) Integrated crop and resource management in rice-wheat system of South Asia. IRRI, Los Banos, pp 133–150

Saharawat YS, Singh B, Malik RK, Ladha JK, Gathala MK, Jat ML, Kumar V (2010) Evaluation of alternative tillage and crop establishment methods in a rice-wheat rotation in North Western IGP. Field Crop Res 116:260–267

Saharawat YS, Ladha JK, Pathak H, Gathala M, Chaudhary N, Jat ML (2012) Simulation of resource-conserving technologies on productivity, income and greenhouse gas GHG emission in rice-wheat system. J Soil Sci Environ Manag 3:9–22

Sapkota TB, Majumdar K, Jat ML, Kumar A, Bishnoi DK, McDonald AJ, Pampolino M (2014) Precision nutrient management in conservation agriculture based wheat production of Northwest India: profitability, nutrient use efficiency and environmental footprint. Field Crops Res 155:233–244

Scheehle EA, Kruger D (2006) Global anthropogenic methane and nitrous oxide emissions. Energy J 27:33–44

Sharma PK, Acharya CL (2000) Carry-over of residual soil moisture with mulching and conservation tillage practices for sowing of rainfed wheat (*Triticum aestivum* L.) in north-west India. Soil Tillage Res 57:43–52

Sharma RK, Babu KS, Chhokar RS, Sharma AK (2004) Effect of tillage on termites, weed incidence and productivity of spring wheat in rice-wheat system of North Western Indian plains. Crop Prot 23:1049–1054

Sharma RK, Chhokar RS, Jat ML, Singh S, Mishra B, Gupta RK (2008) Direct drilling of wheat into rice residues: experiences in Haryana and western Uttar Pradesh. In: Humphreys E, Roth CH (eds) Permanent beds and rice-residue management for rice-wheat system of the Indo-Gangetic plain. Australian Centre for International Agricultural Research (ACIAR) Proceedings. vol 127. ACIAR, Canberra, pp 147–158

Sharma AR, Singh R, Dhyani SK, Dube RK (2010) Effect of live mulching with annual legumes on performance of maize (*Zea mays*) and residual effect on following wheat (*Triticum aestivum*). Indian J Agron 55:177–184

Sharma AR, Jat ML, Saharawat YS, Singh VP, Singh R (2012) Conservation agriculture for improving productivity and resource use efficiency: prospects and research needs in Indian context. Indian J Agron 57:131–140

Sidhu HS, Manpreet-Singh, Humphreys E, Yadvinder-Singh, Balwinder-Singh, Dhillon SS, Blackwell J, Bector V, Malkeet-Singh, Sarbjeet-Singh (2007) The happy seeder enables direct drilling of wheat into rice stubble. Aust J Exp Agric 47:844–854

Singh KM, Meena MS (2013) Information and communication technologies for sustainable natural resource management. http://dx.doi.org/10.2139/ssrn.2244751. Accessed 14 May 2014

Singh S, Sharma SN, Prasad R (2001) The effect of seeding and tillage methods on productivity of rice-wheat cropping system. Soil Tillage Res 61:125–131

Singh S, Ladha JK, Gupta RK, Bhushan L, Rao AN, Sivaprasad B, Singh PP (2007) Evaluation of mulching, intercropping with Sesbania and herbicide use for weed management in dry-seeded rice (*Oryza sativa* L.). Crop Prot 26:518–524

Subash N, Gangwar B, Singh R, Sikka AK (2014) Identification of climate-resilient integrated nutrient management practices for rice-rice cropping system—an empirical approach to uphold food security. Int J Biometeorol doi:10.1007/s00484-014-0825-5 (published online)

Thakur TC, Kishor R, Malik RK, Gupta RK (2004) Socio-economic impact of zero-till technology of wheat in the State of Uttaranchal. NATP Project "Accelerating the adoption of resource conservation technologies (RCTs) for farm level impact on sustainability of rice-wheat systems of the Indo-Gangetic Plains". Department of Farm Machinery and Power Engineering, College of Technology. G.B. Pant University of Agriculture and Technology, Pantnagar, Uttaranchal

Timsina J, Jat ML, Majumdar K (2010) Rice-maize systems of South Asia: current status, future prospects and research priorities for nutrient management. Plant Soil 335:65–82

Timsina J, Buresh RJ, Dobermann A, Dixon J (2011) Rice-maize systems in Asia: current situation and potential. International Rice Research Institute, Los Baños, p 235

Tripathi J (2010) Evaluation and promotion of resource conservation technologies in low land rice-wheat ecosystem. Agron J Nepal 1:28–39

Tripathi J, Adhikari C, Lauren JG, Duxbury JM, Hobbs PR (2006) Assessment of farmer adoption of surface seeded wheat in the Nepal terai. Rice-Wheat Consortium Paper Series 19. Rice-Wheat Consortium, New Delhi

Tripathi RS, Raju R, Thimmappa K (2013) Impact of zero tillage on economics of wheat production in Haryana. Agric Econ Res Rev 26:101–108

Van-Groenigen JW, Velthof GL, Oenema O, Van-Groenigen KJ, Van-Kessel C (2010) Towards an agronomic assessment of N_2O emissions: a case study for arable crops. Eur J Soil Sci 61: 903–913

Verburg PH, Bodegom PM, Denier-Vander-Gon HAC, Bergsma A, Breemen NOV (2006) Up-scaling regional emissions of greenhouse gases from rice cultivation: methods and sources of uncertainty. Plant Ecol 182:89–106

Xu S, Peter RJ, Denise LM (2007) A process-based model for methane emission from flooded rice paddy systems. Ecol Modell 205:475–491

Yan WX, Wen GH, Wen LH, Xiang ZX (2000) Experimental study on runoff and erosion under conservation tillage. Trans Chin Soc Agric Eng 16:66–69

Zou JW, Huang Y, Zheng XH, Wang YS (2007) Quantifying direct N_2O emissions in paddy fields during rice growing season in mainland China: dependence on water regime. Atmos Environ 41:8030–8042

Chapter 12
Conservation Agriculture in Southeast Asia

Jean-Claude Legoupil, Pascal Lienhard and Anonh Khamhoung

Abstract In Southeast Asia (SEA), the joint process of deforestation, agricultural land expansion, and intensification has led to vast soil erosion and a general decrease in soil and water quality. In addition, current agricultural practices such as deep plowing of soil or burning of forest and crop residues favor CO_2 emissions and contribute to global warming. The deforestation rate in SEA is important (0.91 % per year of the forest area) and soil degradation is important either by erosion or acidity (63 % of the total land area). Conservation agriculture (CA) is an alternative land-use system reconciling economic viability, social balance, soil fertility restoration, and environmental conservation as well as climate change adaptation, which are crucial elements for the long-term improvement of smallholders' living conditions and poverty alleviation. A basket of CA technologies, including zero or reduced tillage, direct seeding, crop rotations, soil cover, and residue management has been developed in different countries. Adoption of CA technologies has regenerated fertility of degraded soils, provided livestock with high-quality forage, and increased soil carbon sequestration. New innovative farming systems need to be developed to successfully integrate crops and livestock by offering numerous advantages such as diversification of income through animal products such as milk, meat, fiber and manure, weed control, soil erosion control, increased yield of main crops, and income during the "start-up" period for tree crops. The development of farming systems, which are more intensive and respectful of natural resources and the environment, requires acquisition of new stakeholder knowledge and skills. This is a priority since these stakeholders will initiate the required changes. The Conservation Agriculture Network for Southeast Asia (CANSEA) was created in 2009 to optimize similarities and complementarities among countries and institutions in SEA to improve the efficiency of research carried out by the various programs, and to optimize resources and means.

Keywords Biodiversity · Carbon sequestration · Deforestation · Erosion · Smallholders

---

J.-C. Legoupil (✉) · P. Lienhard
Conservation Agriculture and Systems Engineering, CIRAD, 34398 Montpellier Cedex 5, France
e-mail: legoupil@cirad.fr

A. Khamhoung
Department of Land Management and Development of the Ministry of Agriculture and Forestry, Vientiane, Laos

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_12

12.1 Introduction

Southeast Asian (SEA) countries have demonstrated a comparative advantage in their rate of expansion, resulting in sizable gains in global market shares for key food and agricultural products. The challenge for SEA is to pursue economic development without placing additional pressure on natural resources and the environment. The degradation of agricultural resources is a major hurdle in improving the global situation of agriculture in the region. Natural resources upon which agricultural production depends are deteriorating due to land degradation, forest loss, and poor agricultural practices. The intrinsic fragility of soils, the rate of organic matter decomposition, and increased population pressure have led to yield declines (Dierog et al. 2001; Lienhard et al. 2013a)

The negative impacts of conventional agricultural practices—land degradation, soil erosion (Fig. 12.1), declines in biodiversity, pollution, desertification, etc.—are well known. Added to these are the dramatic social implications of famine, poverty, out-migration, etc. Global food needs are rising with population growth. Agricultural production needs to increase to fulfill these pressing needs. Agricultural systems capable of meeting this challenge must now be productive, profitable, and sustainable. Production and quality must be improved to boost farmers' incomes while preserving natural resources and the environment. Through many positive impacts in the field and for the environment, conservation agriculture (CA) and ecological intensification can effectively meet these substantial challenges in both developing and developed countries. The principal identified route to feeding an increasing population while mitigating climate change, in particular in developing countries, is assisting smallholder farmers in agricultural development and especially with the promotion of agroecological farming practices (De Schutter 2011).

Fig. 12.1 Soil erosion after plowing in North Laos

12.2 History of CA in Southeast Asia

CA is any cropping system, which integrates the three principles of minimal soil disturbance, permanent soil cover, and crop rotations (FAO 2007), and is not dissociable from conservation tillage, defined by Lal (1989) as any tillage system that reduces loss of soil or water relative to conventional tillage. Both approaches have similar objectives (e.g., soil erosion control, soil fertility improvement), promote to some extent similar tools (e.g., use of cover crops, soil mulching, reduction/cancellation of soil tillage, integration of the landscape dimension), and face similar constraints regarding their broad adoption (e.g., opportunity cost of land and labor, field protection against communal grazing, management skills).

In recent decades, agrarian landscapes and livelihoods in the uplands of SEA have undergone dramatic changes. Farming households have had to adapt to the mounting influence of global drivers such as demographic changes, market forces, and government policies that have led to the rapid expansion and intensification of agriculture (Castella 2012). The need to buffer the negative consequences of these land-use changes (e.g., deforestation, land degradation) has rapidly emerged.

Experiments and the promotion of soil and water conservation practices started in the early 1970s (Garrity 1996) and included various technical packages, including contour hedgerows systems, agroforestry practices, natural vegetative strips, and managed fallows. Contour hedgerow systems were developed in the Philippines in the early 1970s and are based on the principle of growing field and permanent crops in 3–5-m-wide bands between double-contoured hedgerows of nitrogen-fixing trees. These leguminous trees are regularly pruned and the cuttings are placed in alleyways to serve as organic fertilizers (MBLRC 2004). Contour hedgerows were widely promoted during the 1980s and 1990s in several SEA countries (e.g., Indonesia, Myanmar, Thailand, Vietnam, and Philippines) to reduce soil erosion and maintain soil fertility. These were the first experiments in SEA showing interest in soil mulching. Two main constraints were identified for their broad diffusion (Garrity 1996): (1) the tendency for perennial pruned-tree hedgerows to compete for growth resources and hence reduce yields of associated annual crops planted in adjacent rows and (2) the enormous amount of labor needed to prune and maintain hedgerows. The diffusion of contour hedgerow systems has also been hindered by the increasing pressure on land to increase and sustain agricultural production (Lal 2005), with smallholders confronted more and more with the opportunity cost of growing hedgerows where staple or cash crops may be grown. Competition between main and relay crops, labor requirements, labor difficulty and, above all, the opportunity costs of land and labor are similar constraints experienced for CA diffusion in SEA, with the main challenge for smallholder farmers being how to make the best use of limited resources (land, labor, and capital).

Considerable agronomic studies were conducted in SEA countries in the 1990s to improve the benefits of fallowing through the establishment and management of leguminous species during fallow periods of less than 2 years. Experiments were based on the use of herbaceous, fast-growing legume cover crops (von Uexkull and Mutert 1995), shrubby legumes (Roder and Maniphone 1998), or forage legumes (Garrity 1996). All studies pointed out the benefits of using legume species in short-term fallows to accelerate soil fertility regeneration, weed suppression, and/or provide a possible source of other economic benefits. The main constraints highlighted for the greater diffusion of cover crops use were: field protection from communal grazing, protection from dry season fires, and a dependable seed supply, all of which are common constraints in CA diffusion.

CA is much more recent with less than a decade of on-field experiments in SEA. The first projects, which included a CA component, were located in continental SEA (Cambodia, Laos, and Vietnam) and have been mainly supported by the French Development Agency (AFD) with technical support from the French Agricultural Research Centre for International Development (CIRAD). More recently, new institutions (US and Australian universities, ICRAF) supported by other donors (United States Agency for International Development, USAID, AusAid, Australian Centre for International Agricultural Research, ACIAR) have similarly initiated work on CA in continental (Cambodia, Vietnam) and insular (Philippines) SEA.

12.3 Current Status of CA in SEA

Since the history of CA in SEA is short (less than a decade), its development has been driven more by the research sector than extension. The main success stories of CA system adoption are with maize cropping due to the expansion of this crop in the region over the past decade (Lestrelin and Castella 2011). Maize cultivation under zero tillage with prior crop residue management and/or relay association with a legume (beans, forage, or shrubby legumes) is the most popular CA system. After 6 years of research and 4 years of extension support, adoption estimates of maize-based CA systems in the south of Sayabouri province (Northern Laos) in 2008 were 1500 ha implemented by 1100 smallholders (Slaats and Lestrelin 2009) and 5000 ha in 2011 (Panyasiri et al. 2011). However, only a limited (~10 %) and highly variable percentage of these areas were implemented in association or rotation with a legume (Slaats and Lestrelin 2009). Maize associated or intercropped with legume crops are the main systems tested and promoted in northern Vietnam (Tuan and Doanh 2008; Hauswirth et al. 2011; Nicetic et al. 2011), Yunnan province (Tao et al. 2008), and the Philippines (Mercado et al. 2011), while in Cambodia, they are mainly based on maize and/or cassava (*Manihot esculenta*) associated with stylo legume (*Stylosanthes guianensis* CIAT 184; Boulakia et al. 2008, 2012a) with about 500 ha of experiments conducted and evaluated with farmers (Chabierski et al. 2011).

12.4 CA and Ecological Intensification: An Alternative to Traditional/Conventional Farming Systems

Feeding an increasing population and mitigating climate change through promotion of agroecological farming practices is how the CIRAD and its national partners (National Agricultural Research Institutes) have come together over the past 10 years to develop CA systems, particularly in Brazil, Cambodia, Cameroon, Laos, Madagascar, and Vietnam.

In these countries, CA systems are evaluated according to the main objectives assigned to agricultural food systems (De Schutter 2011) which include the need to: (i) increase agricultural production (to respond to future needs), (ii) increase farmers' incomes (to reduce poverty), notably smallholders' incomes, and (iii) sustain resources, which support agricultural activities.

There are limited published works on CA in SEA with most of the information coming from grey literature (reports, technical leaflets, and communications to congress), which is accessible on the following websites:

- CIRAD: www.agroecologie.cirad.fr
- Conservation Agriculture Network for Southeast Asia (CANSEA): www.cansea.org.vn
- CA and agroforestry: www.conservationagricultureandagroforestry.org
- ORCATAD: http://orcatad.nafri.org.la/

12.4.1 Economic Returns of CA Systems at Field and Farm Level (Economic Impact)

In the absence of government subsidies for the agricultural sector and/or payment for environmental services, clear economic benefits must be apparent for smallholders to change from conventional to CA. The effects of CA on economic returns—calculated as value of production minus operational costs per unit area—vary according to its effect on the main grain or tuber yield of crops and the implementing costs. The economic valorization of the additional biomass produced by cover crops is important in the short term when used for animal production while the medium- to long-term effect is important for soil fertility; however, for farmers during CA development and dissemination, it is not an argument for changing their farming system (Lienhard 2013b).

In productive lands, subsistence agriculture and extensive systems, the operational costs associated with CA systems are generally higher than under conventional slash and burn systems (Fig. 12.2) with additional outlays for secondary crop seed, minimal fertilization and/or pesticide use, and fencing materials. Economic gains therefore rely on productivity gains, which can be substantial (Husson et al. 2001), modest (Nicetic et al. 2011), or nil (Affholder et al. 2009) depending on the

Fig. 12.2 Slash and burn traditional practice in mountainous area

system tested (diversified rotational system vs. mulching) and the years of experimentation (short to medium term).

On productive land engaged in a process of intensification and marketization of agriculture (mountainous area, newly connected to market areas), farmers often practice high-input cultivation without adequate knowledge (Nicetic et al. 2011). Improved crop and input management and intercropping with legumes can significantly improve maize production and increase profits (Nicetic et al. 2011).

On degrading land with commercial intensive monocropping, 5-year experiments with 2-year rotation of maize with rice bean under tillage significantly increased economic returns (from 20 to 50% depending on the year) compared to maize monocropping due to less production costs for land preparation and weed control and associated increased maize yields (Tran Quoc et al. 2008). In Laos, the fee-for-service requested for disc plowing with a tractor under conventional tillage is higher than the cost for rolling and herbicide spraying under CA (Tran Quoc et al. 2008; Slaats and Lestrelin 2009; Lienhard unpublished). In addition, land preparation costs are significantly higher under the conventional system when herbicides are needed before sowing to supplement tillage for effective weed control, which is the common situation after several years of monocropping under tillage (Bounthong et al. 2005; Tran Quoc et al. 2008). The reduction in production costs is the main reason (28% of answers) given by farmers for expanding their cultivated surface under CA in the south of Sayabouri province (Lestrelin et al. 2012b). Despite no significant differences in grain yields, the differences in costs for land preparation and weed control led to significant differences in economic returns (10–15% higher profits for maize continuous cultivation under no-till and crop residue management compared to conventional monocropping under tillage; Tran Quoc et al. 2008; Slaats and Lestrelin 2009) and explained the rapid and large diffusion of this cropping system.

Cambodian rainfed areas engaged in intensive market-oriented agriculture for some time (Chabierski et al. 2011) had greater economic returns under CA systems than conventional tillage systems for maize (15–25% under CA) and cassava (20–35% under CA) production, due to substantial gains in productivity. However, these increases in productivity were associated with higher investments, which represent the main constraint for broader diffusion of CA (Chabierski et al. 2011).

In degraded acidic and weathered savannah soils of northern Laos, grain and forage production was significantly improved with significant gains in economic returns, but required higher initial investments (machinery, fertilizers) when compared to traditional tilled and unfertilized production systems (Lienhard et al. 2008). In highly degraded, poor, and acidic sandy soils (derived from sandstone with a pH of around 4–5 and often aluminum toxicity), CA techniques of no tillage, rice direct seeding, and rotation with legumes and gramineaes forages increased paddy rice production from 2.5 to 4.6 t/ha (3-year average) with the same level of fertilization. Forage production of *Brachiaria humidicola* and *Stylosanthes guianensis* in rotation (3 years) with rice (3 years) allowed beef-fattening activities during the rainy season. Beef weight gain was around 650 g day^{-1} with meat production of around 500–600 kg ha^{-1} (Legoupil 2013).

12.4.2 CA Systems Impact on Soil Fertility and on Environment

12.4.2.1 Effect on Soil Erosion

Soil erosion is deemed a key reason for CA promotion in SEA sloping areas (Bounthong et al. 2005; Tuan and Doanh 2008; Mercado et al. 2011). Valentin et al. (2008) found that mulching significantly reduced runoff and total sediment yield in different catchments in Laos, Thailand, and Vietnam. Lestrelin et al. (2012b) identified soil conservation issues as an important reason for farmers to experiment with CA systems (12 % of answers) and/or to expand their cultivated land under CA (9 % of answers).

12.4.2.2 Effect on Soil Physicochemical Properties

CA has had a positive effect on soil aggregation, which plays a key role in soil organic turnover and soil susceptibility to erosion. Tivet et al. (2008) observed a significant increase (up to 60 %) in the mean weight diameter (MWD) of aggregates in field top soils (0–10 cm) under no-till management (maize monocropping with residue management and 2-year rotation of maize and rice bean) compared with conventional tilled and maize monocropping systems. Lienhard et al. (2013d) had similar results for a 3-year rotation of rice, maize, and soybean cultivated under no-till management with cover crops prior to and with main crops, or under conventional tillage. Lienhard et al. observed a significant decrease in C and N contents in top soil (0–10 cm) in a Laos savannah grassland under conventional tillage compared to CA management (11 % difference after 2 years' cultivation). Despite similar amendments, the sum of exchangeable bases was 1.5-fold higher under CA systems than under conventional tillage.

12.4.2.3 Effect on Soil Biodiversity and Biological Activity

Several regional studies have shown a significant positive effect of CA systems on soil macrofauna diversity (Husson et al. 2003; Boyer et al. 2008; Boulakia et al. 2012b), density, and biomass (Husson et al. 2003; Boyer et al. 2008; Tivet et al. 2008). All studies notably mentioned the positive effect of CA on earthworm populations with increased earthworm biomass (up to 80 %) under CA compared to conventional burn and/or tillage systems.

Husson et al. (2003) observed similar microbial communities (as estimated by FAME—fatty acid methyl ester—profiles) under a 2-year managed fallow of ruzi grass and a 10-year natural fallow. Boyer et al. (2008) observed significant (30 %) increases in microbial respiration under no-till systems with mulch when compared with bare soils. Lienhard et al. (2013a, c), showed a significant decrease (−20 %) of soil microbial molecular abundance (as estimated by soil DNA extracts quantification) under a conventional tillage compared to CA systems.

12.4.3 Climatic Change Impact and Carbon Sequestration

The joint process of deforestation, new land extension, and agricultural intensification often leads to vast soil erosion and gradual soil exhaustion. Crop residues are at a minimum, organic matter in the soil decreases, and carbon sequestration becomes minimal. In terms of greenhouse gas (GHG) emissions, these traditional systems are polluting the atmosphere since they are based on burning fallow biomass. Alternatives need to be created and developed that reconcile economic viability, social balance, environmental conservation, and climate change adaptation. These are crucial for the long-term improvement of smallholders' living conditions and poverty alleviation.

Analysis of long-term climatic conditions in SEA clearly showed that climate is variable (Lefroy et al. 2010), and is a critical issue for agricultural production. Using projections, the analysis predicted that by 2050 the minimum and mean temperatures will increase by up to 2 °C and the maximum by up to 5 °C. The predictions for rainfall suggest less in May and more in April and October.

12.4.3.1 Resistance to Climate Change

Resistance is the tendency of a system to remain stable in the face of external perturbations. CA improves resistance to climate change as CA has beneficial effects on soil fertility, water management, and water-use efficiency. With an increase in soil organic matter and root density under CA, water infiltration and water holding capacity improve, making water more available throughout the farming cycle (Ricosy and Saxton 2007). Surface mulch and improved soil pore structure also increase infiltration and absorption capacity, while reducing evaporation. These benefits help reduce the risk of erosion and flooding during heavy rains, which contributes to aquifer recharge and makes more water available to crops (Hobbs 2007; Derpsch 2008; Verhulst et al. 2010). Together, these CA characteristics increase crop resistance to drought and tend to reduce yield fluctuations between dry and wet years compared to conventional farming practices.

12.4.3.2 Resilience to Climate Events

Resilience refers to a system's ability to recover quickly from damage or change. Climate change is reflected in the increasing number of extreme weather events. The use of agroecological techniques can significantly reduce the negative effects of these events because resilience is enhanced by the implementation and promotion of agricultural biodiversity at the production system level. It is expected that droughts and floods become more frequent and severe. CA based on species diversity is better able to cope with both weather risks.

12.4.3.3 Carbon Sequestration and Reduction in the Greenhouse Effect

Storing carbon in the soil is an agricultural (enhanced physicochemical and biological soil properties) and environmental (reduced atmospheric CO_2) challenge. CA systems were initially developed to fight soil erosion, but they appear to also favor C storage in soils. It is well-known that agriculture is responsible for substantial atmospheric GHG emissions and these could be reduced by implementing CA cropping techniques. In CA, the balance is markedly in favor of carbon sequestration. The use of direct seeding reduces fuel consumption (less mechanized work) thus reducing CO_2 emissions from tractors. CA also promotes carbon fixation in organic matter accumulated in the soil. By implementing CA, anywhere from 0.5 to more than 3 t ha^{-1} per year of carbon can be fixed over a period of at least 10 years. It is not clear whether this would have a positive effect in the fight against greenhouse emissions because it is unknown if these systems promote further significant emissions of GHG such as CH_4 and N_2O. At two well-structured, clayey sites in Brazil and Madagascar, CH_4 and N_2O emissions were almost negligible (Seguy et al. 2006).

12.5 Challenges and Strategies to Develop and Disseminate CA in SEA

12.5.1 Restoration of Soil Fertility in Degraded Areas

Land degradation refers to land which, due to natural processes or human activity, can no longer sustain economic function and/or the original natural ecological

Table 12.1 Humid tropical forest deforestation areas (in 10^6 hectare (ha) and degradation rates (in % of the initial areas). (Source: Achard et al. 2002)

	Latin America	Africa	Southeast Asia
Total study area ($\times 10^6$ ha)	1155	337	446
Forest cover in 1990 ($\times 10^6$ ha)	669	198	283
Forest cover in 1997 ($\times 10^6$ ha)	653	193	270
Annual deforested area ($\times 10^6$ ha)	2.5	0.85	2.5
Rate	0.38 %	0.43 %	0.91 %
Annual degraded area ($\times 10^6$ ha)	0.83	0.39	1.1
Rate	0.13 %	0.21 %	0.42 %

function due to causes such as deforestation, inappropriate agricultural practices, or overgrazing (GEF 1999). Land degradation involves two interlocking and complex systems: the natural ecosystem and the human social system. Land degradation takes various processes and forms such as soil erosion due to water and wind, physical deterioration (compaction, sealing), chemical deterioration (soil fertility decline, salinization, acidification), or vegetation degradation. Figure 12.1 shows land degradation due to erosion in northern uplands of Laos.

Trends indicate that accelerated land degradation and related environmental problems will continue to impede economic and social development in SEA. One major challenge is to achieve sustainable economic growth in a way that alleviates rural poverty without jeopardizing the quality of the environment.

Unfortunately, the rate of degradation is accelerating in most regions of the world (Table 12.1) and particularly in most countries of the southeast subregion. Some countries face more serious challenges than others do. This is partly due to differences in the rate of overall population increase or the rate of urbanization. Land degradation is also due, in large part, to the failure to engage land users in the mitigation effort. Most soil and water efforts are stand-alone interventions that are not attractive to rural households. Poor farmers have little or no money to invest in conservation measures and have no incentive to change their land use if this increases the risk of not producing enough food for their families.

Water erosion covers all forms of soil erosion by water, including sheet and rill erosion, and gullying. Human-induced intensification of land sliding is caused by vegetation clearance, road construction, etc. Wind erosion refers to loss of soil by wind, which occurs primarily in dry regions. Soil fertility decline is a catchphrase to refer to what is more precisely described as deterioration in soil physical, chemical, and biological properties. While a decline in fertility is indeed a major effect of erosion, the term covers forms of degradation other than erosion. The main processes involved are:

- Lowering soil organic matter with an associated decline in soil biological activity.
- Degradation of soil physical properties such as structure, porosity, and water-holding capacity, due to reduced organic matter.

- Deficiency in soil nutrient resources, including reduced availability of major nutrients (nitrogen, phosphorus, potassium), onset of micronutrient deficiencies, and development of nutrient imbalances.
- Acidification of soils, including aluminum toxicity; these "acrisols" are common in mountainous areas. Acidic soils can exist in rice plains where soils have developed from sandstone.
- Salinization is a term used in its broad sense to refer to all types of soil degradation brought about by increased salts in the soil. It thus covers salinization in its strict sense, the buildup of free salts, and the development of dominance of the exchange complex by sodium.

The key issues in terms of environmental degradation and the main reasons for these soil degradations are explained in Table 12.2. As far as agricultural soils are concerned, the main cause of degradation is soil erosion due to rainfall occurring on bare soil either after slash and burn or after land plowing on steep soils mainly where commercial monocropping is practiced. Plowing on steep slopes and foothills is largely practiced as it is often included in a global package proposed by traders in which credit, hybrid seeds, and chemical inputs are supplied in exchange for grain production.

The vulnerability to and impact of climate change are major concerns for SEA. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007) mentioned that warming of the climate system is evident from observations of increasing global average air and ocean temperatures. Since IPCC's first assessment report in 1990, assessed projections have suggested that global average temperatures will increase anywhere from about 0.15 to 0.3 °C from 1990 to 2005.

The IPCC reported that without further action to reduce GHG emissions, the global average temperature is likely to rise by a further 1.84 °C this century, or up to 6.4 °C in the worst-case scenario. This projected global warming is likely to trigger serious consequences for humankind and other life forms, including a rise in sea levels of between 18 and 59 cm, which would endanger coastal areas and small islands, as well as a greater frequency and severity of extreme weather events. SEA is highly vulnerable to climate change as a large proportion of the population and economic activities are concentrated along coastlines. The region is heavily reliant on agriculture for livelihoods and the level of extreme poverty remains high.

About 21 % of the lands in SEA (91 M ha) is used for agriculture. Of this, approximately 36 % (33 M ha) is classified as lowlands and 64 % (58 M ha) as uplands (Dierog et al. 2001). These uplands represent the greatest potential for agricultural production despite the fact that most have acid soils (Table 12.3). Due to their low fertility status, only 20 % of the uplands are presently being used for agriculture and are characterized by diverse unstable agricultural systems. These areas often have poor infrastructure that limit farmers' access to necessary agricultural inputs to improve productivity.

Table 12.2 Key environmental issues and degradation causes in *ASEAN* zone. (Source: 4th ASEAN State of the Environment Report 2009)

Country	Shared issues	Key causes
Brunei	Seasonal smoke and haze; solid wastes	Transboundary pollution from land and forest fires
Cambodia	*Soil erosion*; sedimentation; water pollution; deforestation; loss of biodiversity; threats to natural fisheries	Unmanaged waste and effluent discharge into Tonle Sap lake; destruction of mangrove wetlands through extensive industrial and aquaculture development
Indonesia	Deforestation; *Soil erosion* and loss of biodiversity; water pollution; air pollution in urban areas; national and transboundary seasonal smoke and haze; land degradation; pollution of Malacca straits	Deficiencies in urban infrastructure—unmanaged industrial wastes and municipal effluents and waste; vehicular congestion and emissions; extensive land clearance and forest fires for pulp wood and oil palm production; extensive and unmanaged mining activities; national and transboundary industrial pollution; tourist developments in coastal regions beyond carrying capacity
Laos	Deforestation; loss of biodiversity; *soil erosion*; limited access to potable water; water-borne diseases	Land clearance; shifting cultivation
Malaysia	Urban air pollution; water pollution; deforestation; loss of biodiversity; loss of mangrove habitats; national and transboundary smoke/haze	Vehicular congestion and emissions; deficiencies in urban infrastructure industrial and municipal effluents; extensive land clearance and forest fires for pulp wood and oil palm production; unmanaged coastal developments; tourist developments in coastal regions beyond existing carrying capacity
Myanmar	Deforestation; *soil erosion*, loss of biodiversity; urban air pollution; soil erosion; water contamination and water-borne diseases	Land clearance; excessive mineral extraction; vehicular congestion and emissions; deficiencies in urban infrastructure—unmanaged industrial and municipal effluents
Philippines	Deforestation in watershed areas; loss of biodiversity; *soil erosion*; air and water pollution in Manila leading to water-borne disease; pollution of coastal mangrove habitats; natural disasters (earthquakes, floods)	Illegal forest-cutting; land clearance; rapid urbanization and deficiencies in urban infrastructure—unmanaged industrial and municipal effluents; inadequate water supply and sanitation; tourist developments in coastal regions beyond existing carrying capacity
Singapore	Industrial pollution; limited natural fresh water resources; waste disposal problems	Seasonal smoke/haze; limited land available for waste disposal
Thailand	Deforestation; loss of biodiversity; land degradation and *soil erosion*; shortage of water resources in dry season and flooding in rainy season; conflict of water users; coastal degradation and loss of mangrove habitat; urban air pollution; pollution from solid waste, hazardous materials, and hazardous waste	Sporadic development and destruction of watersheds; unmanaged aquaculture; tourist growth exceeding growth in carrying capacity; deficiencies in urban and rural infrastructure; freshwater resources polluted by domestic/industrial wastes and sewage runoff

ASEAN Association of Southeast Asian Nations

Table 12.3 Extent of acid soils in Southeast Asian countries in ’000 ha. (Source: Dierog et al. 2001)

Country	Total land	Lowland	% of total	Acid soil	% of total
Brunei	527	2	0.4	467	88.6
Cambodia	17,652	1726	9.8	10,565	59.9
East Timor	1487	30	2.0	274	18.4
Indonesia	181,157	8863	4.9	122,289	67.5
Laos	23,080	448	1.9	19,009	82.4
Malaysia	32,855	606	1.8	26,185	79.7
Myanmar	65,755	3893	5.9	40,642	61.8
Philippines	29,817	3254	10.9	13,743	46.1
Singapore	60	2	3.3	42	85.0
Thailand	51,089	8242	16.1	38,630	75.6
Vietnam	32,549	5843	18.0	23,317	71.6
Total SE Asia	463,029	32,909	7.1	295,163	63.7

12.5.2 *CA Practices to Restore Soil Fertility in Degraded Areas*

Soil erosion control in sloping areas is a major issue in SEA, notably when land preparation is based on soil tillage. Of the existing conservation tillage technologies (e.g., mulching, contour hedgerow systems, natural vegetative strips, strip tillage), crop residue retention requires the least labor (Garrity 1996) with a significant impact on reducing runoff and sediment yields (Valentin et al. 2008). In sloping and soil tillage-based areas, no tillage and crop residue retention are alternatives to tillage for limiting soil erosion.

The 10-year experiment in SEA with CA confirmed that soil organic carbon content was directly linked to land preparation (less C mineralization under no tillage) and the quantity of biomass returned to the soil (Lienhard et al. 2013). A basket of CA technologies, including zero and reduced tillage, direct seeding, and residue management, has been developed and tested in different countries. Promising results were obtained in (i) regenerating fertility to degraded soils, (ii) providing livestock with high quality forage, and (iii) increasing soil carbon sequestration. Despite these promising results, dissemination has been limited. Lestrelin et al. (2012a, b) found that the innovation process was hindered by multiple stakeholder strategies that need to be fully understood and disentangled before new practices could be widely adopted.

In degraded acid and weathered savannah soils (northern Laos), significant gains in economic returns were obtained when initial investments in machinery and fertilizers were made (Lienhard et al. 2008).

In highly degraded, poor, and acid sandy soils of the Savannakhet plain of Laos—with acid soils derived from sandstone, a pH of around 4–5 and often aluminum toxicity—CA techniques of no tillage, rice direct seeding, and rotation with legumes and forage grasses have increased paddy rice production with forage production allowing beef-fattening activities during the rainy season (Legoupil 2013).

12.5.3 Providing Alternatives to Slash and Burn—Intensification and Diversification of Existing Farming Systems in the Uplands

12.5.3.1 Existing Farming Systems in the "Uplands"

Rice is the staple food grain produce in SEA with around 50 % of all agricultural land devoted to its cultivation. Farmers have made great progress during the past decade to improve average rice yields and modestly expand crop areas. However, present food security is highly tenuous given that surplus rice production occurs mainly in lowland areas. The highland regions are still largely deficient in staple food grain production.

Highland areas represent large surfaces in SEA. Most of these areas are subjected to a tropical monsoon climate with two distinct wet and dry seasons; the wet season occurs between May and November. It has been estimated that 70 % of highland areas have a slope greater than 20 %, which precludes its use for permanent agriculture. Most farmers live in subsistence conditions with very little production marketed off-farm. Oilseed, pulses, root crops, fruits, vegetables, coffee, and tea are the other crops.

12.5.3.2 Rainfed Rice-Based Farming Systems

The traditional highland/upland farming system is called "shifting cultivation" or "slash and burn," where land is cleared annually of forest or scrub then traditionally planted with rice using a dibble stick (see Fig. 12.2). Historically, rice was grown for a single season on a plot of land cleared from the forest and then left fallow for a long period (10–20 years). For different reasons such as limited allocated land to farmers, demographic pressure, and extension of commercial monocropping, the fallow period has been drastically reduced to 3 years or less leading to erosion, loss of fertility, and declining production. A short-fallow farming system is simply not sustainable. Farming production systems still rely mainly on upland rice production under slash and burn techniques and cattle production (free grazing in forests and fallow areas), but the recent development of monocropped corn at the expense of former upland rice and fallow areas is becoming increasingly important from an economic perspective. A reduction in grazing areas has resulted in less cattle stock. Producers have sold their cattle to develop corn production and other business activities such as agricultural services and transport.

12.5.3.3 Commercial Monocropping Systems

Despite the government policy to curb slash and burn cultivation to preserve forested lands, the aggregate agricultural land area in the uplands has increased owing to a surge of cash crop cultivation. In the provinces linked with transboundary markets and commercial exchanges, the rural economy is presently based on the production of cash crops. These cash crops are grown under contract for export markets.

The early integration to markets led farmers to clear most of the communal forest areas and mobilize land more than 20 years ago (private land ownership and land titling process) and develop these new farming systems based on cash crop production. As a result, most of the forest areas have disappeared and the development of extensive livestock production systems is thus limited by a minor extension of the remaining forest areas, as forests are also used as grazing areas. These farming systems are completed by legumes, cassava, and Job's tears with mainly paddy rice systems in the lowland areas and some upland rice production for farmers who have little or no access to paddy fields.

As a result of increasing demand for land to produce both staple food grains such as rice and export products such as crops, rubber, or timber, the total forest area has significantly declined. The absence of diversification as well as the use of mechanized tillage practices has gradually resulted in decreased levels of soil fertility and soil degradation. The development of legume production systems in association or in rotation with cash crops has always been limited by market demand and labor constraints. More recently in some areas, farmers have developed other cropping systems such as that based on cassava, which are more adapted to poor soils.

The development of farming systems based on cash crop production has been facilitated by the development of a private sector with traders supplying seeds, inputs, services such as land preparation, credit, and marketing. This dynamic has led farmers to often depend on traders to deliver these services. Some farmers are now engaged in a cycle of debt and de-capitalization due to high interest rates, which range from 30 to 40% per annum. As a result, this farming system has generated a high level of socioeconomic differentiation, despite increases in average rural incomes, based mainly on:

- Access to equipment (tractors, trucks, and two-wheel hand-tractors)
- Level of financial capital for covering the production costs
- Livestock capital

12.5.4 CA Practices to Intensify and Diversify Conventional Farming Systems

In order to overcome problems related to soil degradation and reduced soil fertility linked to the traditional slash and burn system, and the recent development of monocropping cash crops, since 2002 some projects in Laos, Vietnam, and Cambodia have developed alternative techniques based on CA (Slaats and Lestrelin 2009), including direct seeding, management of crop residues, and crop diversification through legumes production in association or rotation with corn. These projects have produced interesting results at the farm level in terms of adopting these techniques as well as economic and ecological benefits.

Farming systems that successfully integrate crop and livestock enterprises stand to gain many benefits, which can in turn have a direct impact on an entire agricultural production. CA practices require critical levels of crop residue and cover crops to maintain or enhance soil chemical, physical, and biological properties as well as prevent land degradation. Crops and livestock compete for the same resources and require proper management to meet CA objectives. Farming systems that successfully integrate crop and livestock enterprises stand to improve synergies that directly impact production and agroecological efficiency offering numerous advantages such as income diversification through animal products such as milk, meat, fiber and manure, weed control, soil erosion control, increased yield of main crops, and incomes during the "start-up" period for tree crops (Sanchez 1995).

The appropriate management of livestock is a key issue for improved grain production and even for livestock itself, by improving the sources and quality of feed, and indirectly by improving the soil. In order to achieve this, the following practices are emphasized:

- Do not overstock; keep some animals according to land availability and forage production capacity which will balance biomass production and consumption throughout the year, avoid overgrazing, and maintain adequate soil coverage
- Increase land-use intensity by establishing fenced areas for production of grasses and legumes for different uses such as cutting, grazing, silage, hay and for corrals
- Control grazing with rest periods, which allows pasture recovery. However, the investment for pasture division and rotational grazing is a real constraint

Unfortunately, the dissemination of these new techniques is slow and a significant number of farmers have abandoned these systems due to several constraints: (i) lack of access to credit, suitable equipment, and markets for legumes; (ii) lack of technical support from government; and (iii) lack of farmer or village crop and animal management organizations. On the other hand, an example of a "development fund for sustainable agriculture" has been implemented in Sayaboury, Lao PDR. Based on a tax of 10 Lao Kip kg^{-1} on exported corn, the fund provides financial and technical support to farmers. This initiative has facilitated the establishment of a favorable socioeconomic context through strong links between farmers and traders for credit, markets, and equipment access, which are essential for the development of similar adoption dynamics for more sustainable cropping systems using direct seeding techniques and promoting diversified production.

12.5.5 Developing Human Resources to Address the Needs of CA Development and Dissemination Groups

12.5.5.1 The Present Context

Training is a central issue for CA and agroecology. The development of farming systems that are more intensive and more respectful of natural resources and the environment requires acquisition of new stakeholder knowledge and skills to trigger these changes. The lack of resources and training managers on these issues is often mentioned as a key sticking point to further development.

Ongoing research and development projects have specific objectives to transfer the knowledge and know-how gained during project implementation to existing national institutions. To be effective, this transfer simultaneously requires a capacity-building program in the area of professional training and communication. Different groups such as farmers, extension agents, researchers, and technicians from national organizations must gain competence to efficiently manage new professional responsibilities. Capacity-building is a long process, which requires adequate human resources and financial means.

This training strategy is not only an accumulation of training sessions, field visits, and other activities. It is a permanent attitude aimed at acquiring and assimilating knowledge and know-how. This will result from three types of actions: (i) facilitating information access; (ii) creating and supporting collective thinking during all the steps of program implementation; and (iii) organizing training sessions to cover the technical, management, and legal aspects of CA implementation.

12.5.5.2 International CA Training Cooperation with Brazil

At the regional level, there are no academic or even technical offers in terms of agroecology and/or CA. Several years ago, a training offer was made by the University of Ponta Grossa (UEPG-Brazil). This initiative has been supported by various Brazilian research and extension organizations. The UEPG benefits from the university structures and has been developing specific curricula on CA and direct seeding since 1984. Six international training sessions were organized between 2006 and 2011 thanks to support from the "Multi-Country Project for Agroecology—PAMPA." To date, these courses have trained 78 agronomists, researchers, and academics involved in the field of CA. These researchers came from 12 countries, including Cambodia, China (Shanghai and Yunnan), Laos, Thailand, and Vietnam.

12.5.5.3 Technical Training in Laos

To meet the challenges of sustainable agricultural intensification in Laos, the Centre for Research and Training in Conservation Agriculture (CERFAC) in Ban Poa (Xieng Khouang Province) was created in 2007 (Fig. 12.3). The aims of the CERFAC Ban Poa Centre are:

- Training and awareness for a wide audience of students, technicians, farmers, and policy makers. The center began to assume a regional role of exchanges in the framework of the CANSEA network. In 2011, 7 Chinese technicians from

Fig. 12.3 Technical training in North Laos

the Yunnan province and in 2012, 12 Vietnamese technicians received general training in CA-direct seeding mulch-based crop system (DMC) techniques

- Conducting innovative research to support the training program, including development of ecologically more intensive innovative farming systems based on CA principles.

12.6 Problems and Constraints Encountered in Scaling-Up/Out CA

The factors influencing farmers' decisions to adopt (or not) CA practices are both highly context-specific (e.g., biophysical characteristics, involvement of local elites, extension staff motivation, and capacity; Lestrelin et al. 2012b) and fast changing (e.g., market opportunities, land degradation stage, and/or production costs changes).

General constraints learned from this decade of CA experiments in SEA include those specific to CA systems (e.g., local unavailability of suitable equipments, relay crop, and residue management) and, more importantly, those common to all innovations dealing with agricultural intensification in the uplands and with smallholders (e.g., lack of land tenure security, communal land-use plan, poor public resources and support, unadapted credit access).

12.6.1 Lack of Availability of Suitable Implements Locally

The lack of availability at a local level of suitable equipments for CA implementation, notably for smallholders, is a major constraint already described for other small-scale agricultural contexts (Harrington and Erenstein 2005; Kassam et al.

2009; Johansen et al. 2012). Manual sowing in a mulch increases labor force requirements (Affholder et al. 2009; Lestrelin et al. 2012b), drudgery-induced delays in crop establishment with negative impacts on productivity, and increased competition for labor with other farm activities, notably transplanting lowland paddy rice (Lienhard et al. 2008). Different no-till planters have been introduced from Brazil and tested/adapted in Laos and Cambodia. This equipment has significantly reduced sowing drudgery and improved labor productivity (Lienhardet al. 2013d). The importation process and cost of such equipment, as well as the local need for equipment maintenance and continuous adaptation, has highlighted the need for increased involvement of local (national/regional) manufacturers in the development and deployment of affordable and effective no-till implements.

12.6.2 Communal Grazing and Cover Crop Protection

Communal grazing after crop harvest is a widespread traditional territory management rule in SEA mountainous areas (Garrity 1996). Animals are located far from cultivated areas during the cropping season and brought back after harvest, threatening cover crop development and effective residue management.

Cover crops must provide clear economic benefits for smallholders to shift from conventional monocropping to systems with crop association and/or succession. Most successful stories of CA intercropping systems in SEA are associated with edible or commercial bean production and/or forage use for livestock system intensification.

Fencing is often required to supplement local bylaws on cattle roaming and ensure effective management and share of crop residues and cover crops between in situ recycling, livestock, and energy supply.

12.6.3 Unadapted Credit System

Regardless of annual production costs, the practice of CA often requires high initial investments hardly affordable by smallholders in the absence of adequate credit support. Credit needs are highly context-specific and depend notably on the cultivation system (manual vs. mechanized), productivity of the land (fairly productive vs. degraded), and local prices of commodities.

The access of smallholders to financial capital is a major issue for CA adoption in SEA. With limited guarantees (e.g., land titles) to support their credit demand, Lao farmers have been shown to encounter difficulties in gaining access to bank loans, which are, in any case, subject to high interest rates and short-term refund periods—hardly compatible with the timeframe required for such investments (Lienhard et al. 2008).

12.6.4 Weed Management and Herbicide Use in CA Systems

Changing from a conventional system to CA changes the nature of weeds and weeding patterns (Kassam et al. 2009; Johansen et al. 2012). The traditional reliance on burning and/or full tillage for initial weed control is not compatible with CA principles of maximum soil cover and minimal disturbance, respectively. Beyond considering soil disturbance, traditional hoeing of weeds during the crop cycle is hindered under CA by the presence of crop residues; and this leads to increased labor requirements.

To replace tillage and/or burning for weed control, CA-based projects have promoted slashing (in place of hoeing), rolling (in mechanized areas), crop rotations, use of cover crops, adjustment of sowing time and methods, use of competitive crop genotypes, planting pattern, adjustment of fertilizer strategy, and herbicides, all of which are part of an integrated weed management strategy (Johansen et al. 2012).

12.6.5 High Specialization of Agriculture at Local Level

If local agriculture in SEA is increasingly integrated into market (ADB 2011), they also become more specialized. Lestrelin and Castella (2011) showed that for Laos, total annual maize production increased tenfold between 2000 and 2009 from 117,000 to 1,130,000 t, representing more than 90 % of total rainfed cultivated land in several areas. In Cambodia, Boulakia et al. (2010, 2012a) described highly specialized production systems in the uplands, and the difficulty to introduce crops in rotation with cassava due to the high-selling prices of cassava since 2008 (> US\$ 200 Mg^{-1}).

If higher integration to market is truly a chance for smallholders for their increased income (Lestrelin and Castella 2011), the high specialization of agriculture also limits the development of more ecologically intensive CA systems.

12.6.6 Limited Public Resources to Ensure Adequate On-field Research, Sensitization, and Technical Support

SEA countries are not equal with regard to public support to research, education, and agricultural extension but many are considered low-income countries with limited means to invest in the agricultural development sector.

CA local adaptation and promotion takes time. Harrington and Erenstein (2005) stated that it is not unusual for CA implement development and adaptation to take at least 10 years of (continuous) research and extension. If CA economic and environmental benefits can be seen quickly at field and farm level, then their assessment at watershed/regional scale requires more resources (human and financial) and time. Low governmental salaries and means are also common constraints leading to limited motivation and effective support from agricultural extension agents.

12.7 The CANSEA Regional Network

12.7.1 Introduction: Background of CANSEA

Several research for development (R4D) projects in the subregion have developed and disseminated systems of CA based on DMC-SCV, which contribute to ecological intensification and sustainable diversification. These projects have produced a significant set of results and data on CA farming systems in SEA. The CANSEA was created in September 2009 to address various regional problems of research and development, which cannot be solved at the national level. CANSEA is a structured regional organization aimed at implementing projects of regional interest with regional comparable research designs, harmonized environmental and economic assessment methods, and comparable impact indicators (Legoupil 2013).

12.7.2 Organization and Governance of the CANSEA Network

This regional network of research for development is made up of eight institutional partners from six SEA countries.

Eight founding members of the network are:

- Cambodia: the Ministry of Agriculture, Forestry, and Fisheries (MAFF)
- China: the Yunnan Academy of Agricultural Sciences (YAAS)
- Indonesia: the Indonesian Agency for Agriculture Research and Development (IAARD)
- Laos: the National Agriculture and Forestry Research Institute (NAFRI)
- Thailand: the University of Kasetsart
- Vietnam: the Northern Mountainous Agriculture and Forestry Science Institute (NOMAFSI) and the Soils and Fertilizers Research Institute (SFRI)
- The French “Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD)” which cooperates with all partners in SEA. The CANSEA network is considered by CIRAD as its own platform in partnership for CA development in SEA

The CANSEA network is a regional nonprofit structuring organization for research institutions and/or CA-dedicated groups. Network members agreed to: (i) share experiences and results, (ii) define regional priorities and design corresponding R&D programs, and (iii) research and mobilize funding to implement regional programs. CANSEA allows members to do together what cannot be achieved individually.

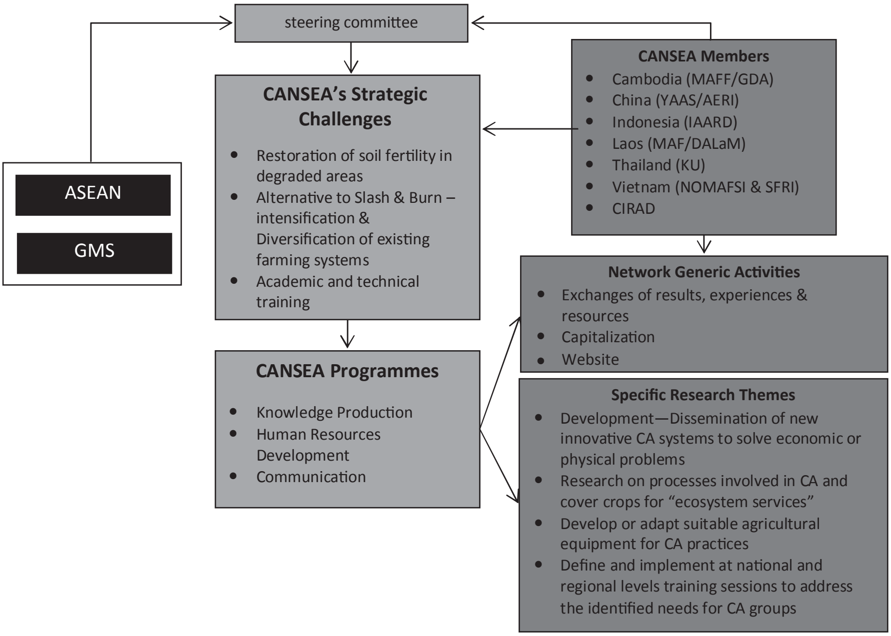


Fig. 12.4 The *CANSEA* organizational structure

Table 12.4 Interactions between *CANSEA*'s strategic topics and geographical areas

	Fertility restoration of degraded areas (erosion—acidity)	Intensification diversification of traditional farming systems	Human resources development
Traditional rainfed agriculture in mountainous areas (slash and burn systems)	Acidity of mountain soils (acrisols) Water erosion of steep lands	Intensification Diversification of subsistence rainfed and rice-based farming systems	Academic training with: National agriculture faculties Specific regional role of Kasetsart University Technical training for CA practices with: Network of national institutions
Commercial agriculture Cash monocropping systems in steep lands	Water erosion of steep lands Soil fertility	Intensification Diversification of conventional farming systems linked to markets	
Large plains with soil fertility problems	Soil acidity (sandstone) Salinity General fertility problems		

The network is managed by a steering committee and a regional coordination unit (Vientiane Laos). The organizational structure of the regional network is given in Fig. 12.4 (Legoupil 2013).

Table 12.4 shows how the CANSEA strategy areas link to, and are coherent with, national interests for defining common priority objectives. This demonstrates the clear opportunities and entry points for CANSEA members to cooperate with each other.

12.8 Conclusion

While CA investigations are currently mainly in the research sector, recent field experiences in SEA have indicated their potential as a viable and accepted alternative to plow-based agricultural intensification, even in the context of small-scale farming. Several lessons can be learned from the past decade of in situ CA experiments:

- *Agriculture and cropping patterns in SEA are spatially diverse and constantly evolving*. The identification of windows of opportunity for CA, i.e., key moments for intervention along specific agroecological transition pathways corresponding to successive stages of land-use intensification and land degradation, may facilitate the design of appropriate CA technologies and spatially differentiated policies.
- *Agricultural trajectories often repeat themselves in time and space*, so that lessons can be drawn from past experiences and/or neighboring countries. The recent CANSEA network may play a key role in facilitating the exchange of results and experiences within the region, and hence in CA diffusion.
- *Increase the participation of the private sector*. Undoubtedly, there is a need for higher sensitization and enrollment of the private sector to not only improve local availability of suitable implements but also provide credit facilities and/or technical support to farmers' groups.
- *Need for long-term active research, training, and technical mentoring on CA*. A shift from projects on CA to programs on CA is required at the national and regional level to better capitalize on research results and human resources. Of the research topics related to continuous improvement of CA agronomic, economic, and environmental performances, the question of enhancing the diversification of farming systems and reducing pesticide use are two important ones.

References

ADB (2011) Core Agriculture Support Program Phase II 2011–2015. GMS working group on Agriculture. ADB, Mandaluyong City

Affholder F, Jourdain D, Quang DD, Tuong TP, Morize M, Ricome A (2009) Constraints to farmers' adoption of direct-seeding mulch-based cropping systems: a farm scale modeling approach applied to the mountainous slopes of Vietnam. Agric Syst 103:51–62

Boulakia S, Kou P, San S, Leng V, Chhit K (2008) Five years of adaptative research for upland DMC-based cropping systems creation in Cambodia. In: Chanphengxay M et al (eds) Proceedings of the regional workshop on investing in sustainable agriculture: the case of conservation agriculture and direct seeding mulch-based cropping systems. MAF, Vientiane, pp 37–49

Boulakia S, Vuth P, Vathana S, Chabierski S, Gilard O (2010) Conservation agriculture in Cambodia: a triple-win option. Paper presented at the conference the environments of the poor in the context of climate change and the green economy: making sustainable development more inclusive. 24–26 November, New Delhi, India

Boulakia S, Chabierski S, Kou P, Sona S, Kong R, Leng V, Sar V, Chhit K, Séguy L (2012a) Adaptation of direct-seeding mulch-based cropping systems for annual cash crop production in Cambodian rainfed uplands. In: Hauswirth et al (eds) Conservation agriculture and sustainable upland livelihoods. Innovations for, with and by farmers to adapt to local and global changes—Proceedings of the 3rd International Conference on Conservation Agriculture in Southeast Asia. CIRAD, Montpellier; NOMAFSI, Phu Tho; University of Queensland, Brisbane, pp 92–108

Boulakia S, Seguy L, Tantachasatid P, Thanisawanyankura S, Leng V, Boyer J (2012b) Diversity and structure of soil macrofauna communities under plant cover in a no-till system in Cambodia. In: Hauswirth et al (eds) Conservation agriculture and sustainable upland livelihoods. Innovations for, with and by farmers to adapt to local and global changes—Proceedings of the 3rd International Conference on Conservation Agriculture in Southeast Asia. CIRAD, Montpellier; NOMAFSI, Phu Tho; University of Queensland, Brisbane, pp 234–235

Bounthong B, Tivet F, Tran Quoc H, Lienhard P, Panyasiri K, Julien P, Séguy L (2005) Direct seeding mulch-based cropping systems—a holistic research approach implemented in Northern Laos. Third World congress on Conservation Agriculture, Nairobi, 3–7 October 2005

Boyer J, Tantachasatid P, Tangtrakanpong P, Thanisawanyangkura S, Séguy L (2008) Dynamic and structure of soil macrofauna communities under plant covers used in DMC systems in Sakon Nakhon Province. Communication presented at the regional workshop on investing in sustainable agriculture: the case of conservation agriculture and direct seeding mulch-based cropping systems, Phonsavanh, 28 October–01 November, Thailand 2008

Castella JC (2012) Agrarian transition and farming system dynamics in the uplands of South-East Asia. In: Hauswirth et al (eds) Conservation agriculture and sustainable upland livelihoods. Innovations for, with and by farmers to adapt to local and global changes—Proceedings of the 3rd International Conference on Conservation Agriculture in Southeast Asia. CIRAD, Montpellier; NOMAFSI, Phu Tho; University of Queensland, Brisbane, pp 4–21

Chabierski S, Tyneth L, Rada K, Sona S, Penot E, Boulakia S (2011) First impacts of DMC adoption among smallholders in Cambodia. Communication presented at the second International Conservation Agriculture Workshop and Conference in Southeast Asia, Phnom Penh, 4–7 July 2011

De Schutter O (2011) Agroécologie et droit à l'alimentation. Rapport présenté à la 16e session du Conseil des droits de l'homme de l'ONU [A/HRC/16/49]. Genève, 8 mars 2011. http://www.srfood.org/images/stories/pdf/officialreports/20110308_a-hrc-16-49_agroecology_fr.pdf

Derpsch (2008)

Dierog T et al (2001) A toolkit for acid, upland soil fertility management in South East Asia

FAO (2007) Agriculture and consumer protection department, food and agriculture organization of the United Nations, Rome. http://www.fao.org/ag/ca/. Accessed 15 June 2009

Garrity DP (1996) Conservation tillage: Southeast Asian perspective. Paper presented at the conservation tillage workshop, Los Banos, 11–12 November 1996

GEF (1999)

Harrington L, Erenstein O (2005) Conservation agriculture and resource conserving technologies. A global perspective. In: Abrol IP, Gupta RK, Malik RK (eds) Conservation agriculture-status and prospects. Centre for advancement of Sustainable Agriculture, New Delhi, pp 1–12

Hauswirth D, Boulakia S, Le Quoc D, Dang VT (2011) Designing sustainable tea-based cropping systems fitting with development goals and agroecology concepts for smallholders in highlands of Vietnam: lessons from the ADAM Project. Communication presented at the second International Conservation Agriculture Workshop and Conference in Southeast Asia, Phnom Penh, 4–7 July 2011

Hobbs (2007)

Husson O, Lienhard P, Seguy L, Tuan HD, Doanh LQ (2001) Development of direct sowing and mulching techniques as alternatives to slash-and-burn systems in northern Vietnam. In: Conservation agriculture, a worldwide challenge. Proceedings of the 1st World Congress on Conservation Agriculture, Madrid, pp 29–33

Husson O, Tuan HD, Boyer J, Chabanne A, Caesar-Thon That TC, Séguy L (2003) Impacts of direct planting on permanent soil cover (DPPSC) techniques on soil biological activity in Northern Vietnam. In: Producing in harmony with nature, vol II. Proceedings of the 2nd World Congress on Conservation Agriculture, Iguassu falls, pp 460–463

IPCC (2007)

Johansen C, Haque ME, Bell RW, Thierfelder C, Esdaile RJ (2012) Conservation agriculture for small holder rainfed farming: opportunities and constraints of new mechanized seeding systems. Field Crop Res 132:18–32

Kassam A, Friedrich T, Shaxson F, Pretty J (2009) The spread of conservation agriculture: justification, sustainability and uptake. Int J Agric Sustain 7:292–320

Lal R (1989) Conservation tillage for sustainable agriculture - tropics versus temperate environments. Adv Agron 42:85–197

Lal R (2005) World crop residues production and implications of its use as a biofuel. Environ Int 31:575–584

Lefroy et al (2010)

Legoupil JC (2013) Conservation agriculture network in South East Asia, CANSEA strategic plan 2014–2018. National Library of Laos cataloging in publication data (CIP), Laos, p 33 (ISBN 978-9932-00-121-7)

Lestrelin G, Castella JC (2011) Opportunities and challenges for the adoption of conservation agriculture in maize production areas of Laos. In: Resilient food systems for a changing world. Proceedings of the 5th World Congress on Conservation Agriculture. WCCA/FSD, Brisbane, pp 42–44

Lestrelin G, Nanthavong K, Jobard E, Keophoxay A, Lienhard P, Khambanseuang C, Castella JC (2012a) "To till or not to till?" Opportunities and constraints to the diffusion of conservation agriculture in Xieng Khouang Province, Lao PDR. Outlook Agric 41:41–49

Lestrelin G, Tran Quoc H, Jullien F, Rattanatray B, Khamxaykhay C, Tivet F (2012b) Conservation agriculture in Laos: diffusion and determinants for adoption of direct seeding mulch-based cropping systems in smallholder agriculture. Renew Agric Food Syst 27:81–92

Lienhard P, Tivet F, Bounkhampone B, Sosomphou T, Sayphoummie S, Phanthavivong I, Séguy L (2008) Direct seeding mulch-based cropping systems for rice-beef production in the plain of Jars, Xieng Khouang Province, Lao PDR: an example of 'creation-validation' methodological approach. In: Chanphengxay M et al (eds) Proceedings of the regional workshop on investing in sustainable agriculture: the case of conservation agriculture and direct seeding mulch-based cropping systems. MAF, Vientiane, pp 210–223

Lienhard P, Terrat S, Prévost-Bouré NC, Nowak V, Régnier T (2013a) Pyrosequencing evidences the impact of cropping on soil bacterial and fungal diversity in Laostropical grassland. Agron Sustain Dev. doi:10.1007/s13593-0130162-9

Lienhard P, Panyasiri K, Sayphoummie S, Leudphanane B, Lestrelin G, Seguy L, Tivet F (2013b) Profitability and opportunity of conservation agriculture in the acid savannah grasslands of Laos. PHD CIRAD/INRA/CNRS

Lienhard P, Tivet F, Chabanne A, Dequiedt S, Lelièvre M, Sayphoummie S, Leudphanane B, Prévost-Bouré NC, Seguy L, Maron PA, Ranjard L (2013c) No-till and cover crops shift soil microbial abundance and diversity in Laos tropical grassland. Agron Sustain Sci 33(2):375–384. doi:10.1007/s13593-012-0099-4

Lienhard P, Terrat S, Mathieu O, Levêque N, Prévost-Bouré NC, Nowak V, Régnier T, Faivre C, Sayphoummie S, Panyasiri K, Tivet F, Ranjard L, Maron PA (2013d) Tillage system and cropping intensity shift the links between microbial diversity and carbone turnover in Laos tropical grassland. Environ Chem Lett. doi:10.1007/s10311-013-0420-8

Lienhard P, Tivet F, Chabanne A, Dequiedt S, Lelièvre M, Sayphoummie S, Leudphanane B, Chemidlin Prévost-Bouré N, Séguy L, Maron PA, Ranjard L (2013e) No-till and cover crops shift soil microbial abundance and diversity in Laos tropical grasslands. Agron Sustain Dev 33(2):375–384

MBLRC (2004) How to farm your hilly land without losing your soil? The sloping agricultural land technology (salt) farming system, 1st edn (Series No 1). Asian Rural Life Development Foundation International, Bansalan

Mercado A, Reyes M, Ella V (2011) Developing conservation agriculture in the Philippines. Communication presented at the second International Conservation Agriculture Workshop and Conference in Southeast Asia, Phnom Penh, 4–7 July 2011

Nicetic O, Le Huu H, Trinh Duy N, Nguyen Hoang P, Pham Thi S, Kirchhof G, van de Fliert E (2011) Impact of erosion prevention methods on yield and economic benefits of maize production in North West Vietnam. Communication presented at the second International Conservation Agriculture Workshop and Conference in Southeast Asia, Phnom Penh, 4–7 July 2011

Panyasiri K, Sen PT, Baokun L, Autfray P (2011) Regional conservation agriculture project proposal in degraded annual cropping systems areas in South East Asia. In: Resilient food systems for a changing world. Proceedings of the 5th World Congress on Conservation Agriculture. WCCA/FSD, Brisbane, pp 324–327

Ricosy, Saxton (2007)

Roder W, Maniphone S (1998) Shrubby legumes for fallow improvement in northern Laos: establishment, fallow biomass, weeds, rice yield, and soil properties. Agrofor Syst 39:291–303

Sanchez (1995)

Seguy L, Bouzinac S, Husson O (2006) Direct-seeded tropical soil systems with permanent soil cover: learning from Brazilian experience. In: Uphoff N, Ball AS, Fernandes E, Herren H, Husson O, Laing M, Palm C, Pretty J, Sanchez P (eds) Biological approach to sustainable soil systems. CRC, Boca Raton, pp 323–342

Slaats J, Lestrelin G (2009) Improving cropping systems by introducing conservation agriculture: taking stock of the results and methodology of research-development in southern Sayaboury province, Lao PDR. PCADR, Vientiane, p 115

Tao D, Kong L, Zhu H, Hu F, Xu P, Zhou J, Deng X, Li J, Deng W (2008) Integration of conservation and intensification agricultural technology in Yunnan. Communication presented at the Regional workshop on investing in sustainable agriculture: the case of conservation agriculture and direct seeding mulch-based cropping systems, Phonsavanh, 28 October–01 November 2008

Tivet F, Tran Quoc H, Boyer J, Inthavong C, Senephansiri S, Keodouangsy L, Chounlamountry T, Khamxaykhay C, Panyasiri K, Séguy L (2008) Changes in soil aggregation, soil water holding capacity and soil biological activity under no-till systems and cropping sequence in Lao PDR. In: Chanphengxay M et al (eds) Proceedings of the regional workshop on investing in sustainable agriculture: the case of conservation agriculture and direct seeding mulch-based cropping systems. MAF, Vientiane, pp 130–144

Tivet F, Desbrosse A, Tran Quoc H, Jullien F, Khamxaykhay C, Chabanne A, Choulamountry T, Senephansiri S, Lienhard P, Sa JCM, Briedis C, Panyasiri K, Séguy L (2012) Implications of land use changes for soil organic C assessed by multi-temporal satellite imagery in southern Xayabury province, Laos. In Hauswirth et al (eds) Conservation agriculture and sustainable upland livelihoods. Innovations for, with and by farmers to adapt to local and global changes—Proceedings of the 3rd International Conference on Conservation Agriculture in Southeast Asia. CIRAD, Montpellier; NOMAFSI, Phu Tho; University of Queensland, Brisbane, pp 45–48

Tran Quoc H, Tivet F, Senephansiri S, Keodouangsy L, Chounlamountry T, Khamxaykhay C, Séguy L (2008) Maize yield and profit increase under no-tillage system and crop rotation with leguminous in southern Xayaburi province, Lao PDR. Communication presented at the regional workshop on investing in sustainable agriculture: the case of conservation agriculture and direct seeding mulch-based cropping systems, Phonsavanh, 28 October–01 November 2008

Tuan HD, Doanh LQ (2008) Conservation agriculture on sloping lands in Northern mountainous regions of Vietnam. In: Chanphengxay M et al (eds) Proceedings of the regional workshop on investing in sustainable agriculture: the case of conservation agriculture and direct seeding mulch-based cropping systems. MAF, Vientiane, pp 27–36

Valentin C, Agus F, Alamban R, Boosaner A, Bricquet JP, Chaplot V, De Guzman T, De Rouw A, Janeau JL, Orange D, Phachomphonh K, Phai DD, Podwojewski P, Ribolzi O, Silvera N, Subagyono K, Thiébaux JP, Toan TD, Vadari T (2008) Runoff and sediment losses from 27 upland catchments in Southeast Asia: impact of rapid land use changes and conservation practices. Agric Ecosyst Environ 128:225–238

Verhulst et al (2010)

Von Uexkull HR, Mutert E (1995) Global extent, development and economic impact of acid soils. Plant Soil 171:1a–15a

Chapter 13
Conservation Agriculture in Rainfed Areas of China

Lingling Li, Bill Bellotti, Renzhi Zhang and Hailin Zhang

Abstract Conservation agriculture (CA) is now widely recognized as a viable concept for practicing sustainable agriculture. Grouped under the title "conservation agriculture," an inter-related and synergetic set of principles and practices have been developed to combat land degradation, falling soil fertility, rapidly declining production levels, inefficient use of scarce water resources, and desertification. China is an ancient agricultural country, its agriculture dates back at least 8000–9000 years. It has a long history of practices of soil and water conservation. Presently—due to a wide range of soil types and climate, and the cropping systems practiced in China—diverse CA systems exist in different agroecological regions of China. However, modern conservation tillage (CT) is fairly new. The total area under CT in China exceeded 6.67 million ha in 2012 with a ten-fold increase in past 10 years. A 13-year case study on the Loess Plateau showed that no-till with stubble retention (NTS) improved grain yield significantly. With NTS, water stored in surface layers is more available for crops than that in deeper layers; surface (0–10 cm) soil water content under NTS improved up to 90 % when compared with conventional tillage. Soil organic carbon improved. Crops under NTS had better growth and yield. Soil quality, water use efficiency, and nitrogen use efficiency improved, and soil erosion significantly decreased. Profitability improved under NTS within two rotation cycles of spring wheat–field pea; total profitability of NTS was 81, 38, 75, 165, and 66 % higher than that of conventional tillage (T), no-till without stubble retention (NT), conventional tillage with stubble incorporated (TS), conventional tillage with plastic mulch (TP), and no-till with plastic mulch (NTP). Therefore, NTS is

---

L. Li (✉)
Gansu Provincial Key Laboratory of Aridland Crop Science/Faculty of Agronomy,
Gansu Agricultural University, Lanzhou 730070, People's Republic of China
e-mail: lill@gsau.edu.cn

B. Bellotti
University of Western Sydney, Parramatta, Australia

R. Zhang
Faculty of Resource and Environment, Gansu Agricultural University, Lanzhou 730070,
People's Republic of China

H. Zhang
College of Agronomy and Biotechnology, China Agricultural University, Beijing,
People's Republic of China

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_13

the best CA practice for improving crop productivity and sustainability. Although the importance of CA has been increasingly recognized, there are many barriers to its widespread adoption including traditional intensive agriculture attitude, small farm sizes, lack of suitable machines, lack of diverse CA technologies, and the high opportunity cost of straw/residues. Therefore, further investment into technical research, machine design, demonstration and extension, and substitutes for fuel and forage are important for a breakthrough on CA adoption in China.

Keywords Soil and water conservation · Loess Plateau · History · Present state · Adoption challenge

13.1 Introduction

Conservation agriculture (CA) is now widely recognized as a viable option for practicing sustainable agriculture. CA is an interrelated and synergetic set of principles and practices developed to combat land degradation, falling soil fertility, rapidly declining production levels, inefficient use of scare water resources, and desertification (Benites et al. 2003). Conservation tillage (CT) is the main component of CA, which has three principles viz. continuous minimum mechanical soil disturbance, permanent soil cover (crop or mulch), and the diversification of crop species in sequence/association (www.fao.org/ag/ca). Based on experiences in agricultural history, CA in China in this chapter refers to all soil and water conservation practices in agriculture. The area under CT expanded rapidly from 45 million ha in 1999 to 111 million ha in 2009, with a growth rate of 6 million ha per annum (Derpsch and Friedrich 2009; Kassam et al. 2009), and has even expanded to soils and climates earlier thought inadequate for successfully practicing the technology. The superiority of this system in relation to unsustainable intensive tillage practices, time, labor and fuel savings, as well as higher economic returns are the driving forces for this development (Derpsch et al. 2010).

China is an ancient country with its agriculture dating back about 9000 years. The arid and semiarid regions account for 52.5% of the land area in China with rainfed farming systems occurring widely across most of the country, especially in Northwest and North China (Wei and Wang 1999). Soil conservation has been an eternal topic of research and development for rainfed farming systems; China has a long history of practicing CA (Huang 2003) with some CA systems dating back to ancient times (e.g., mulch tillage). A classic example, gravel mulch, has been used to preserve soil moisture on many cash crops and vegetables for hundreds of years. Systematic research on modern mechanical CT only commenced recently in the 1990s. Due to the wide range of soil types and climates in China, the cropping systems practiced are also diverse as are CA practices. The semiarid Loess Plateau is the most important region of rainfed agriculture in China (Fig. 13.1). Soil erosion on the Loess Plateau is the highest in China (Liu 1999), and indeed among the highest in the world (Fu 1989). This chapter discusses CA in China, particularly in

Fig. 13.1 Loess Plateau, the most important rainfed agriculture regions in China

rainfed areas, including its early history and progress on research and adoption for better soil and water conservation.

13.2 History of CA in China

In a global context, research on CT started when the "Dust Bowl" occurred in Midwest USA in the 1930s. Soon after, the Soil Conservation Service (SCS) and Soil Conservation Society of America (SCSA) came into existence in 1935 and 1945, respectively, to research CT for soil and water conservation. In 1951, Edward H. Faulkner published a book titled *Ploughman's Folly,* where he explained that the "Dust Bowl" resulted from plowing (Faulkner 1951). After that, CT research started around the world. Before 1977, the term "conservation tillage" was called minimum tillage, which aimed to reduce the number of tillage actions over a field (Uri 2000). Tillage provided many benefits, including weed control and creating a favorable environment for crop sowing and emergence (Kuipers 1991). During World War II, postemergence herbicides (2,4-D and MCPA) were discovered. Other herbicides followed in the 1950–1960s including triazines, etc. (Rijn 1982). With time, herbicides increasingly provided an economic substitute for the weed control function of tillage (Unger 1990). Another crucial component for mechanized agriculture was the development in postwar years of planting equipment (direct seed drills) that could adequately sow through crop residues. Both the herbicides and planting equipment enabled successful crop establishment while using CT. The USA is generally perceived to be the cradle of this technology—with a large body of literature to document the advances of research and its use (Hatfield and Stewart 1994). The success of the technology in the USA generated substantial interest to replicate such conservation farming systems elsewhere. The total area under CT was 111 million ha in 2009 (Derpsch and Friedrich 2009; Kassam et al. 2009).

CA systems in China date back to ancient times (e.g., mulch tillage); several ancient agricultural books such as *Lv shi chun qiu* (Buwei Lv, circa (ca.) AD 239) and *Qi min yao shu* (Sixie Jia, ca. AD 540) have described CA systems (Liu 2008). Many techniques of soil and water conservation have been used in rainfed areas of China with the most common being mulch.

Prior to 1960, soil and water conservation practices were dominated by gravel and sand mulch, which were adopted widely in some marginal areas that theoretically were not suitable for crop production in terms of quantity of annual precipitation (Liang et al. 2012). The system involved growing crops on gravel, pebble, and/or sand mulched land. The most important impact of the system was soil water conservation. The gravel or pebble mulch reduced surface water runoff, increased infiltration and decreased evaporation (Wang et al. 2003; Xie et al. 2003; Zhao and Li 2009). The improved microenvironment was more favorable to plant growth, resulting in larger root systems, more leaf area, higher photosynthesis and transpiration rates, and earlier maturity (Xie et al. 2003). Furthermore, since gravel and pebbles contain selenium, there was often higher selenium content in the produce. By using this technique, a satisfactory crop yield could be obtained even in an arid climate of 200–300 mm annual precipitation (Chen et al. 2008). Gravel and sand mulch was invented much earlier but became popular only 200–300 years ago. Nowadays, it is still a popular technique in the Loess Plateau for all kinds of vegetables, fruits, and field crops (Fig. 13.2).

Although gravel and sand mulch offer many benefits for soil and water conservation, there is no benefit to soil organic matter (SOM)—unlike crop residue retention—and may lead to the long-term decline in SOM and degraded soil structure. In the late 1970s, plastic mulch was introduced into China. As it can reduce evaporation, conserve soil moisture, and increase soil temperature, thereby improving crop productivity and water use efficiency (WUE), plastic mulching has become more and more popular and is now a dominant technology in rainfed agriculture. In 2012, in Gansu alone, a province on the Loess Plateau, the plastic-mulched area was about 146 million ha, which consumed 0.13 million t of plastic film and improved annual grain output from 8 to 101 million t (Wang 2012a). Like gravel and sand mulch, plastic mulch reduces evaporation, conserves soil moisture, and increases soil temperature, but it does not increase SOM and soil structure; and the plastic is a pollution problem.

From the early 1980s, single techniques such as no-till, stubble cover, etc. were introduced from overseas. However, the adoption rate was low due to the traditions of intensive cultivation, even though no-till and stubble retention achieved very good field results.

Modern CT research in China started in the 1990s. From 1992, China Agricultural University, in cooperation with the University of Queensland and Shanxi Farm

Fig. 13.2 Major crops and fruit trees growing in gravel and sand mulch fields (*top,* from left to right: linseed, sweet pepper, and watermelon; *bottom,* from left to right: apple, corn, and wheat)

Machinery Bureau, started CT experiments in Shanxi Province (Gao and Li 2003), mainly to develop no-till machinery for various crops. From 2001, Gansu Agricultural University and Gansu Grassland Ecological Research Institute, in cooperation with the University of Adelaide, NSW Department of Primary Industries and Agricultural Production Systems Research Unit at CSIRO, started CT research on the western Loess Plateau of Gansu Province (Huang et al. 2003; Li et al. 2004). The results from this research showed that CT is an advanced technology, which can help solve ecological environment problems, increase crop productivity, reduce input costs, and generally improve sustainability of rainfed agriculture.

13.3 Present State of CA in China

As mentioned above, China has a long agricultural history, which has used many soil and water conservation techniques more than hundreds or thousands of years. At present, due to the wide range of soil types and climates, the cropping systems practiced in China are diverse, as are the tillage systems that are practiced (Zhang et al. 2014).

In northeast China, with its cold and semiarid climate, ridge tillage is practiced by most farmers as a means to improve soil temperatures and conserve soil water; other CA systems, such as no-till without stubble retention (NT) under original ridges and subsoiling, have been developing gradually. In North China, NT for summer corn and rotary tillage for winter wheat are the dominant soil tillage systems. In northwest China, CA practices are diverse with different crops and agroecological regions, and include contour tillage and strip cropping on slopes, plastic mulch, gravel and sand mulch, raised beds in irrigation regions, and modern CT practices of no-till with stubble retention (NTS). In southern paddy fields, double- and triple-cropping systems of rice are popular. Rotary tillage has become the dominant tillage method, with benefits of labor and fuel savings; CA is also used in most paddy fields. NT for both early and late paddy fields has been conducted in small parts of this region (Zhang et al. 2014).

Although mechanical CT started only about 20 years ago, it increasingly became the most important CA practice in China. Central government also invested to accelerate its adoption. In 2012, central government invested 300 million RMB (about US$ 50 million) for 80 counties, which increased the area under CA by 1.6 million ha, or 30 % compared to 2011; the total area under CT in China exceeded 6.67 million ha in 2012, ten times more than 10 years ago (Wang 2012a), but only about 4.5 % of total arable and permanent cropland area in the country, and much lower than the world average of 7.5 % (Kassam et al. 2012).

13.4 Experiences with CA in China: A Case Study on the Loess Plateau

13.4.1 Background

Severe soil erosion on the Loess Plateau is a serious and continuing problem contributing to uncertainty with regard to food security and poverty in the region. The reasons are many, among which traditional agricultural practices are a leading cause. These traditional practices involve intensive cultivation, where the soil is plowed three times using a moldboard plow and harrowed twice between harvest and spring sowing. According to Fig. 13.3, these traditional practices were used in the Xihan dynasty (202 BC–AD 9) and have continued largely unchanged to modern times.

In a traditional system, the soil surface is left uncovered for the 7–8-month-long fallow period, which includes part of the rainy season. All stubble and residues are removed at crop harvest for use as forage, fuel, etc. The combination of these practices leaves the soil highly vulnerable during this critical period, resulting in extensive erosion, soil degradation, and reduced production potential. Consequently, local farmers are trapped in a cycle of soil degradation and poverty. These severe erosion and poverty problems have been recognized by central and provincial governments. The government responded with a policy called “grain for green.” However, implementation has met with some resistance, as the area has a tradition of crop cultivation several thousand years long, and local farmers are reluctant to convert their cropland to grass and forestry (Shi and Shao 2000; Rui et al. 2002; Zhang et al. 2004). Therefore, the development of farmer friendly agronomic practices is needed to empower farmers to reduce erosion, increase crop productivity, ameliorate poverty, and improve the environment.

Fig. 13.3 Traditional agricultural practices. (*top left*, photo taken from wall painting in Dunhuang Grotto, *right*, typical tillage in the 1980s; *bottom left*, typical tillage practice in the late 1990s, *right*, no-till seeder introduced for CT)

13.4.2 Aim of the Research

Conservation tillage has been thoroughly studied in large areas under many cropping systems worldwide, such as the USA, Canada, Australia, South America (Fabrizzi et al. 2005), etc. In general, CT can help improve food availability for the growing populations of many countries, reduce production costs and erosion, and help to ease environmental problems (Gao and Li 2003). However, CT is not an easily transferable single component technology. The CT knowledge base developed in the USA, Canada, and Australia and as a result is not directly transferable to developing countries, thus the need for research into CT on the Loess Plateau. For this purpose, an experiment on different tillage systems was designed for a 1-year one-crop rotation of spring wheat and field pea, and implemented from August 2001 in Dingxi, a typical semiarid area on the Loess Plateau. The experimental design included six treatments, replicated four times, and included both phases of the wheat/pea rotation each year. The six treatments included traditional farmer practice (T, conventional tillage with crop residues removed) and a CA treatment (NTS). To separate the effects of tillage and crop residues, these factors were combined factorially as follows:

- T, traditional tillage with crop residues removed
- NT, no-till without stubble retention
- TS, conventional tillage with stubble incorporated
- NTS, no-till with stubble retention

The design also incorporated plastic mulch with and without tillage. The main aim of this research was to develop suitable CT practices for the rainfed Loess Plateau.

Table 13.1 Soil water profile at sowing under different no-till scenarios with stubble retention compared with conventional tillage (V%). (Li et al. 2005)

Crop	Soil depth (cm)	2002		2003		2004	
		T	NTS	T	NTS	T	NTS
Wheat	0–5	10.2	19.5	7.0	12.4	15.7	20.2
	5–10	15.2	20.1	9.6	13.5	19.9	21.1
	10–30	20.1	21.5	15.3	16.2	19.9	20.2
	30–50	15.1	16.3	13.5	13.7	19.2	20.0
	50–80	13.3	13.9	13.4	13.2	18.2	18.8
	80–110	14.0	13.4	13.6	14.0	17.7	17.4
	110–140	14.8	14.0	14.2	14.2	17.2	17.9
	140–170	15.9	14.9	15.6	14.9	16.6	17.4
	170–200	16.1	16.2	15.0	15.6	17.0	16.8
Field pea	0–5	16.9	21.8	14.2	22.1	9.9	11.0
	5–10	23.3	24.3	17.1	21.3	18.4	19.4
	10–30	21.4	22.5	14.3	16.9	20.0	21.7
	30–50	15.3	16.9	11.8	12.1	19.1	19.3
	50–80	13.6	14.9	12.4	11.3	18.4	19.2
	80–110	13.6	14.1	13.7	12.3	17.2	18.2
	110–140	14.8	14.7	14.2	13.3	16.2	17.2
	140–170	16.1	15.2	15.6	14.1	16.0	16.5
	170–200	17.0	16.5	15.5	15.2	17.1	16.2

NTS no-till with stubble retention, *T* conventional tillage

13.4.3 Key Results

13.4.3.1 Conservation of Soil Water

Soil water conservation is highly important in rainfed areas. Research on the western Loess Plateau highlighted that NTS considerably increased surface soil (0–10 cm) moisture at sowing. This is important for crop emergence, and to mitigate against spring droughts which are frequent in the area (Table 13.1). However, the different CT patterns had no strong effect on total soil water storage (0–200 cm). The ratio between plant transpiration and soil evaporation of NTS increased significantly, thus, grain yield and WUE of NTS improved significantly compared with conventional tillage (Li et al. 2005).

13.4.3.2 Improving Soil Quality

Increase Soil Organic Carbon The research results show that total organic carbon (TOC) and readily oxidizable organic carbon (ROOC) decreased with soil depth, but not uniformly with all treatments. The average content of TOC and ROOC at 0–30 cm soil depth over the 12 years for the different treatments was NTS > TS > NTP (no-till with plastic mulch) > NT > T > TP (conventional tillage with plastic mulch). Compared with T, average ranges of TOC and ROOC under NT, NTS, NTP, and TS increased, respectively by 1.2–7.2 and 5.3–16.6 %. Both no-till and straw mulching

Table 13.2 Dynamic changes in total organic carbon in the 0–30 cm soil layer under different tillage practices (g kg^{-1}; $P<0.05$). (Wang et al. 2013)

Treatment	2002	2004	2006	2008	2010	2012	Mean
T	8.89a	8.26c	8.07b	8.62c	7.61ab	7.70c	8.19b
NTS	8.13c	8.9a	9.20a	9.88a	8.22a	8.35b	8.78a
NT	8.64a	8.39bc	8.13b	8.64c	7.60ab	8.34b	8.29b
TS	8.54ab	8.61ab	8.83a	8.93bc	7.67ab	8.82a	8.57a
TP	8.16bc	8.19c	7.52c	7.96d	7.42b	7.80bc	7.84c
NTP	8.49ab	8.16c	8.31b	9.37b	8.11ab	8.14bc	8.43b

Different letters represent significant difference (5%) in the columns.
NTS no-till with stubble retention, *T* conventional tillage, *TS* conventional tillage with stubble incorporated, *TP* conventional tillage with plastic mulch, *NTP* no-till with plastic mulch, *NT* no-till without stubble retention

Table 13.3 Dynamic changes of readily oxidizable organic carbon in the 0–30 cm soil layer under different tillage practices (g kg^{-1}; $P<0.05$). (Wang et al. 2013)

Treatment	2002	2004	2006	2008	2010	2012	Mean
T	4.04ab	4.65b	5.58bc	5.59b	3.87ab	3.32c	4.51bc
NTS	3.89b	5.56a	6.52a	6.67a	4.51a	4.38ab	5.26a
NT	4.04ab	4.90b	5.41c	5.61b	3.90ab	4.66a	4.75bc
TS	4.12ab	4.92b	6.10ab	6.08ab	3.75ab	4.31ab	4.88ab
TP	3.84b	4.62b	5.23c	5.49b	3.62b	3.54bc	4.39c
NTP	4.49a	4.87b	5.74bc	6.19ab	4.13ab	3.62bc	4.84ab

Different letters represent significant difference (5%) in the columns.
NTS no-till with stubble retention, *T* conventional tillage, *TS* conventional tillage with stubble incorporated, *TP* conventional tillage with plastic mulch, *NTP* no-till with plastic mulch, *NT* no-till without stubble retention

increased TOC and ROOC contents, but the NTS treatment produced the optimum result. Compared with 2002, the average contents of TOC and ROOC under NTS increased, respectively, by 9.5 and 42.9 %, 13.2 and 67.6 %, 21.5 and 71.5 %, 1.1, and 15.9 %, 2.7 and 12.6 % in 2004, 2006, 2008, 2010, and 2012. ROOC was more sensitive to tillage practices than TOC (Tables 13.2 and 13.3), and was thus used as an early indicator for changes in soil organic carbon in loess soil on the western Loess Plateau.

Additions of organic matter, such as manure, compost, aboveground crop residue or increases inSOM, belowground crop residue, microbial biomass, etc. can improve soil organic carbon (Loveland and Webb 2003). NT and/or minimum till reduce soil compaction and prevent SOM decomposition.

Improving Soil Structure and Increasing Soil Infiltration The research on the Loess Plateau highlighted that although NTS had no strong effect on soil bulk density and total porosity, the non-capillary porosity and aggregates under NTS greatly improved (Table 13.4). Thus, soil saturation conductivity improved (Fig. 13.4), and soil infiltration increased.

Soil infiltration is determined by soil structure and aggregate stability. The favorable effect of CT systems on soil structure has been reported in different soil types

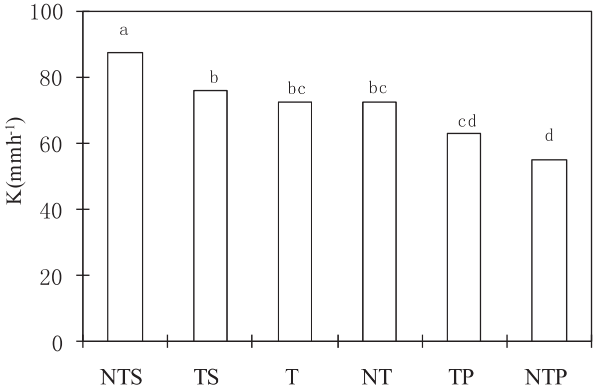


Fig. 13.4 Soil saturation conductivity under different tillage systems. (Luo 2008)

and climates (Oyedele et al. 1999). In contrast, conventional tillage promotes loss of SOM, which leads to disruption of soil aggregates and increased erosion (Roldán et al. 2003). Crop residues in CT protect the soil from raindrop impact, reduce slaking of surface aggregates, and prevent pore sealing and crust formation. When asked why they practice traditional tillage, farmers mentioned that they needed to break down crusts that quickly formed in their low SOM soils after rain. So, CA can only work if both reduced tillage and stubble retention are practiced together, like in our NTS treatment.

Residues left on the soil surface also reduce surface flow and runoff, and thus increase the opportunity for water to infiltrate. The combination of these beneficial effects of residues increases water infiltration (Potter et al. 1995).

13.4.3.3 Reducing Soil and Water Erosion

Data from rainfall simulation on soils of the western Loess Plateau showed that NTS significantly increased cumulated infiltration and alleviated runoff, and soil loss (sediment load) from erosion decreased by 62.4% (Table 13.5).

Field observations also showed an obvious effect of reducing soil and water erosion during crop growth (Fig. 13.5).

13.4.3.4 Increasing Crop Productivity

Long-term research on the western Loess Plateau in China showed that grain yield was generally higher under NTS than under conventional tillage over a 12-year wheat-pea rotation. It also illustrated the advantage of NTS in drier years (2003, 2007; Table 13.6).

Management of crop residues under CT was the most important factor affecting crop yield. The water conserving effect of crop residues on the soil surface ensured at least some degree of yield and often a substantial yield increase when drought stress was an issue (Huang et al. 2008). Organic matter used in crop residue mulch,

Table 13.4 Soil physical properties under different tillage systems in 2007 ($P<0.05$). (Luo 2008)

Depth (cm)	Treatment	Bulk density (g cm^{-3})	Total porosity (%)	Capillary porosity (%)	Non-capillary porosity (%)	Aggregates > 0.25 mm (%)
0–5	T	1.24a	53.09b	48.70a	4.39b	14.90b
	NT	1.21ab	54.40ab	49.10a	5.30ab	14.57bc
	TS	1.15b	56.47a	49.81a	6.67a	10.28d
	NTS	1.22ab	53.94ab	47.62a	6.31a	16.53a
	TP	1.23ab	53.53ab	49.65a	3.96b	10.98d
	NTP	1.22ab	53.97ab	49.66a	4.31b	13.57c
5–10	T	1.26a	52.54a	48.92a	3.62b	6.87d
	NT	1.21a	54.28a	49.07a	5.21ab	8.58c
	TS	1.25a	52.87a	47.68a	5.20ab	10.15b
	NTS	1.25a	52.72a	46.94a	5.78a	12.22a
	TP	1.24a	53.14a	49.52a	3.63b	5.82e
	NTP	1.22a	53.99a	49.90a	4.09ab	11.47a
10–30	T	1.32a	50.22a	46.59 a	3.63b	7.55cd
	NT	1.25a	52.73a	48.15a	4.58ab	8.50bc
	TS	1.31a	50.71a	46.35 a	4.37ab	11.82a
	NTS	1.28a	51.85a	46.89a	4.96a	11.68a
	TP	1.27a	52.13a	48.63a	3.50b	6.60d
	NTP	1.26a	52.58a	48.97a	3.61b	8.85b

Different letters represent significant difference (5%) in the columns.
NTS no-till with stubble retention, *T* conventional tillage, *TS* conventional tillage with stubble incorporated, *TP* conventional tillage with plastic mulch, *NTP* no-till with plastic mulch, *NT* no-till without stubble retention

Table 13.5 Cumulated runoff, infiltration and sediment under different tillage systems ($P<0.05$). (Zhao et al. 2007)

Treatment	Rainfall (mm)	Cumulated runoff (mm)	Cumulated infiltration (mm)	Sediment (g m^{-2})
T	85	53.10b	31.90b	27.77ab
NT	85	62.90a	22.10b	32.73a
TS	85	66.26a	18.74c	23.79b
NTS	85	44.85c	40.15a	14.89c

Different letters represent significant difference (5%) in the columns.
NTS no-till with stubble retention, *T* conventional tillage, *TS* conventional tillage with stubble incorporated, *NT* no-till without stubble retention

however, had different short-term implications, typically hinging on the quality of organic matter as reflected by the C to N ratio. Crop residue mulch also helped control crop weeds, pests, and diseases.

13.4.3.5 Improving Resource Use Efficiency and Profitability

Water Use Efficiency Water deficiency is a major constraint to dryland crop production in the semiarid areas on the western Loess Plateau, where long-term average annual precipitation is 390 mm. Low WUE results from the uneven distribution of

Fig. 13.5 Runoff at the end of plots (*left*: NTS, *right*: TP)

Table13.6 Grain yield under different tillage systems (kg ha^{-1}; $P<0.05$)

Rotation	Year	Crop	T	NT	TS	NTS	TP	NTP
Pea→ wheat	2002	Pea	1653a	1416c	1527b	1790a	1614ab	1529b
	2003	Wheat	1416d	1545d	1646cd	1825b	2033ab	2140a
	2004	Pea	1708a	1496a	1681a	1668a	1762a	1512a
	2005	Wheat	2900b	3076ab	2988b	3327ab	3277ab	3578a
	2006	Pea	758bc	552c	872ab	890ab	1020ab	1049a
	2007	Wheat	561c	633bc	666bc	944a	732b	926 a
	2008	Pea	1342ab	1306ab	1190b	1661a	1063b	1250ab
	2009	Wheat	1232bc	985c	1670a	1607ab	1471ab	1241bc
	2010	Pea	1353ab	1240b	1446a	1435a	1419a	1473a
	2013	Wheat	1229b	1419ab	1526ab	1723a	1468ab	1857a
	Sum		14154	13669	15212	16858	15825	16597
Wheat →pea	2002	Wheat	1816b	1414c	1736b	2151a	1385c	1258c
	2003	Pea	881bc	803c	823c	1269a	1062b	1022b
	2004	Wheat	2189b	1664c	2162b	2382a	2625a	2171b
	2005	Pea	1686b	1816ab	1911ab	2119a	1980ab	2148a
	2006	Wheat	1428bc	1316c	1565b	1549b	1847a	1821a
	2007	Pea	206cd	277bc	342b	553a	180d	249cd
	2008	Wheat	1632a	1818a	1851a	2100a	2136a	1858a
	2009	Pea	762a	727a	857a	873a	738a	863a
	2010	Wheat	1356b	1365b	1482b	1648ab	2378a	2100a
	2013	Pea	839c	1050b	1052b	1428a	1106b	1241b
	Sum		12 796	12 252	13 782	16072	15 437	14 730

Different letters represent significant difference (5%) in the columns.
NTS no-till with stubble retention, *T* conventional tillage, *TS* conventional tillage with stubble incorporated, *TP* conventional tillage with plastic mulch, *NTP* no-till with plastic mulch, *NT* no-till without stubble retention

limited rainfall. Conventional tillage practices hinder increases in WUE and crop productivity. Conventional tillage in the area using a moldboard plow as three primary tillage implements followed by two harrows is the standard method for controlling weeds during the fallow year. This practice incorporates surface crop

Table 13.7 Water use efficiency of crops based on grain yield (kg ha^{-a} mm^{-m})

Crop	Year	T	NT	TS	NTS	TP	NTP	Mean	LSD1	LSD2
Pea	2002	9.03	8.11	8.44	10.26	8.70	8.28	8.80	1.03	1.03
	2003	5.03	4.76	4.87	6.79	6.29	6.06	5.63	1.03	1.03
	2004	11.22	9.81	11.15	11.00	12.62	10.59	11.07	1.83	1.83
	2005	9.31	9.52	9.43	10.63	10.40	10.98	10.05	1.83	1.83
	Mean	8.65	8.05	8.48	9.67	9.50	8.98	8.89		
	LSD	1.39	1.39	1.39	1.39	1.39	1.39			
Wheat	2002	6.48	5.52	6.20	7.49	5.90	5.84	6.24	1.39	1.39
	2003	5.26	4.95	5.40	6.79	6.27	6.39	5.84	1.39	1.39
	2004	8.67	7.23	8.91	8.22	9.83	8.15	8.50	1.73	1.73
	2005	9.54	9.71	9.96	10.64	10.39	11.31	10.26	1.73	1.73
	mean	7.49	6.85	7.62	8.28	8.10	7.92	7.71		
	LSD	1.42	1.42	1.42	1.42	1.42	1.42			

LSD1 tested the difference between treatments in group 1 (T, NT, TS, and NTS); LSD2 tested the difference between treatments in group 2 (TP and NTP); LSD in rows tested the difference between years within a certain treatment

NTS no-till with stubble retention, *T* conventional tillage; *TS* conventional tillage with stubble incorporated; *TP* conventional tillage with plastic mulch, *NTP* no-till with plastic mulch, *NT* no-till without stubble retention

residues, which may increase soil water losses by evaporation (Aase and Siddoway 1982).

Research elsewhere has considered CT as an alternative to conventional tillage to reduce evaporation losses and to increase water storage and WUE of crops in rainfed farming systems (Fisher 1987; Unger et al. 1991). Before CT practices can be readily adopted in any region, the suitability of these management systems must be assessed locally (López and Arrúe 1997).

In this research, retaining stubble on the soil surface significantly increased soil water content in the 0–10 cm layer at sowing, but this was not the case over the whole profile (0–200 cm). However, water consumption and grain yield improved significantly using NTS. Consequently, WUE and soil water availability under different CT practices was investigated in this research for the semiarid areas on the western Loess Plateau (Table 13.7).

Many factors affected WUE of field pea and spring wheat (Table 13.7; for more detail, see Huang et al. (2008). For field pea, the year effect (i.e., climate variability, mainly rainfall) was greater than the treatment effect. Average WUEs across treatments in 2002, 2003, 2004, and 2005 were 8.80, 5.63, 11.07, and 10.05 kg ha^{-1} mm^{-1}. WUE of field pea in 2003 was extremely low; total and in-crop rainfall was very high that year, but low at pivotal stages. Among treatments, significant differences appeared in 2002 and 2003, where WUE of field pea under NTS was much higher than others. In 2004 and 2005, average WUE was higher than the previous 2 years, but there was no significant difference between treatments. The average WUE of field pea under NTS across years was 9.67 kg ha^{-1} mm^{-1}, being 12, 20, 14, 2, and 8 % higher than that of T, NT, TS, TP, and NTP, respectively. No-till without stubble retention had the lowest WUE, highlighting that reducing or eliminating tillage without retaining crop residues results in low crop productivity and soil degradation. This finding supports an important principle of CA that reduced tillage must be combined with crop residue retention. Average WUE of two groups cross years and treatment was only slightly different from each other.

For WUE of spring wheat, year effect was greater than treatment effect. The average WUE across treatments was the highest in 2005; it was 64, 76, and 21 % higher than that in 2002, 2003, and 2004. Among treatments, significant differences appeared in 2002 and 2003, where WUE of spring wheat under NTS was much higher than others. There was no significant difference between treatments in 2004 and 2005. The average WUE of spring wheat under NTS across years was 8.28 kg ha^{-1} mm^{-1}, being 11, 21, 9, 2, and 5 % higher than that of T, NT, TS, TP, and NTP, respectively. Again, NT had the lowest WUE. Average WUE of two groups cross years and treatment was only slightly different from each other.

For different tillage practices, climate (year) variability affected WUE of field pea more strongly than treatment differences. One practice stood out—NTS—increasing the WUE of both field pea and spring wheat, while NT was the worst practice for WUE. Dingxi is a typical drier area for rainfed farming on the western Loess Plateau with rainfall being the only water source for agriculture and humans. Therefore, increasing WUE is the key to increasing agricultural productivity in the area; NTS is the best tillage practice since it can improve WUE.

Nitrogen Fertilizer Use Efficiency From 1949 to 1995, crop productivity increased greatly with increasing fertilizer application in China; however, the incremental increases in productivity associated with fertilizer application have decreased, with the main reason being lower fertilizer use efficiency (Gu and Gao 2000). Nitrogen fertilizer use efficiency in the year of application is only 30–35 % in China (Fan and Liao 1998). Lower fertilizer use efficiency means substantial fertilizer is lost into the soil, underground water, or atmosphere; this not only reduces the benefits to crop production, but contaminates the environment, contributing to human health problems. To improve crop productivity and reduce environment problems in the area, it is important to explore efficient agricultural practices to increase fertilizer use efficiency of crops in Dingxi. Nitrogen fertilizer use efficiency of spring wheat from 2002 to 2004 and nitrogen balance of two rotation cycles were determined in this research.

Average soil NO_3-N under NTS was 90 kg N ha^{-1}, the lowest among six treatments being 21, 5, 26, 32, and 17 % lower than that under T, NT, TS, TP, and NTP. Total nitrogen uptake of wheat plants was less than half of soil N at sowing, and the difference between treatments was smaller than sowing soil nitrogen. Spring wheat under NTS and TP absorbed the most nitrogen over the growing period, which was reflected in higher grain yields and harvest dry matter. The nitrogen fertilizer use efficiency of different treatments calculated from soil NO_3-N at wheat sowing, fertilizer amount and total nitrogen uptake of wheat differed. NTS had the highest nitrogen fertilizer use efficiency, being 26, 50, 41, 20, and 14 % higher than that of T, NT, TS, TP, and NTP (Table 13.8).

Table 13.8 Nitrogen fertilizer use efficiency of wheat under different treatments from 2002 to 2004

	Year	T	NT	TS	NTS	TP	NTP	Mean
Soil NO_3 at sowing (kg N ha^{-1}; 0–140 cm)	2002	109	68	112	80	132	95	99
	2003	126	104	116	106	148	69	111
	2004	108	114	135	84	115	161	119
	Mean	114	95	121	90	132	108	110
Total N uptake (kg ha^{-1})	2002	37	27	28	47	34	32	34
	2003	41	36	41	44	49	49	43
	2004	45	36	44	48	55	50	46
	Mean	41	33	38	46	46	44	41
Nitrogen use efficiency (%)	2002	17	16	13	25	14	16	17
	2003	18	17	19	21	19	28	20
	2004	21	16	18	25	25	19	21
	Mean	19	16	17	24	20	21	19

NTS no-till with stubble retention, *T* conventional tillage, *TS* conventional tillage with stubble incorporated, *TP* conventional tillage with plastic mulch, *NTP* no-till with plastic mulch, *NT* no-till without stubble retention

Profitability of CT Poverty is a serious problem on the western Loess Plateau. It is therefore important to conduct a detailed profitability study on different CT practices before introducing new tillage systems in the area. CT systems are promoted for their soil conservation benefits; however, short-term economics—specifically in regard to profitability—provide an incentive for the adoption of soil conservation practices (Boehm and Burton 1997). Some studies have confirmed the economic superiority of specific forms of CT (Fletcher and Featherstone 1987; Brown et al. 1989; Williams et al. 1990), because in addition to higher yields, CT can reduce production costs by eliminating tillage operations practiced under conventional systems (Landers et al. 2001; Govaerts et al. 2004). However, some studies have shown no economic benefit to using CT systems when compared to conventional tillage systems. Other research has indicated that minimum tillage generally produces similar or only slight differences in crop yields under similar inputs (i.e., fertilizer and herbicide) when compared with conventional moldboard plowing (Carter 1991a, b; Carter et al. 1997).

Inputs, outputs, and benefits of different tillage systems with two phases are presented in Table 13.9. Inputs differed between treatments; NT and NTS had the least inputs as these two practices did not require tillage or plastic film as mulch, while TP had the highest inputs (675 yuan ha^{-1} for tillage operations and 675 yuan ha^{-1} for plastic film as mulch). As for outputs, the different treatments produced different yields. Consequently, the benefits of different tillage practices varied greatly. For both phases, NTS had the best benefit over two rotation cycles because it had the lowest inputs and highest grain yield output, while the practice of tillage with plastic film mulch had the least benefit because of its high inputs. The average net benefit of NTS at the end of two rotation cycles was 8492 yuan ha^{-1}, being 80.6, 37.9, 74.8, 164.6, and 65.9 % more than that of T, NT,

Table 13.9 Profitability of a wheat–pea rotation under different tillage systems from 2002 to 2005. (Li 2006)

Year	Crop	Items	T	NT	TS	NTS	TP	NTP
2002	Wheat	Inputs (yuan ha^{-1})						
		Seeds	225	225	225	225	225	225
		Fertilizers	685	685	685	685	685	685
		Herbicides		97.5		97.5		97.5
		Tillage	675		675		675	
		Plastic film					675	675
		Total inputs	1585	1008	1585	1008	2260	1683
		Outputs						
		Grain yield (kg ha^{-1})	1816	1413	1735	2150	1385	1258
		Price (yuan kg^{-1})	1.5	1.5	1.5	1.5	1.5	1.5
		Total outputs (yuan ha^{-1})	2724	2120	2603	3226	2078	1887
		Benefits (yuan ha^{-1})	1138	1112	1018	2218	−182	204
2003	Pea	Inputs (yuan ha^{-1})						
		Seeds	252	252	252	252	252	252
		Fertilizers	337	337	337	337	337	337
		Herbicides		97.5		97.5		97.5
		Tillage	675		675		675	
		Plastic film					675	675
		Total inputs	1264	687	1264	687	1939	1362
		Outputs						
		Grain yield (kg ha^{-1})	881	803	823	1269	1062	1022
		Price (yuan kg^{-1})	1.5	1.5	1.5	1.5	1.5	1.5
		Total outputs (yuan ha^{-1})	1322	1204	1234	1904	1592	1533
		Benefits (yuan ha^{-1})	58	518	−30	1217	−347	172
2004	Wheat	Inputs (yuan ha^{-1})						
		Seeds	225	225	225	225	225	225
		Fertilizers	685	685	685	685	685	685
		Herbicides		97.5		97.5		97.5
		Tillage	675		675		675	
		Plastic film					675	675
		Total inputs	1585	1008	1586	1008	2260	1683
		Outputs						
		Grain yield (kg ha^{-1})	2189	1664	2162	2382	2625	2171
		Price (yuan kg^{-1})	1.5	1.5	1.5	1.5	1.5	1.5
		Total outputs (yuan ha^{-1})	3283	2496	3243	3573	3938	3256
		Benefits (yuan ha^{-1})	1698	1488	1658	2565	1678	1573

Table 13.9 (continued)

Year	Crop	Items	T	NT	TS	NTS	TP	NTP
2005	Pea	Inputs (yuan ha^{-1})						
		Seeds	252	252	252	252	252	252
		Fertilizers	337	337	337	337	337	337
		Herbicides		97.5		97.5		97.5
		Tillage	675.0		675.0		675.0	
		Plastic film					675.0	675.0
		Total inputs	1264	687	1264	687	1940	1362
		Outputs						
		Grain yield (kg ha^{-1})	1686	1816	1911	2119	1980	2148
		Price (yuan kg^{-1})	1.5	1.5	1.5	1.5	1.5	1.5
		Total outputs (yuan ha^{-1})	2530	2724	2867	3179	2970	3222
		Benefits (yuan ha^{-1})	1265	2037	1602	2492	1031	1860
Total inputs 2002–2005 (yuan ha^{-1})			5700	3390	5700	3390	8400	6090
Total outputs 2002–2005 (yuan ha^{-1})			9859	8545	9948	11882	10579	9899
Total profitability (yuan ha^{-1})			4159	5155	4248	8492	2179	3810

NTS no-till with stubble retention, *T* conventional tillage, *TS* conventional tillage with stubble incorporated, *TP* conventional tillage with plastic mulch, *NTP* no-till with plastic mulch, *NT* no-till without stubble retention

TS, TP, and NTP. Furthermore, as mentioned earlier, plastic does not build up soil fertility like crop residues and presents a source of pollution.

Therefore, NTS is the most profitable practice from this research. Adoption of this practice on the western Loess Plateau of Gansu Province should ameliorate poverty in the area.

13.4.4 Summary

To sum up, 13 years' research showed that NTS significantly improved the rotation grain yield, while NT had the lowest grain yield compared to conventional tillage. With NTS, water stored in surface layers is more available for crops than that in deeper layers. Surface (0–10 cm) soil water content under NTS improved by up to 90 % compared to conventional tillage. Under NTS, crops grew and yielded better, soil quality improved, and WUE improved. NTS also had the highest wheat nitrogen use efficiency. Profitability improved under NTS within two rotation cycles of spring wheat–field pea, being 81, 38, 75, 165, and 66 % higher than that of T, NT, TS, TP, and NTP. Therefore, CA (NTS treatment) is the best crop husbandry practice for the rainfed western Loess Plateau.

13.5 Challenges and Barriers for Increased Uptake of CA in China

China is an ancient country with thousands of years of intensive agriculture represented by intensive tillage. There is no doubt that intensive tillage has contributed to China's historic crop production; intensive tillage made it possible for China to feed 22 % of the world's population on 7 % of the world's cultivated land area (Zhang 2011). However, China's agriculture has paid a heavy price for intensive farming. These intensive agricultural practices inadvertently led to accelerated soil erosion, especially on the Loess Plateau, where it coincides with summer-dominated rainfall, erodible soils, and erodible hilly and gully topography. Furthermore, intensive tillage is tedious and costly; it requires numerous steps prior to sowing, such as residue removal, plowing, harrowing, land leveling, and seeding. As more and more of the rural population moves to urban areas, farm labor shortages require labor-saving agricultural practices to ensure food production.

The demand for CT is increasing in China. The world pace of CA adoption is 45 million ha in 1999, 72 million ha in 2003, and 111 million ha in 2009 (Derpsch et al. 2010). Taking Australia as an example, demonstrations of the benefits of reduced and no-tillage conservation farming practices for improved productivity and soil conservation began in the mid-1970s (Thomas et al. 2007) and by 2009, the total area under CA was 17 million ha (Derpsch et al. 2010). China started introducing and researching CT in the early 1990s, and by 2012, the adoption area was 6.67 million ha (Wang 2012a). Therefore, although the pace of CA adoption is not too bad, total adoption rate has been low. The main obstacles and challenges are summarized below.

13.5.1 Traditional Intensive Agriculture Attitude

As mentioned earlier, intensive agriculture has been practiced in China for thousands of years. At least since the Xihan dynasty until now, tillage practices have been practiced without change (Fig. 13.3), thereby, evolution from traditional agriculture to CT is a kind of revolution, in both technological and attitude context. In *Plowman's Folly*, Edward Faulkner (1951) addressed that "no one has ever advanced a scientific reason for plowing." A typical answer to why plow?" by farmers in our research area was, "my parents did, as did my grandparents, great grandparents and great great grandparents" which reflects how traditional attitudes are adversely affecting adoption of CA in China.

13.5.2 Small Farm Size and Lack of Suitable Machines

Behind the increasing rate of CA adoption around the world, the most common denominator of those countries with >100,000 ha of CA adoption is the large farm-scale. After the Chinese government finished implementing the policy of household production and small peasant economy in the early 1980s, most farms averaged about 0.3 ha per household with this small area further divided into several spatially separated fields. This small field size requires appropriate-sized agricultural machinery for CA. Specially designed sowing and harvesting machines, used successfully for CT in other countries, cannot be used in China. In this case, suitable small seeders need to be developed to meet the needs of scattered small plots.

13.5.3 Lack of Diverse CA Technologies

Diverse soil, climate, topography, and cropping systems in different agroecological regions require diverse CA technologies. Long-term research is always needed to measure the tillage system effect. It takes time to develop suitable CA technologies for different agroecological regions, followed by on-farm demonstrations. However, although China has a long history of soil and water conservation, modern mechanical CA is quite new. The duration of most CA experiments is relatively short (5 years; Zhang et al. 2014). With regard to improving the adoption rate, long-term extensive research on CA technologies and demonstrations are needed, followed by strong financial support.

13.5.4 High Opportunity Cost of Straw/Residue

In rainfed areas of China, especially less-developed regions, crop stubble and stalks are used as fuel for cooking and heating, and/or as feed for animals. This is a necessary part of farming systems in China, and will remain an obstacle to adoption of CT until suitable substitutes for feed and fuel are available (Li et al. 2013).

13.6 Common and National Policies Affecting CA

13.6.1 Research Support

China has a long history of CA practices (Huang 2003; Liu 2008). As soil and water conservation is an eternal subject of rainfed agriculture, many research projects centering around soil and water conservation have been financially supported at prefectural, provincial, and national levels.

Modern mechanical CT first commenced in 1992 in Shanxi, a province on the eastern Loess Plateau (Gao and Li 2003), and focused on developing no-till machinery for small-scale operations for rainfed agriculture in China. In 2001, two CA experiments were established on the western Loess Plateau of Gansu Province to study the long-term effects of CA on soil chemical, physical, and biological processes, as well as crop productivity and profitability for rainfed farming systems (Huang et al. 2008); this project was financially supported by the Australian Center for International Agriculture Research (ACIAR). After that, two key projects supported by national research were under the "National Science & Technology Pillar Program during the Eleventh Five-year Plan Period" (2006–2010). One focused on CT research and demonstration in China, including the Northeast, Loess Plateau area, transition zone between cropping area and nomadic area, northern China Plain, and Yangzi River basin. The other focused on "study and demonstration of conservation tillage in ridge tillage areas." There were many other projects supporting technical, machinery, and demonstration of CA in different parts of China.

It has been increasingly realized that adoption of CA is important in China to combat severe soil erosion and low WUE (Gao and Li 2003; Gan et al. 2008; Huang et al. 2008), hence central government has endeavoured to accelerate its adoption. In 2008–2009, only about 1.33 million ha of agriculture land practiced CA, making up 0.9 % of total arable and permanent cropland area for 2008–2009 (Kassam et al. 2009). In 2012, the adoption area increased to 6.67 million ha (Wang 2012b). Although it increased quickly, the percentage of CA relative to total arable land is still very low due to the challenges mentioned early in this chapter.

In countries where adoption of CA is high, farmers themselves have been critical regarding successful innovation and adoption of CA. This may be part of the reason why adoption of CA in China is low. Increased engagement of farmers in CA research is needed in future Chinese research and development.

13.6.2 Grain for Green

This is a national strategy in response to serious erosion issues in western China, which endanger food security and result in poverty in the Loess Plateau. Traditional agriculture is the main man-made reason for the occurrence of soil erosion. Addressing rural poverty and improving the environment across western China has been a priority of government policy over the past several decades (MOA 2001). In Gansu, provincial strategies aim to reduce farmer reliance on grain production, increase production of cash crops and livestock, and relocate farming villages to more fertile lands (MOA 2001; Feng et al. 2003). However, the Loess Plateau is an area with a tradition of crop cultivation several thousand years long. Local farmers are reluctant to convert their cropland to grass and forestry (Shi and Shao 2000; Rui et al. 2002; Zhang et al. 2004). Therefore, CA can also take this chance, that is, "grain for green" is also an opportunity for CA.

13.6.3 Strategies Responding to Climate Change

Climate change is a global issue. As a result of recent developments in the Kyoto protocol, there has been increased interest to identify management practices that enhance carbon (C) sequestration in soil (Malhi 2011). As CA could increase soil carbon sequestration (Paustian et al. 1997), it has attracted more attention regarding this problem. As mentioned above, CA adoption in China increased quickly from 2008 to 2012, an important reason for this is the government response to climate change. In the “2012 Annual Report of Policy and Action of China Responded to Climate Change,” CT effects on energy-saving and emission-reduction were highly supported. The related practical action was that, in 2012, central government invested 300 million RMB for a demonstration base in 80 counties, which increased the area under CA by 1.6 million ha, and the total area under CT in China exceeded 6.67 Mha (Wang 2012a). FAO took achievements of China as a typical promotion in Asia to promote.

13.7 Conclusions

CA is gaining global acceptance toward achieving sustainable aquiculture due to its strong environmental, economic, and social benefits (Kassam et al. 2012). Although China has a long history of soil and water conservation practices, modern CT is fairly new. A case study on the Loess Plateau showed that NTS—which conserved surface soil moisture, improved crop productivity and soil quality, and increased WUE, nitrogen use efficiency, and profitability of crop production—is the best CA practice for the rainfed western Loess Plateau. However, due to obstacles with traditional intensive agriculture attitudes, small farm sizes, lack of suitable machines, lack of diverse CA technologies, and the high opportunity cost of straw/residues, the adoption rate has been slow, but increased quickly in recent years. Therefore, further investment on technical research, machine design, demonstration and extension, substitutes for fuel and forage, and closer engagement with farmers in future research and development of CA are important for a breakthrough on CA adoption in China in the future.

References

Aase JK, Siddoway FH (1982) Evaporative flux from wheat and fallow in a semiarid climate. Soil Sci Sot Am J 46:619–626

Benites J R, Derpsch R et al (2003) Current status and future growth potential of conservation agriculture in the world context. In: International soil tillage research organization 16th triennial conference. The University of Queensland, Brisbane, Australia

Boehm M, Burton S (1997) Socioeconomics in soil-conserving agricultural systems: implications for soil quality. Elsevier, Amsterdam

Brown HJ, Cruse RM et al (1989) Tillage system effects on crop growth and production costs for a corn-soybean rotation. J Prod Agric 2:273–279

Carter MR (1991a) Evaluation of shallow tillage for spring cereals on a fine sandy loam. 1. Growth and yield components, N accumulation and tillage economics. Soil Tillage Res 21:23–35

Carter MR (1991b) Evaluation of shallow tillage for spring cereals on a fine sandy loam. 2. Soil physical, chemical and biological properties. Soil Tillage Res 21:37–52

Carter MR, Sanderson JB et al (1997) Feasibility of minimum tillage practices for potato rotations in Prince Edward Island. In: International tillage research organization 14th international conference. Pulawy, Poland

Chen N, Liu D et al (2008) Research and development of Shatian production in Gansu province. China Melons Veg 2:29–31

Derpsch R, Friedrich T (2009) Global overview of conservation agriculture adoption (Invited Paper). In: 4th World Congress on Conservation Agriculture, New Delhi

Derpsch R, Friedrich T et al (2010) Current status of adoption of no-till farming in the world and some of its main benefits. Int J Agric Biol Eng 3(1):1–26

Fabrizzi KP, Garcia FO et al (2005) Soil water dynamics, physical properties and corn and wheat responses to minimum and no-tillage systems in the southern Pampas of argentina. Soil Tillage Res 81:57–69

Fan X, Liao Z (1998) Controlled release fertilizer, equilibrium fertilizing and improving fertilizer use efficiency. J Plant Nutr Fertil 4(3):219–223 (in Chinese)

Faulkner EH (1951) http://ourcivilisation.com/smartboard/shop/flknreh/

Feng Z, Yang Y et al (2003) Grain-for-green policy and its impacts on grain supply in West China. Land Use Policy 22:301–312

Fisher RA (1987) Responses of soil and crop water relations to tillage. Inkata, Melbourne

Fletcher JJ, Featherstone AM (1987) An economic analysis of tillage and timeliness interactions in corn ± soybean production. North Cent J Agric Econ 9:207–215

Fu B-J (1989) Soil erosion and its control on the Loess plateau of China. Soil Use Manag 5:76–82

Gan YT, Huang GB et al (2008) Unique conservation tillage practices in Northwest China. No-till farming systems. In: Goddard T, Zoebisch M, Gan Y et al (ed) World Association of Soil and Water Conservation(WASWC), Bangkok. Special publication No. 3, pp 429–444

Gao HW, Li WY (2003) Chinese conservation tillage. International soil tillage research organization 16th triennial conference, Brisbane, Australia

Govaerts B, Sayre KD et al (2004) Stable high yields with zero tillage and permanent bed planting? Field Crops Res (in press)

Gu J, Gao H (2000) A review on technology innovation for improving fertilizer use efficiency. Trans CSAE 16(2):17–20 (In Chinese)

Hatfield JL, Stewart BA (1994) Advances in soil science. Lewis, Boca Raton

Huang GB (2003) Suggestions on conservation agriculture development in Gansu Province. In: Zhang T (ed) Blue book of science and technology development in Gansu province in 2003. Gansu People, Lanzhou (In Chinese)

Huang GB, Zhang RZ et al (2008) Productivity and sustainability of a springwheat-field pea rotation in a semi-arid environment under conventional and conservation tillage systems. Field Crops Res 107:43–55

Huang G B, Zhang RZ et al (2003) Conservation tillage effects on spring wheat and field pea in the western Loess Plateau China. International soil tillage research organization 16th triennial conference. Brisbane, Australia

Kassam A, Friedrich T et al (2009) The spread of conservation agriculture: justification, sustainability and uptake. Int J Agric Sustain. 7(4):292–320

Kassam A, Friedrich T et al (2012) Conservation agriculture in the dry Mediterranean climate. Field Crops Res 132:7–17

Kuipers H (1991) Agronomic aspects of ploughing and non-ploughing. Soil Tillage Res 21(1–2):167–176

Landers JN, Saturnino HM et al (2001) Organizational and policy considerations in zero tillage. In: Saturnino HM, Landers JN (eds) The environment and zero tillage. Associação de Plantio Direto no Cerrado, Federacão Bras. Plantio Direto na Palha, Brasil

Li LL (2006) Crop productivity and resource use efficiency under conservation tillage in a dry land spring wheat-field pea rotation system. Ph. D. Thesis, Gansu Agricultural University, Lanzhou (in Chinese)

Li LL, Huang GB et al (2004) Conservation tillage development research on the Western Loess Plateau of Gansu Province. Food security and farming systems. Hunan Sci & Tech Press, Changsha (in Chinese)

Li LL, Huang GB et al (2005) Effects of conservation tillage on soil water regimes in rainfed areas. Acta Ecol Sin 25(9):2326–2332 (in Chinese)

Li L, Komarek A et al (2013) Hungry goats and a cold bed: barriers to adoption of conservation agriculture in western China. 4th international symposium for farming systems design. Gansu Sci-tech Press, Lanzhou

Liang W-l, Gao W-S et al (eds) (2012) Soil water and agronomic productivity, Chapter 17: historical and present usage of Shatian gravel mulch for crop production in arid and semiarid regions of Northwestern China. In: Advances in soil science. CRC, Boca Raton

Liu G (1999) Soil conservation and sustainable agriculture on the Loess Plateau: challenges and prospects. Ambio 28(8):663–668

Liu XH (2008) Present situation and prospect of conservation tillage in China. Res Agric Modern 29:208–212 (in Chinese with English abstract)

López MV, Arrúe JL (1997) Growth, yield and water use efficiency of winter barley in response to conservation tillage in a semi-arid region of Spain. Soil Tillage Res 44(1–2):35–54

Loveland P, Webb J (2003) Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. Soil Tillage Res 70:1–18

Luo Z (2008) Integrated evaluation on soil quality under different tillage systems in semi-arid area of the loess plateau. Ph.D. thesis, Agronomy Faculty. Gansu Agricultural University, Lanzhou

Malhi SS, Nyborg M et al (2011) Long-term straw management and N fertilizer rate effects on quantity and quality of organic C and N and some chemical properties in two contrasting doils in Western Canada. Biol Fertil Soils 47:785–800

MOA (2001) China agriculture yearbook 2001. English edition. China Agricultural Press, Beijing

Oyedele DJ, Schjønning P et al (1999) Aggregation and organic matter fractions of three Nigerian soils as affected by soil disturbance and incorporation of plant material. Soil Tillage Res 50:105–114

Paustian K, Andren O et al (1997) Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Manag 13:230–244

Potter KN, Torbert HT et al (1995) Tillage and residue effects on infiltration and sediment losses on vertisols. Trans ASAE 38:1413–1419

Rijn PJV (1982) No-tillage crop production in the tropics. Abstr Trop Agric 8:9–27

Roldán A, Caravaca F et al (2003) No-tillage, crop residue additions, and legume cover cropping effects on soil quality characteristics under maize in Patzcuaro watershed (Mexico). Soil Tillage Res 72:65–73

Rui L, Liu G-B et al (2002) Ecosystem rehabilitation on the loess plateau. Regional water and soil assessment for managing sustainable agriculture in China and Australia. In: McVicar T, Rui L, Walker J, Fitzpatrick R, Changming L (eds) ACIAR Monograph, vol. 84, pp 358–365, ACT, Canberra

Shi H, Shao M (2000) Soil and water loss for the Loess Plateau in China. J Arid Environ 45:9–20

Thomas GA, Titmarsh GW et al (2007) No-tillage and conservation farming practices in grain growing areas of Queensland—a review of 40 years of development. Aust J Exp Agric 47:887–898

Unger PW (1990) Conservation tillage systems. Adv Soil Sci 13:27–68

Unger PW, Stewart BA et al (1991) Crop residue management and tillage methods for conserving soil and water in semi-arid regions. Soil Tillage Res 20(2–4):219–240

Uri ND (2000) Conservation practices in US agriculture and their implication for global climate change. Sci Total Environ 256:23–38

Wang B (2012a) “White pollution” affects crop field extensively. http://news.xinhuanet.com/energy/2012-12/22/c_124133250.htm. Accessed 8 Jan 2014

Wang G (2012b) Adoption of conservation tillage in China exceeded 6.67 Mha. http://www.amic.agri.gov.cn/nxtwebfreamwork/ztzl/js_bhxgz/detail.jsp?articleId=ff8080813bcb2b00013bd12657e905a2&lanmu_id=402880052552f1cc0125574866480020. Accessed 8 Jan 2014

Wang L, Li L et al (2013) Effect of long-term conservation tillage on total organic carbon and readily oxidizable organic carbon in loess soils. Chin J Eco-Agric 21(9):1057–1063 (in Chinese with English abstract)

Wang Y, Xie Z et al (2003) Effect of rainwater harvesting for supplementary irrigationon watermelon in gravel and plastic mulched field in Gansu. J Des Res 23(3):300–305

Wei H, Wang J (1999) Climate basis of rainwater-harvesting agriculture in the semi-arid Loess Plateau of China. J Southwest China Norm Univ (Nature science) 24(6):695–701

Williams JR, Gross LK et al (1990) Economic analysis of tillage for corn and soybean rotations with government commodity programs. J Prod Agric 3:308–316

Xie ZK, Wang YJ et al (2003) Effect of supplemental irrigation with harvested rainwater on watermelon production in gravel-and-plastic mulched fields in the Loess Plateau of Northwest China. Acta Ecol Sin 23(10):2033–2039 (in Chinese)

Zhang J (2011) China's success in increasing per capita food production. J Exp Botany 62:3707–3711

Zhang Q-J, Fu B-J et al (2004) Dynamics and driving factors of agricultural landscape in the semiarid hilly area of the Loess Plateau, China. Agric Ecosyst Environ 103(3):535

Zhang H-L, Lal R et al (eds) (2014) Chapter 1: Opportunities and challenges of soil carbon sequestration by conservation agriculture in China. In: Advances in Agronomy. Elsevier, Amsterdam

Zhao JF, Huang GB et al (2007) Conservation tillage effects on run-off and soil erosion. Bull Soil Water Conservation 27(6):16–19

Zhao Y, Li C et al (2009) Study on development and application of Shatian in Ningxia. J Agric Sci 30(2):35–38

Chapter 14
Conservation Agriculture in Australia and New Zealand

P. R. Ward and Kadambot H. M. Siddique

Abstract The adoption and implementation of conservation farming principles have followed very different paths in Australia and New Zealand. In Australia, severe erosion events, and the obvious advantages of conservation farming practices, led to rapid adoption, and currently around 90 % of farmers use some form of conservation agriculture. In New Zealand, advantages of conservation farming practices are not so obvious, and the perceived risks have resulted in adoption rates of less than 10 %. In this chapter, we briefly review the adoption in both Australia and New Zealand, and then look in greater detail at how the principles of conservation agriculture are currently being applied in Australia. Because agriculture in Australia is largely non-irrigated and reliant on rainfall, we have a specific focus on impacts of conservation farming practices on soil water balance. We also look at the future of conservation farming in Australia and New Zealand, and discuss recent advances in weed control strategies.

Keywords Conservation farming · Water balance · No-till · Zero-till · Reduced tillage · Residue retention · Stubble retention

14.1 Introduction

Conservation farming as a term was defined in 1959 as ‘making the most efficient use of the land over a long period of time’ (Kohnke and Bertrand 1959). Subsequent definitions have focused on various aspects of profitability and environmental protection, but all definitions come back to the simple principles of profitable agricultural production while protecting the environmental resource base. Core components of conservation farming tend to revolve around three main areas: reducing soil disturbance, increasing vegetative ground cover, and increasing the diversity of crops. Within each of these areas, there is plenty of scope for local adaptation of

---

P. R. Ward (✉)
CSIRO Agriculture Flagship, Private Bag No 5, Wembley, WA 6913, Australia
e-mail: phil.ward@csiro.au

K. H. M. Siddique
The UWA Institute of Agriculture, The University of Western Australia,
35 Stirling Hwy, Crawley, WA 6009, Australia

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture*,
DOI 10.1007/978-3-319-11620-4_14

suitable techniques. Therefore, conservation farming is not a well-defined sequence of processes or technologies, but is rather an attitude in which the long-term stability of production is as important as the short-term profitability.

Of course, ‘conservation farming’ as a philosophy was in evidence long before 1959, in Oceania and all around the world. Australian farmers proved themselves to be adaptable and innovative, and rapidly responded to challenges as they adapted European farming knowledge to the more fragile Australian conditions.

Farming in the conventional sense commenced in Australia and New Zealand in the late eighteenth century, with the arrival of European settlers. Initially, farming used techniques directly imported from the UK, but these techniques quickly proved unsuitable for Antipodean conditions (Cornish and Pratley 1987). Because of the ready availability of land, a form of ‘shifting’ farming became normal, in which land was cleared, and wheat was grown for a few years until yield declined. The decline in yield was caused by decline in soil fertility and encroachment of weeds. After a few years of crop production, the cycle was repeated on new land, and the previous land was abandoned. Often, the abandoned land was returned to cropping after a period of several years, during which organic matter, nutrients, and weed populations recovered to reasonable levels. In this way, a form of rudimentary crop rotation was established very early in the history of agriculture in Oceania.

Over the past 200 years, innovative Australian farmers have solved many of the problems associated with early agriculture. Inventions including the stump-jump plough in 1876, and the Ridley Stripper in 1843, made major contributions to the development of productive and sustainable farming systems. However, the main factor pushing farmers in southern Australia towards a modern conservation farming system was major erosion events in the 1930s. Erosion was associated with the practice of long fallowing, an idea borrowed from farming systems prevalent in the USA at the time. In this system, soils were kept bare from January in one year until seeding in June of the next year, a period of up to 18 months. Frequent cultivation ensured a weed-free soil surface, but also left a soil with poor structural stability. This proved to be particularly damaging on soils of sandy texture, as is common throughout southern Australia. By 1940, Hore (1940) demonstrated the value of surface cover in reducing the erosion risk, and other research (Callaghan and Millington 1957) showed that a 16-month fallow was no more effective than fallows of 11–12 months. The lessons learned during this time have resulted in a farming system with retained residue, and minimum cultivation, in line with worldwide understanding of conservation farming principles.

More recently, the decline in wool prices during the 1980s resulted in increased cropping intensity, with an associated increase in the need for timely farming operations (Llewellyn et al. 2012). At the same time, the price of glyphosate and trifluralin also declined, further increasing the appeal of reduced tillage in favour of herbicide options for weed control (D’Emden et al. 2008). The ability of farmers to plant crops over larger areas in a more timely manner resulted in increased average farm size (Kirkegaard et al. 2014). In Western Australia, the average farm size in the wheat belt region (excluding farms with gross production values of less than Australian $ 150,000 per year, which account for less than 4 % of the total value of production) in 2011 was 3300 ha (Trestrail et al. 2013).

Farmers in Australia and New Zealand are now looking towards international best practice, as they strive to improve their conservation farming systems even further. In 2005, Rolf Derpsch, a conservation farming specialist from Paraguay, was invited to Australia. During his visit, he observed that in Australia, '…no till has reached a plateau and it appears difficult to advance the system to a higher level…' (Derpsch 2005). For Australian farming, he recommended full year-round stubble retention, diverse rotations including cover crops, and integrated weed management.

A major factor in the development and extension of conservation farming practices in Australia and New Zealand was the establishment of farmer groups. Groups such as the Western Australian No-Till Farmers Association (WANTFA), South Australian No-Till Farmers Association (SANTFA), Victorian No-Till Farmers Association (VNTFA), Conservation Agriculture and No-till Farming Association (CANFA), Conservation Farmers Inc (CFI), and the New Zealand No-Tillage Association (NZNTA) assisted farmers at local and regional level to adopt conservation farming practices. These groups have been instrumental in encouraging farmers to test and refine practices to suit local conditions.

14.2 Climatic Conditions and Conservation agriculture

There are three main climatic zones represented in the cropping regions of Australia and New Zealand (Fig. 14.1), and each has developed slightly different forms of conservation agriculture (CA).

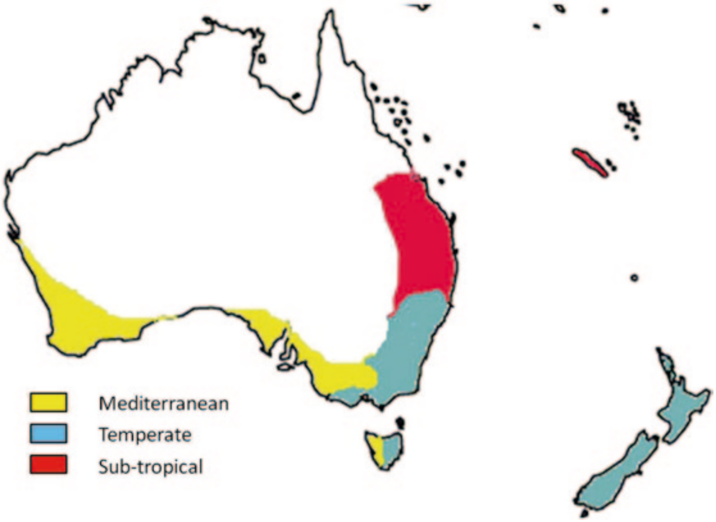


Fig. 14.1 Major climatic zones in Australia and New Zealand

14.2.1 Mediterranean

The Mediterranean region encompasses the south-west and portions of the south coast of mainland Australia, and the western coast of Tasmania. These areas are characterised by hot, dry summers, and because of the general lack of suitable irrigation sources, crop growth is only possible during winter and spring. Large parts of this region also have sandy-textured top soils, and these factors to a large degree have shaped the evolution of agriculture.

Conservation agriculture, encompassing minimum tillage and residue retention, has been widely adopted throughout the region (D'Emden et al. 2006), particularly in the west. Currently about 90 % of farmers in the western region use no-tillage (defined in Sect. 14.3; Llewellyn et al. 2012). The initial key driver for large-scale adoption was prevention of wind erosion, and the development of suitable herbicides, machinery, and a sharp decrease in the wool price lead to the high adoption rate.

14.2.2 Temperate

The temperate region includes New Zealand and the southeastern parts of Australia. In this region, rainfall is roughly equally distributed throughout the year. In warmer parts of the region, reliable crop production is restricted to the winter and spring months, as evaporation increases markedly during summer. In cooler parts, the best time for crop production is summer, as it is too cold during winter. The soils tend to be fine textured and more productive than those of the Mediterranean region, particularly in New Zealand.

Conservation farming practices have been readily adopted in the temperate regions in Australia (D'Emden et al. 2006; Llewellyn et al. 2012), for similar reasons as experienced in the Mediterranean region. For example, average adoption in southern New South Wales was recently estimated at 89 % (Llewellyn et al. 2012). However, adoption has been less extensive in New Zealand, with rates of less than 10 %. Low adoption in New Zealand was attributed largely to the better soils (Baker et al. 2003, 2007), because the benefits of conservation farming practices were not as evident as in Australia. With recent advances in machinery, particularly for seeding, and increases in the fuel price, adoption may be increasing (Safa et al. 2010).

14.2.3 Subtropical

The subtropical agricultural region extends along the east coast of Australia, and is characterised by summer dominant rainfall. In this region, either summer or winter crops can be grown reliably, due to the rainfall patterns and good soil-water-holding capacity, but growing two crops in a 12-month period is rare. Intense rainfall associated with summer thunderstorms caused major erosion, and by the 1950s, farmers were encouraged to retain residue to reduce the erosion risk (McFarlane 1952).

As a result of an effective extension programme, residue retention was adopted during the 1950s in this region (Cornish and Pratley 1987). No-tillage was adopted later, and by 2011, no-tillage was used by 72–82 % of farmers (Llewellyn et al. 2012).

14.3 Experiences of Conservation Farming

14.3.1 Reduced Tillage

No-till farming in Australia arose mostly in response to the threat posed by soil erosion, and there is no doubt that erosion was substantially controlled by the changes implemented. Additional advantages of a reduced-tillage system, such as allowing earlier seeding, also allowed for better crop production. For these reasons, no-till, or some form of reduced soil disturbance, was enthusiastically adopted by farmers right across southern Australia (D'Emden et al. 2006).

The continuing evolution of reduced tillage in farming systems has seen the introduction of the disc seeder (Fig. 14.2), resulting in even less soil disturbance, and this also allows seeding machinery to cope with larger residue quantities (Fig. 14.3). Disc seeding technology was seen by Derpsch (2005) to be a core component of advanced conservation farming systems in the Australian context.

More recently, there has been considerable interest in 'strategic' tillage, in which a general no-till farming system is occasionally tilled for various benefits including weed control and lime or phosphorus incorporation (Kirkegaard et al. 2014). Preliminary evidence under Australian conditions suggests that occasional strategic tillage does not cause damage to the soil, or impact negatively on crop yields.

Fig. 14.2 Disc seeders cause minimal soil disturbance and can cope with large residue loads

Fig. 14.3 A wheat crop growing through canola stubble

14.3.2 *Residue Management*

In a conservation farming system, residue provides a number of important benefits. Principally, residue protects the soil surface during rainfall so that the impact of droplets does not dislodge soil particles, resulting in potential for surface sealing, increased run-off, and the associated increased erosion risk (Hunt and Kirkegaard 2011). The presence of residue on the soil surface also slows down the rate of water movement across the soil, which helps to restrict soil erosion (Fig. 14.4).

In some situations, residue can also decrease evaporation from the soil surface. By shading the soil surface and lowering the average wind speed at the soil surface, residue can absorb or deflect some of the energy, which would otherwise be used to evaporate water (Ji and Unger 2001). However, research under Australian conditions

Fig. 14.4 A good reason for residue retention

shows that impacts of residue on evaporation are generally minor (Ward et al. 2009, 2012; Hunt and Kirkegaard 2011; Hunt et al. 2013). Where residue retention may have a large positive impact is in slowing down evaporation at the time of crop seeding, which may extend the sowing window to allow more crop to be sown in a timely manner (Ward et al. 2012).

Residue retention can also have an impact on soil temperature, through shading the soil surface and protecting it from direct sunlight (Swella et al. unpublished data). During the hot and dry summer, soil temperatures at the surface can rise above 70°C, and lower soil temperatures are thought to be positive for maintaining diverse soil biology. However, in cooler parts of Australia and New Zealand, lower soil temperatures during periods of crop growth can slow growth and potentially restrict crop yield.

Residue retention also plays a direct role in increasing biological activity in the soil. While residue can harbour crop diseases (see the section on crop diversity), residue also encourages other soil organisms, many of which are beneficial to crop production. Earthworms are encouraged by residue retention, and generally have a positive impact on crop yield (Buckerfield et al. 1997), particularly in the temperate and cooler parts of the Mediterranean zones. Earthworms are less suited to hotter and drier parts of Australia, but in a recent study near Geraldton, the exclusion of ants and termites and other soil insects was associated with a 30 % decline in crop production (Evans et al. 2011). Residue provides a key food source for termites, so residue retention is likely to increase termite numbers, with potential long-term benefits for crop production.

14.3.3 Cover Crops

Cover crops, crops grown specifically to generate ground cover, have been proposed as a means of increasing the quantity of residue. In the subtropical zone, and wetter parts of the temperate zone, there is a scope to plant a summer cover crop between two conventional winter/spring crops. In this way, cover can be maintained year-round without losing a year of production. However, in the Mediterranean zone and drier parts of the temperate zone, cover crops will normally be grown during winter and spring, replacing a conventional crop. Therefore, winter cover crops must provide considerable benefits to subsequent crops, and the whole farming system, in order to be financially attractive.

Some of the benefits that cover crops may provide are in weed control, subsoil amelioration, and for leguminous cover crops, nitrogen fixation (Flower et al. 2012). Because cover crops are not grown for grain, they can be killed at maximum biomass, which gives good options for weed control. One of the options for killing the cover crop is knife-rolling (Fig. 14.5). The blades on the roller damage the stems, which kills the plants (and any weeds) and also prevents re-sprouting (Flower et al. 2012). In South America, knife-rolling alone has been effective, which reduces pressure on herbicides. However, under Australian conditions, herbicide application prior to rolling is usually required to ensure a good crop and weed kill.

Fig. 14.5 Knife-rolling a Saia oat cover crop. (Photo: N. Cordingley)

In an experiment at Wellington, NSW, summer cover crops of pigeon pea or millet were effective in increasing residue quantity by around 1 t/ha. Water use by the crops resulted in lower soil water contents at the time of cover crop termination, but if the cover crops were terminated early (February or March), impacts on crop production were small (see the section on infiltration, below; M. McNee, unpublished data).

Winter cover crops, sprayed at anthesis in trials in southwestern Australia at Mingenew and Cunderdin, did not result in greater levels of residue when compared with residue after traditional grain crops (Fig. 14.6; Ward et al. 2012). However, there was a significant increase in ground cover following a cover crop (Fig. 14.7).

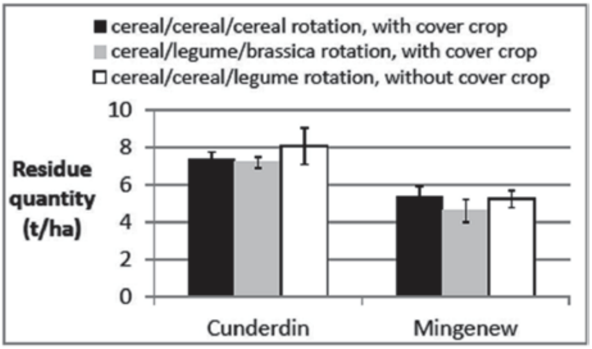


Fig. 14.6 The inclusion of a winter cover crop on its own is not enough to increase residue quantity. (Ward et al. 2012)

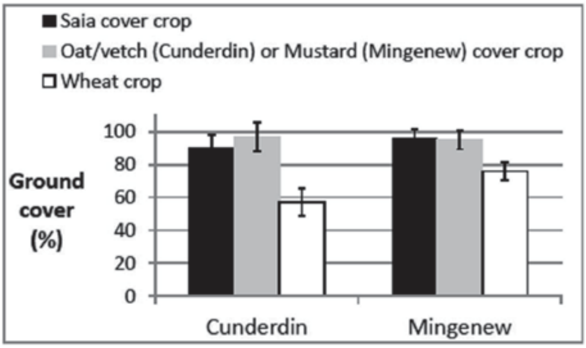


Fig. 14.7 Despite not increasing residue quantity in the rotation, cover crops increased ground cover for the summer immediately following. (Ward et al. 2012)

14.3.4 *Diverse Rotations*

The benefits of rotation in crop production have been known nearly since the dawn of agriculture. Ancient Egyptians and Romans quickly discovered that crops grown without rotation were subject to disease and yielded poorly. In modern agriculture with greater emphasis on residue retention, rotation and crop diversity become even more important. The residue from a crop can act as a refuge for pathogens, enabling them to react quickly if another susceptible crop is grown (Watt et al. 2006; Gupta et al. 2011).

Diversity in the crop rotation also allows for different weed control options, which reduces the risk and impacts of resistance to any specific form of weed control. Herbicide resistance is becoming a real problem in reduced-till farming, and so the use of a diverse range of crops will help to overcome this.

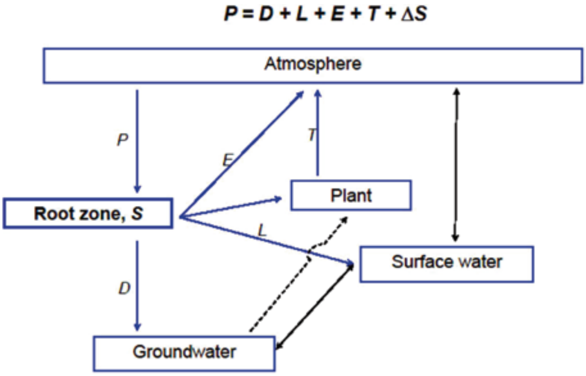
A key benefit of cover crops is that they do not need to be traditional crops such as wheat, barley, canola, or lupins. This can add considerable diversity to the crop rotation and offer farmers additional weed control options. In Australia, many cover crops are killed chemically prior to seed set, enabling good control of weed seed numbers (Flower et al. 2012).

14.4 Water Balance

Because most of the agricultural areas in Australia and New Zealand are rain-fed, knowledge of the water balance, and the influence that conservation farming has on components of the water balance, can be critical.

The soil water balance (Fig. 14.8) is a simple equation that states that the inputs of water into the soil (in southern Australia, usually just rainfall, P) must equal the outputs from the soil, plus any change in soil water storage (ΔS). Outputs are either upwards (evaporation E or transpiration T), sideways (run-off or lateral flow through the soil L), or downwards (deep drainage D).

Fig. 14.8 Components of the water balance



Because it is a 'balance', if one of the components changes, others must also change. For example, if evaporation decreases, one or more of transpiration, lateral flow or drainage to groundwater must increase to maintain the balance.

14.4.1 Infiltration and Soil Water Storage

One of the biggest impacts that conservation farming practices has on water balance is to increase infiltration. Soil is comprised of solid particles and the spaces, or pores, between them. For most soils, total porosity is about 40–50 % by volume, and so in theory, the total amount of water that can be stored in the soil varies between 0 (dry) and 50 % v/v (saturated). In practice, the lower limit (LL) of soil water content is largely determined by the ability of plants to extract water from the soil, and the upper limit of soil water storage is determined by the ability of the soil to hold water against the force of gravity. Both the upper limit and LL are strongly influenced by soil texture (Fig. 14.9). The term drained upper limit (DUL), or field capacity, denotes the practical upper limit of soil water storage, and the LL is sometimes called the permanent wilting point. Water in the soil between the DUL and LL is called plant available water (PAW), because this is the water that can be used by plants.

Numerous studies conducted in the 1980s and 1990s in Western Australia, South Australia, Victoria, New South Wales, and Queensland, using rainfall simulators and models, demonstrated that both stubble retention and reduced tillage lead to faster rainfall infiltration, and consequently, increased levels of soil water storage, via a reduction in losses due to run-off. Differences such as the one shown in Fig. 14.10 are seasonally dependent, but can happen if summer rainfall conditions are favourable (Hamblin 1984).

A recent study in Western Australia (Evans et al. 2011) also found that the tunnels created by ants and termites encourage infiltration of water away from the soil surface. Deep soil water is less prone to evaporation from the soil surface, so ants and termites (encouraged by conservation farming practices) could

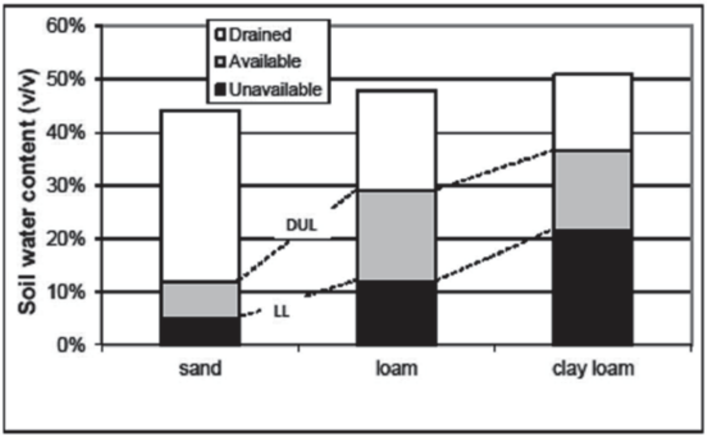


Fig. 14.9 Plant available soil water varies with soil type. DUL is the drained upper limit, and LL is the lower limit for plant water extraction

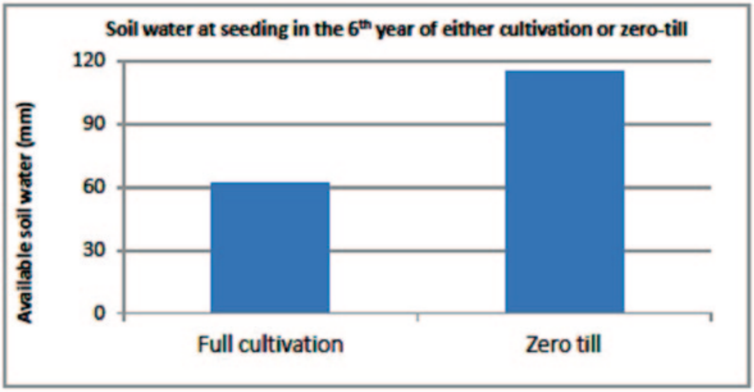


Fig. 14.10 Zero-till can increase soil water in some situations. (Hamblin 1984)

also lead to higher levels of soil water storage, but this has not yet been widely demonstrated.

In other trials in the Mediterranean region of Western Australia, no consistent differences in soil water storage were observed between the different residue management treatments (Ward et al. 2012) in terms of soil water storage during summer. As indicated earlier, the cover crop treatments did not consistently leave more residue than the 'district practice' treatments, but within any specific growing season, there was considerable variation in residue quantity depending on crop type. For example, after the 2009 growing season, residue loads ranged between 6.2 and 9.0 for barley crops at the Cunderdin site. In 2010 and 2011, differences between residue levels were enhanced by stubble removal from the 'district practice' treatment, so that residue levels in the trial ranged between 1.7 and 7.7 t/ha after the 2010 season, and 3.5 and 9.0 t/ha after the 2011 season. Despite these differences, there were no clear differences between the treatments in average soil water over the summer period (Fig. 14.11) in both wet (e.g. 2011–2012) and dry (e.g. 2009–2010) summers.

However, as rainfall increases during late autumn and winter, the presence of residue can increase infiltration into the soil. For example, at two sites in the Mediterranean region of southern Australia (near the towns of Maitland and Wirrabara), soil below a depth of 20 cm wet up considerably more at the start of the 2009 season in the plots where residue was retained (Figs. 14.12; 14.13) (G. Butler, unpublished data). Here, the residue protected the soil surface, allowing greater infiltration to deeper in the soil. At both sites, soil water storage below a soil depth of 20 cm increased by about 20 mm due to the presence of retained stubble on the soil surface.

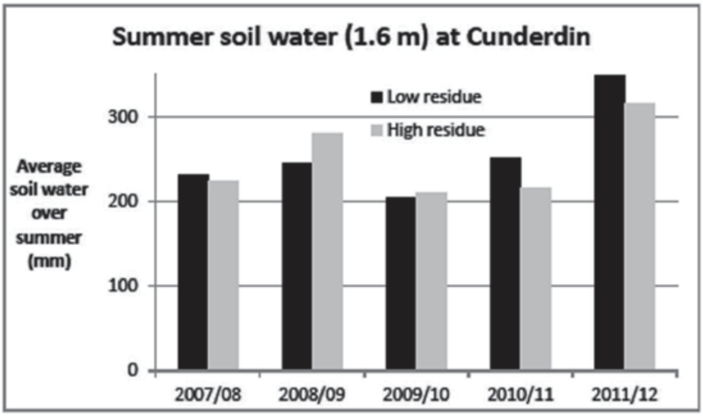
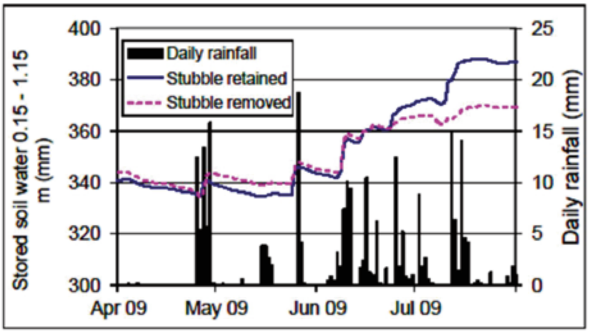


Fig. 14.11 Residue quantity has little impact on average summer soil water storage. (Ward et al. 2012)

Fig. 14.12 Residue retention increased soil water early in the growing season (late June and July) compared with residue removal at the Maitland (SA) trial. (G. Butler, unpublished data)



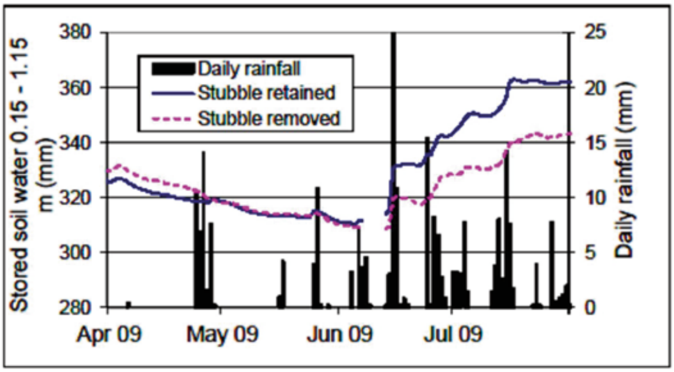


Fig. 14.13 Residue retention also increased infiltration in June and July at the Wirrabara (southern Australia) trial. (G. Butler, unpublished data)

In the longer term, changes in soil organic carbon can lead to changes in soil structure and infiltration. In the Maitland and Wirrabara sites, after 4 years of residues being either retained or removed, soil organic carbon differed by about 2 t/ha in the top 10 cm of soil. Organic carbon is pivotal in maintaining good soil structure, and a difference of this magnitude could have significant impacts on infiltration rate.

In the temperate region of eastern Australia, plots with a short-season summer cover crop were drier during the 2009 autumn and early winter than traditional 'fallow' plots (M. McNee, unpublished data). However, soil water storage in the plots with the cover crop responded more to rainfall at the start of the winter growing season, indicating that the cover crop was protecting the soil surface and allowing more rainfall to infiltrate (Fig. 14.14). By the time flowering commenced, there was little difference between the treatments in terms of soil water.

In other years of the trial, there was little difference between the early-season summer cover crop treatments and the 'summer fallow' treatments, thanks largely to good autumn rains and increased infiltration due to the summer cover crop residue. However, the 'late season' and 'long season' summer crops used soil water during autumn, and soil water contents were lower in these treatments at wheat sowing, which impacted crop yield.

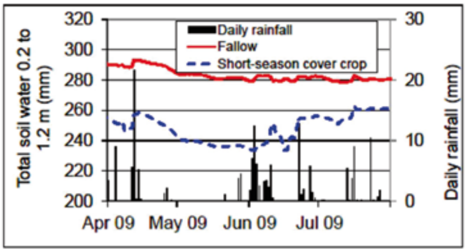


Fig. 14.14 Although soil was drier after a summer cover crop in the temperate region of New South Wales, it responded more to winter rainfall (M. McNee, unpublished data)

14.4.2 *Run-off*

A major benefit of stubble retention is that it protects the soil surface. Raindrop impact can lead to a break down in surface soil structure, which leads to reduced rates of infiltration and increased run-off. Residue intercepts the raindrops and prevents damage to the soil structure (Hillel 1971), thereby ensuring good infiltration. Reduced tillage also has a direct effect on soil structure, with soils generally having a much more stable structure when physical disturbance is minimised. Through these two effects, conservation farming practices generally lead to decreased run-off compared with systems, where tillage and residue removal are practised. For example, at a trial on a red-brown earth in the Mediterranean zone of southern Australia, soil loss under simulated rainfall was reduced from 0.8 to 0.4 t/ha, when residue was increased from 0.5 to 5.0 t/ha (Malinda 1995). Earlier trials in the subtropical areas of southern Queensland undertaken by Freebairn and colleagues showed similar results (e.g. Freebairn and Boughton (1980). In other trials in the subtropical zone, Lang (1979) found that run-off and erosion increased markedly when ground cover fell below 75 %. This promoted the idea of 'threshold' values for ground cover, and it is generally accepted now that a value of 2 t/ha of residue is adequate to minimise the erosion risk (Scott et al. 2010).

14.4.3 *Evaporation*

14.4.3.1 Evaporation Rate

Evaporation involves the transport of water to the soil surface, and its conversion into water vapour. This conversion requires energy, which in southern Australia and New Zealand mostly comes from sunlight, with a minor contribution from wind.

Evaporation from an initially saturated soil can be broken down into three stages (Fig. 14.15). In stage 1, there is plenty of water at the soil surface, and evaporation

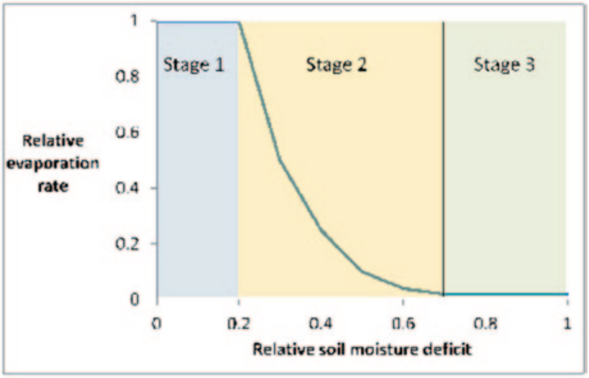


Fig. 14.15 The three stages of evaporation. For soil moisture deficit, 0 is a wet soil, and 1 is a dry soil

is limited only by the amount of available energy. However, as the soil dries, the ability of the soil to transmit water to the soil surface starts to diminish, and the evaporation rate rapidly falls (stage 2). In stage 2, the evaporation rate is related to the surface soil water content. When the surface soil is air dry, the only way that water from deeper soil layers can reach the soil surface is by diffusion of water vapour (stage 3), which is a slow process. In stage 3, the rate of relative evaporation is roughly constant.

Many studies around the world have demonstrated that residue can slow the rate of evaporation from a wet soil, and it does this by restricting energy available for the evaporation process. Initially, residue shades the soil surface, which instantly reduces the amount of available energy for evaporation. Residue also reduces wind speed at the soil surface, which reduces the input of energy to the soil.

Therefore, while evaporation from the soil is limited by energy availability (that is stage 1 evaporation), residue is likely to reduce the rate of evaporation. However, as a general rule, stage 1 evaporation usually only happens for, at most, a few days. During stage 2 and stage 3 evaporation, residue has little impact on evaporation rate.

For example, Ward et al. (2012) measured evaporation rate at midday a few hours after 18.6 mm of rainfall in January 2009 at a site in southwestern Australia. Evaporation rate from plots with a cover crop averaged 0.28 mm/h, but evaporation from wheat stubble was 0.35 mm/h. However, a few days after rainfall, the evaporation rate had fallen to 0.065 mm/h, and there was no difference between plots with high and low residue loads.

After extended dry periods, as is common during summer in zones with a Mediterranean climate, evaporation rates were even lower, and once again, there was little difference between treatments with high and low residue loads. In three trials in southern Australia, the evaporation rate was measured at midday in March 2010, and at all three sites, evapotranspiration (ET) was slightly faster from the plots with the retained stubble (Table 14.1; G. Butler, unpublished data). This has also been observed at a trial in Western Australia (Ward et al. 2009). Although ET appeared to be faster from plots with retained stubble, the difference was small, and only amounted to a few millimetres if summed over a period of 5 months.

For the Wirrabara (SA) trial, evaporation rate was also measured at the same time on plots newly raked to remove the stubble, and evaporation from these plots was 0.075 mm/h (about three times faster than from the undisturbed plots). This demonstrates the immediate impact that soil disturbance can have on evaporation rate simply by exposing different soil surfaces to direct sunlight. Although evaporation rate was not measured at this trial on the next day, we expect that the increase in ET caused by soil disturbance would have been temporary.

Table 14.1 Midday evaporation rate for three trials in southern Australia in March 2010. (G.Butler, unpublished data)

Site	Soil type	Evaporation rate (mm/h)	
		Stubble retained	Stubble removed
Buckleboo	Sand	0.041	0.031
Ardrossan	Clay	0.083	0.075
Wirrabara	Clay	0.033	0.018

14.4.3.2 Total Evaporation over Summer

As discussed in Sect. 14.3.1, there can be differences in evaporation due to residue retention, depending on the time elapsed since the last rainfall. However, over a longer time period, such as the period between harvest of one crop and sowing the next, differences tend to even out. If the ET rate is reduced for a few days after rain by residue retention, then after a few days, the soil is wetter than the soil where residue was not retained. The wetter soil under the residue then loses water faster than the drier soil without the residue, and the total soil water storage tends to even out regardless of residue quantity (Fig. 14.11).

For example, the total evaporation over a whole summer in response to different cereal residue management was studied in trials at Cunderdin and Mingenew in the Mediterranean zone in Western Australia. In both trials, there were substantial differences in residue generated by either retaining or windrowing residue, but differences in summer evaporation were not related to residue levels (Ward et al. 2012). Similar results were observed for the trials in Buckleboo, Wirrabara, and Ardrossan (SA), and also in trials in the temperate region of NSW (Hunt and Kirkegaard 2011).

The exception to this rule could be for rainfall received close to seeding time. Evaporation rates at this time of the year are generally much lower than during the height of summer, and so rainfall received at this time is likely to stay in the soil for longer. Therefore, a reduction in evaporation rate, induced by residue, could lead to higher soil water contents for up to a week. In combination with the impacts of residue on infiltration discussed above, this could have large impacts on extending the sowing opportunity for crops.

14.4.3.3 Evaporation During Crop Growth

The presence of large quantities of residue on the soil surface may reduce evaporation, leaving more water in the soil available for transpiration through crop leaves (Yunusa et al. 1994). Evaporation rates at midday were measured in the trials in Western Australia at Mingenew and Cunderdin during the early crop growth stage in June or July. On a sandy soil at Mingenew, total ET rate at midday was 0.17 mm/h from both the ‘residue retained’ and ‘residue burned’ plots, suggesting that on this soil type, residue did not influence evaporation rate. However, at the loamy Cunderdin site, midday ET rate was 0.21 mm/h where residue was removed, and 0.15 mm/h where residue was retained. This suggests that residue retention on a loamy soil reduced evaporation from the soil surface, which could potentially allow more water to be transpired.

14.4.4 Deep Drainage

The water balance component of deep drainage is of crucial importance in southern Australia through its link with groundwater recharge, and associated dry land salinity (Peck and Williamson 1987). Although deep drainage is generally a small component of the overall annual water balance (Ward 2006), an increase of just a few millimetres per year (caused by clearing native perennial vegetation, and replacing it with annual crops and pastures) has lead to a substantial increase in the area affected by dry land salinity (Ferdowsian et al. 1996). Any farming practice that increases soil water storage could also increase deep drainage, and so conservation farming practices need careful scrutiny to ensure that the risk of dry land salinity is not increased.

14.4.4.1 Residue Retention

Very few studies have quantified the impact that conservation farming practices have on deep drainage and groundwater recharge. In trials across southern Australia (Ward et al. 2012), impacts of increased residue retention on soil water storage were minimal at all times of the year. Calculations of deep drainage from measurements of the water balance concluded that there was no significant impact of residue retention on deep drainage. Although this was only a few trials, all indications at this stage are that increased residue retention will not change the risk of deep drainage and associated dry land salinity.

14.4.4.2 Early Termination of Cover Crops, Crops, or Pastures

At a trial on a sandy soil near Mingenew in Western Australia, there were several instances where crops or pastures were terminated early, around anthesis in August or September. Some of these were planned as a part of the cover crop inclusion, designed to increase residue levels quickly. On other occasions, crops and pastures were terminated early to assist with weed control or to simulate grazing. On all these occasions, extra water was conserved in the soil, and some of this water was carried over until sowing of the next crop. Averaged over three summers (2008–2009, 2009–2010, and 2010–2011), the extra water stored in the soil at sowing following early termination was around 20 mm.

This extra water at sowing did not lead to increased crop yield at the Mingenew trial, but increased the quantity of deep drainage by around 10 mm in the 2009 and 2011 seasons (Fig. 14.16). Seasonal conditions were particularly dry in 2010, and deep drainage was zero from all treatments. However, on a loamy soil in Western Australia where early crop termination was also practised, there was no clear link between early crop termination and deep drainage, suggesting that increased groundwater recharge is most likely on sandy soils.

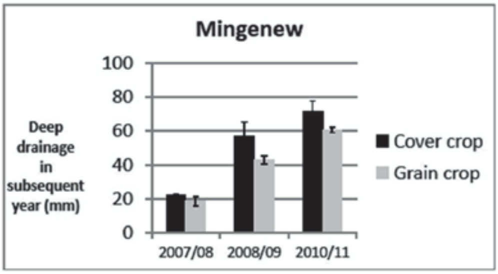


Fig. 14.16 Early crop or pasture termination can increase the deep drainage risk in the subsequent year. (P. Ward, unpublished data)

14.5 Weed Control

In Australia, one of the principal technologies enabling widespread adoption of conservation agriculture was the introduction of herbicides for weed control. In particular, glyphosate proved successful in killing weeds without cultivation, allowing earlier sowing and crop establishment (D'Emden et al. 2006; Llewellyn et al. 2012). However, the frequent use of glyphosate, and lack of equally efficacious alternatives, resulted in the development of weed populations resistant to glyphosate (Walsh and Powles 2007; Farooq et al. 2011). In Australia, resistant populations of annual ryegrass (*Lolium rigidum*) and wild radish (*Raphanus raphanistrum*) are widespread throughout the cereal-producing regions. Furthermore, some herbicides (e.g. trifluralin) need to be incorporated into the soil, and so conservation agriculture practices with minimal soil disturbance and residue retention can reduce their effectiveness. For these reasons, weed control in conservation agriculture in Australia is becoming a major issue, leading to farmers following a more pragmatic line of strategic tillage (Kirkegaard et al. 2014).

Obviously, an integrated approach to weed control is a core component of conservation farming strategies (Derpsch 2005). With this in mind, an opportunity for weed seed control was highlighted by Walsh and Powles (2007), with the observation that many weed seeds went through the harvester with regular grain harvest operations. Collection and destruction of the chaff fraction was effective in reducing ryegrass seed numbers, but less effective for wild radish control. Alternatively, concentration of chaff in a windrow behind the harvester, followed by burning of the windrow, could control weed seed numbers. However, neither of these operations is consistent with conservation agriculture principles of maximising residue retention.

More recently, a Western Australian farmer, Ray Harrington, developed and tested an attachment for a harvester that physically damages weed seeds in the chaff fraction before returning the entire residue fraction to the soil surface. The Harrington Seed Destructor (Walsh 2012) has proved as effective as windrow burning and chaff removal in reducing ryegrass emergence in the subsequent year.

14.6 Future Outlook

In most of Australia, adoption of conservation farming has nearly reached its maximum level. The biggest threat to a continued high level of adoption is suitable weed control methods. Clearly, an integrated approach to weed control, reducing the reliance on herbicides or any other single control strategy, will be necessary to maintain the current use of conservation farming practices.

In New Zealand, current adoption of conservation farming is still relatively low. Greater adoption will rely on demonstration of the advantages of conservation farming principles over current practices. One of these advantages is likely to come from the increased price of fuel, with the lower fuel requirements of reduced tillage likely to prove attractive. With recent developments in seeding machinery making crop and pasture establishment less risky, adoption of conservation farming practices is likely to increase.

In terms of water balance, there is a scope for long-term changes in soil-water-holding capacity, associated with long-term residue retention and potential organic matter accumulation. Increases in soil-water-holding capacity could prove enormously beneficial to crop growers, especially in the southern and western parts of Australia where many soils currently have low water-holding capacity. Several research trials around the world have demonstrated improvements in soil-water-holding capacity and soil structure after 5–10 years of conservation tillage practices, and these benefits need to be quantified under Australian conditions.

The current research has also highlighted the role that residue might play in reducing evaporation during early crop growth. This has the potential to increase transpiration, which should flow through to increased water use efficiency and crop yield. However, this has not yet been demonstrated under Australian conditions, and needs further research.

14.7 Conclusions

Farmers in cereal-producing regions of Australia have enthusiastically adopted no-till farming systems, with excellent outcomes from the reduced soil erosion. Local and regional farmer groups have been instrumental in encouraging adoption and developing systems suitable for local conditions. Adoption has been slower in New Zealand, due to the perceived risks of crop and pasture establishment, and lack of clear advantages with a conservation farming system.

In terms of water balance:

- Residue retention, on its own, has little impact on soil water storage, when measured over periods of several months. However, over periods of days or weeks, residue retention can increase infiltration and reduce evaporation, which can be particularly beneficial in extending the sowing window.
- Winter cover crops do not have much impact on residue quantity, but do increase ground cover when residues are ‘rolled’.

- In regions or years with adequate early summer rainfall, summer cover crops increase residue quantity and infiltration of autumn rains. Early termination of summer cover crops (e.g. February) is desirable to maximise storage of autumn rains for subsequent crop production.
- Increased residue during early crop growth has the potential to reduce evaporative losses of water, with a complementary increase in transpiration. This should increase water-use efficiency, but has not yet been demonstrated.
- Increased residue retention does not increase the risk of deep drainage and associated dry land salinity. However, early termination of crops or pastures can lead to increased risk, particularly in soils of low water-holding capacity, and in wet years or regions.

An integrated approach to weed control is essential to maintain the current high level of conservation farming use in Australia, and to encourage adoption in New Zealand. The Harrington Seed Destructor, in combination with other weed control mechanisms, may be beneficial in this regard.

References

Baker CJ, Collins RM, Choudhary MA (2003) Factors affecting the uptake of no-tillage in Australia, Asia and New Zealand. In: García-Torres L, Benites J, Martínez-Vilela A, Holgado-Cabrera A (eds) Conservation agriculture. Springer, Dordrecht, pp 13–20

Baker CJ, Saxton KE, Ritchie WR, Chamen WCT, Reicosky DC, Ribeiro MFS, Justice SE, Hobbs PR (2007) No-tillage seeding in conservation agriculture. In: Baker CJ, Saxton KE (eds) Food and Agriculture Organization of the United Nations and CAB International, Rome

Buckerfield JC, Lee KE, Davoren CW, Hannay JN (1997) Earthworms as indicators of sustainable production in dryland cropping in southern Australia. Soil Biol Biochem 29(3–4):547–554

Callaghan AR, Millington A (1957) The wheat industry in Australia. Angus and Robertson, Sydney

Cornish PS, Pratley JE (1987) Tillage: new directions in Australian agriculture. Inkata, Melbourne

D'Emden FH, Llewellyn RS, Burton MP (2006) Adoption of conservation tillage in Australian cropping regions: an application of duration analysis. Technol Forecast Soc Change 73(6):630–647

D'Emden FH, Llewellyn RS, Burton MP (2008) Factors influencing adoption of conservation tillage in Australian cropping regions. Aust J Agric Resour Econ 52(2):169–182

Derpsch R (2005) Situational analysis of no-tillage systems in WA and recommendations for the way forward. WANTFA, Northam

Evans TA, Dawes TZ, Ward PR, Lo N (2011) Ants and termites increase crop yield in a dry climate. Nat Commun 2:262

Farooq M, Flower KC, Jabran K, Wahid A, Siddique KHM (2011) Crop yield and weed management in rainfed conservation agriculture. Soil Till Res 117:172–183

Ferdowsian R, George R, Lewis F, McFarlane D, Short R, Speed R (eds) (1996) The extent of dryland salinity in Western Australia. Promaco, Albany

Flower KC, Cordingley N, Ward PR, Weeks C (2012) Nitrogen, weed management and economics with cover crops in conservation agriculture in a Mediterranean climate. Field Crops Res 132:63–75

Freebairn DM, Boughton WC (1980) Surface runoff experiments on the eastern Darling Downs. Aust J Soil Res 19:133

Gupta VVSR, Rovira A, Roget D (2011) Principles and management of soil biological factors for sustainable farming systems. In: Tow P, Cooper I, Partridge I, Birch C (eds) Rainfed farming systems. Springer, Dordrecht, pp 149–184

Hamblin AP (1984) The effect of tillage on soil surface properties and the water balance of a xeralfic alfisol. Soil Till Res 4(6):543–559

Hillel D (1971) Soil and water: physical principles and processes. Academic, New York

Hore HL (1940) Sand drift and control measures. J Dep Agric Vic 38:219

Hunt JR, Kirkegaard JA (2011) Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. Crop Pasture Sci 62(11):915–929

Hunt JR, Browne C, McBeath TM, Verburg K, Craig S, Whitbread AM (2013) Summer fallow weed control and residue management impacts on winter crop yield though soil water and N accumulation in a winter-dominant, low rainfall region of southern Australia. Crop Pasture Sci 64(9):922–934

Ji SN, Unger PW (2001) Soil water accumulation under different precipitation, potential evaporation, and straw mulch conditions. Soil Sci Soc Amer J 65(2):442–448

Kirkegaard JA, Conyers MK, Hunt JR, Kirkby CA, Watt M, Rebetzke GJ (2014) Sense and nonsense in conservation agriculture: principles, pragmatism and productivity in Australian mixed farming systems. Agric Ecosys Environ 187:133–145

Kohnke H, Bertrand AR (1959) Soil conservation. McGraw-Hill, New York

Lang RD (1979) The effect of ground cover on surface runoff from experimental plots. J Soil Conservation Serv NSW 35(2):108–114

Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. Field Crops Res 132:204–212

Malinda D (1995) Factors in conservation farming that reduce erosion. Aust J Exp Agric 35(7):969–978

McFarlane GC (1952) Soil management practices on north-western wheat farms. Rev Market Agr Econ 20:161

Peck AJ, Williamson DR (1987) Effects of forest clearing on groundwater. J Hydrol 94:47–65

Safa M, Samarasinghe S, Mohssen M (2010) Determination of fuel consumption and indirect factors affecting it in wheat production in Canterbury, New Zealand. Energy 35(12):5400–5405

Scott BJ, Eberbach PL, Evans J, Wade L (2010) Stubble retention in cropping systems in southern Australia: benefits and challenges. Orange, NSW

Trestrail C, Martin P, New R, Corrie K, Frakes I (2013) Agriculture, fisheries and forestry in the wheat belt region of Western Australia. ABARES, Canberra (Contract No.: 13.42)

Walsh MJ (2012) Harrington Seed Destructor—comparison with chaff carts and windrow burning systems. 2012 WA Agribusiness Crop Updates. Western Australian Agriculture Authority, Perth

Walsh MJ, Powles SB (2007) Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. Weed Technol 21(2):332–338

Ward PR (2006) Predicting the impact of perennial phases on average leakage from farming systems in south-western Australia. Aust J Agric Res 57(3):269–280

Ward PR, Whisson K, Micin SF, Zeelenberg D, Milroy SP (2009) The impact of wheat stubble on evaporation from a sandy soil. Crop Pasture Sci 60(8):730–737

Ward PR, Flower KC, Cordingley N, Weeks C, Micin SF (2012) Soil water balance with cover crops and conservation agriculture in a Mediterranean climate. Field Crops Res 132:33–39

Watt M, Kirkegaard JA, Passioura JB (2006) Rhizosphere biology and crop productivity—a review. Aust Soil Res 44(4):299–317

Yunusa IAM, Sedgley RH, Siddique KMH (1994) Influence of mulching on the pattern of growth and water-use by spring wheat and moisture storage on a fine textured soil. Plant Soil 160(1):119–130

Chapter 15
Conservation Agriculture in Europe

G. Basch, T. Friedrich, A. Kassam and E. Gonzalez-Sanchez

Abstract This chapter provides a description of the past and recent development of conservation agriculture (CA) in Europe. It reviews scientific and technical literature as well as empirical evidence reported by the European Conservation Agriculture Federation (ECAF) and its national member associations.

Starting from the early beginnings of CA in Europe, this chapter reviews the development of CA until its current status. This clearly indicates that Europe lags far behind other regions in the world in terms of the adoption and spread of CA. This chapter presents actual data of adoption in several European countries as far as it is reported by national CA associations. It also reviews the most relevant experiences gained throughout Europe, focussing on crop performance, impact on soil quality, and weed, insects and disease incidence, as well as environmental and economic aspects of CA. Challenges and possible reasons for the relatively low uptake of CA in Europe are discussed, including the influence of national and European agricultural policies and regulations on the past evolution of CA uptake in Europe. Finally, this chapter provides an outlook into future prospects for up-scaling of CA in Europe, and what the likely impact of global changes and constraints may mean for the adoption and spread of CA in Europe.

Keywords Aggregate stability · Biodiversity · Common Agricultural Policy · European Conservation Agriculture Federation · Weed management

---

G. Basch (✉)
Institute of Mediterranean Agricultural and Environmental Sciences, University of Évora,
P-7002-554 ÉVORA, Portugal
e-mail: gb@uevora.pt

T. Friedrich
Plant Production and Protection Division, Food and Agriculture Organization, Rome, Italy

A. Kassam
School of Agriculture, Policy and Development, University of Reading, Reading RG6 6AR, UK

E. Gonzalez-Sanchez
Rural Engineering Department, University of Córdoba, Córdoba, Spain

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_15

15.1 Introduction

Conservation agriculture (CA) is a relatively recent concept which has its origins in soil and water conservation systems, which were developed in the 1940s and 1950s in response to the dust bowls in the USA that became known as conservation tillage. Since the middle of the twentieth century, both the need for soil and water conservation due to the intensification of agricultural land use and technological advances led to an increased demand and interest in conservation tillage systems and the gradual replacement of conventional plough tillage, which for many centuries, was the most effective way to guarantee satisfactory weed control, nutrient mineralization and seedbed preparation.

This chapter reviews developments in the science and practice of CA in Europe over the last few decades beginning in the late 1960s. It reviews reported information from several European countries, most of which have national associations dedicated to the promotion of CA and are members of the European Conservation Agriculture Federation (ECAF).

Today, compared to other regions, Europe is lagging behind in terms of the adoption of CA. Only the African continent with about 1 million ha under CA—corresponding to 1 % of the global arable land—has a lower relative uptake when compared to Europe's approximately 1.36 million ha (not including Russia) under CA, which corresponds to approximately 2 % of the global arable cropland. These rates of uptake of CA lag far behind other regions in the world. For example, countries and regions such as USA, Canada, Paraguay and western Australia show adoption rates of 15, 30, 79 and 100 %, respectively (Friedrich et al. 2014).

Based on the history of CA in Europe, this chapter provides a sketch of the present state of CA and reviews experiences that may or may not help to explain the reason for the low adoption of CA in Europe in general and why adoption is much higher in some countries than in others. Challenges and opportunities are analysed in the light of both research findings and farmer experiences as well as under the economic and political conditions within the Common Agricultural Policy (CAP) framework.

15.2 History of CA in Europe

The initial adoption of conservation tillage was driven by different motives in different regions of the world where these techniques are widely applied today. In the USA, it was mainly the concern for the degradation of highly erodible prairie soils subject to both wind and water erosion due to intensive mechanical soil disturbance. Soon, the economic benefits of reduced and no-tillage crop production systems became as relevant as the concern for soil conservation, leading to the massive adhesion of farmers to the new technology for crop establishment and grassland renovation. Despite the occurrence of severe soil erosion in many parts of Brazil, it was

Table 15.1 Results of the first experiences with CA in some European countries

Country	Year	Experience	Reference
UK	1955	++	Christian (1994)
The Netherlands	1962	––	Van Ouwerkerk and Perdok (1994)
Germany	1966	+	Bäumer (1970)
Belgium	1967	+	Cannell and Hawes (1994)
Switzerland	1967	+	Cannell and Hawes (1994)
Italy	1968	+/–	Sartori and Peruzzi (1994)
France	1970	+	Boisgontier et al. (1994)
Spain	1982	++	Fernández-Quintanilla (1997)
Portugal	1984	++	Carvalho and Basch (1994)

+=positive, ++=very positive, ––=not feasible

mainly the economic aspect that led farmers to initially adopt no-tillage, there in the early 1970s (IAPAR 1981).

In Europe, the first step towards CA in the form of no-till was driven by the attempt to reduce plough tillage and thus production costs associated with machinery, fuel, time and labour. The replacement of soil tillage, partly or entirely, both for crop establishment and for pasture renovation, began at the end of the first half of the last century, but only the availability of chemicals such as plant growth regulators and herbicides triggered a wider application of conservation tillage and the consequent research in reduced and no-tillage (Phillips and Phillips 1984). Despite intensive research on the different aspects of conservation tillage after the invention of paraquat in 1955 and its commercial release in 1961, no-tillage and even reduced tillage were applied only at a very small scale until the end of the last century.

Throughout Europe, the history of CA varies considerably from country to country as did the first experiences with the use of no-till (Table 15.1). In the UK, the first, very positive results made the area under no-till grow to almost 300,000 ha in the early 1980s. However, the straw burn ban caused farmers to abandon this technique due to increasing problems of weed control and volunteer cereals (Christian 1994). On the contrary, the first experiences carried out by Bakermans and de Wit in the Netherlands were far from successful, which made Van Ouwerkerk and Perdok (1994) conclude that no-tillage was not feasible in Dutch arable farming. Already in the early 1980s, very positive results were reported from Spain and Portugal, where both water scarcity during spring and summer and severe water erosion potential during winter encouraged the use of soil conservation measures. While in many countries, the reduced adoption of CA was driven initially by research institutions, already in the 1960s and 1970s in Denmark and at the very end of the last century in Finland, the initial adoption was farmer-driven. In Denmark, however, the no-till practice was replaced by reduced or minimum tillage before seeding, whereas the spread of no-till among farmers in Finland was rather fast, reaching 13 % of the total area of cereals and oilseed crops by 2008 (Soane et al. 2012).

At the end of the last century, CA in Europe was mostly characterized by the adoption of different levels of reduced tillage with little correspondence to the full CA system as defined by FAO (FAO 2013a). The establishment of the ECAF in

1999, which, together with the UN Food and Agriculture Organization held the first World Congress on Conservation Agriculture in 2001 in Madrid, contributed to a ‘renaissance’ not only of conservation tillage practices but also an increased concern regarding the two other main principles of CA: permanent soil cover both in annual and perennial crops and the utilization of balanced but market-oriented crop rotations to reduce the input of agrochemicals and to overcome a potential increase of problem weeds, pests and diseases. Still, Europe lags far behind other regions in the uptake of CA and continues to be a ‘developing’ continent in the adoption of CA.

15.3 Present State of CA in Europe

Since the end of the last century, not least because of the action of ECAF and its affiliated member associations, some advances in the uptake and spread of CA has occurred in Europe, albeit with large differences between countries. As far as information on the extent of adoption is concerned, difficulties persist because in most European countries there are no official statistics differentiating different crop establishment or soil management systems. In countries or regions where so-called agri-environmental measures support the use of CA, official data are available which, however, may not cover the total area under CA. In addition, the definition of farming practices considered compliant with CA also may differ somewhat from country to country. In some countries, mulch sowing systems and ‘temporary’ no-till are considered and reported as areas under CA. Therefore, some authors distinguish between area under no-till and under CA (Friedrich et al. 2014). The most reliable information on the area under CA and its percentage of cultivated area, even for European countries, can be retrieved from the FAO Aquastat webpage (FAO 2013b; Fig. 15.1). The data obtained by ECAF from its member associations in Europe are incorporated in this worldwide database.

In 2011, the areas under CA in the countries listed in Fig. 15.1 add up to 1.36 Mha, which corresponds to a share of 1.92 % of the total arable land in these countries. In 2005, although not covering exactly the same countries, an average percentage of adoption for Europe was estimated at 1.1 % (Basch et al. 2008). Spain is by far the leading Western European country in terms of no-till adoption, with around 650,000 ha under CA corresponding to almost 5 % of total arable land. Only Finland presents a higher share of arable land under CA with more than 7 %. Surprisingly, this figure was achieved within a short period of time (since 1998) and can be explained by the farmer-driven process of adoption that only later was supported by extension services and research organizations as well as the agribusiness sector. Within the bigger countries, it is only the UK that surpasses the 2 % of adoption, whereas France and Italy present adoption rates of around 1 %. Despite the existence of an increasing number of successful CA practitioners in Germany, adoption of CA remains low as the main interest of farmers continues to be mulch-tillage systems, not at least due to the growing pressure from ecologists pointing at CA

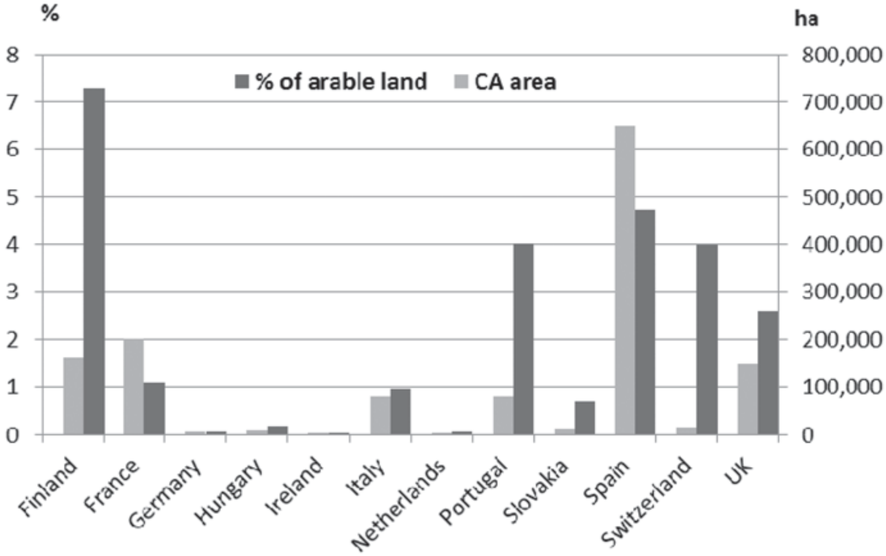


Fig. 15.1 CA adoption in annual crops in some European countries. (Source: FAO (2013b), ECAF (2013, personal communication))

being allegedly a farming system dependent on the use of more herbicides, which in practice is not proven.

Over the last two decades, there has been an increased perception in Europe for the need for effective soil conservation in perennial crops. Considering that nearly 80 % of the 10.4 Mha of perennial crops in the European Union (EU) are covered by olives and grapes (48 and 32 %, respectively), it is evident that a considerable part of this area is under Mediterranean conditions, and often on undulated and even hilly areas (Jones et al. 2006). Although the principles of CA were mainly developed for arable cropping systems, they are considered equally feasible in perennial cropping systems, especially with regard to minimum soil disturbance and permanent soil cover, applied not only for tree crop establishment but also, and more importantly, for growing. It is therefore not astonishing that the adoption of CA principles can be found in Spain and Italy with around 0.9 and 0.5 million ha under CA, respectively (personal communication: AEAC/SV 2013, AIGACoS 2013, the Spanish and Italian CA associations, respectively), which correspond to almost 20 % of the total area under perennial plantations in these two countries. Smaller areas under CA are reported for Portugal (30,000 ha; personal communication: APOSOLO 2013) and Slovakia (10,000 ha; personal communication: SNTC 2013). In Germany, both in vineyards and fruit orchards, the most frequent soil management system is based on cover crop establishment in every second inter-row space. For other countries, at least to our knowledge, there are no data available on the adoption of CA in perennial crops.

15.4 Experiences with CA in Europe

As mentioned above, research work on CA in countries in Europe started soon after the release of paraquat in the early 1960s. Since then—and earlier in western and central Europe than in Southern Europe—many experiments, some long term, have been undertaken to compare the performance of no-till and reduced or min-till crop establishment with the traditional, mainly plough-tillage-based soil management system. This focus on field experiments and research solely comparing pure soil tillage systems rather than concentrating on improving CA-based systems has certainly not contributed to optimizing the performance of CA systems under different pedo-climatic conditions and cropping systems. Therefore, many of the available research results may not reflect the potentially attainable performance of CA cropping systems when compared to conventional systems.

The following sections review the most relevant results obtained in several countries and regions throughout Europe covering the crucial aspects of crop performance, soil quality, weed, disease and pest incidence, environmental aspects including ecosystem services and economic aspects including input use efficiency.

15.4.1 Crop Performance

The comparison of the performance of different agricultural practices is mostly done through the determination of crop yields. In many European countries, data on crop yields with no-till compared to conventional tillage are available. Some of these data covering regions from North to South are summarized in Table 15.2. No clear pattern can be deduced when comparing crops or seeding period. However, in general, it appears that crops under NT perform relatively better in central and southern European countries when compared to northern European countries. For the same country and the same crops, very different results are reported (Känkänen et al. 2011; Alakukku et al. 2009). Other reviews and results on comparative crop yields in different countries are reported for Scandinavia (Arvidsson 2010; Alakukku et al. 2009; Riley et al. 1994), the UK (Christian and Ball 1994), Germany (Tebrügge and Böhrnsen 1997a) and Spain (González et al. 1997; Cantero-Martínez et al. 1994; Hernánz and Sánchez-Girón 1994).

As an overall result of the analysis of crop yields from the manifold experiments under different conditions, most of NT yields range within 10 % of those under conventional tillage. The results presented in Table 15.2 show increasing yield levels under drier conditions. Detailed analysis indicates that lower yields under NT are often the result of problems related to soil compaction, poor residue management or weed management (Soane et al. 2012). Especially under high-yielding conditions producing high quantities of crop residues, management poses increasing challenges to crop establishment. Lower temperatures in the topsoil, partially due to crop residues, were also reported to adversely affect both crop and weed seed germination (Morris et al. 2010; Riley et al. 1994).

Table 15.2 Selected examples of crop yields obtained with no-till and ploughing in various locations in Europe. (Adapted from Soane et al. 2012)

Country	Crop	No. of harvests	Ploughed yield ($t\ ha^{-1}$)	No-till as % of ploughed	References
Norway	Winter wheat/ barley	27	5.17	99	Riley et al. (1994)
Sweden	Winter wheat/ Barley	22	4.89	91	Riley et al. (1994)
Sweden	Winter wheat	n.a.	6.26	95	Arvidsson (2010)
	barley	n.a.	4.25	88	
Finland	Spring barley Spring barley	8 7	4.3 4.3	95 100	Alakukku et al. (2009)
Finland	Spring barley Oats	4 4	5.89 6.38	61 91	Känkänen et al. (2011)
Denmark	Winter	5	2.44	89	Rasmussen (1994)
	Oilseed rape	5	4.13	96	
	Winter wheat	6	5.52	101	
	Spring barley	6	4.36	83	
Denmark	Winter wheat	6	8.57	83	Schjønning et al. (2010)
Scotland	Spring barley	15	4.79	91	Soane and Ball (1998)
	Winter barley	9	8.8	99	
England	Winter wheat Winter wheat	4 4	8.40 7.79	105 92	Cannell et al. (1986)
Germany	Winter wheat	32	6.57	100	Tebrügge and Böhrnsen (1997a)
	Sugar beet	8	67.9	100	
	Oilseed rape	3	3.64	109	
	Silage corn	3	50.7	88	
	Sugar corn	3	10.6	99	
France	Maize	8	8.37	102	Labreuche (pers. communication)[a]
	Wheat	11	8.59	102	
	Barley	12	7.82	101	
Portugal	Wheat	4	2.22	103	Basch et al. (1997)
	Wheat	10	1.73	98	
	Barley	4	1.89	113	
Spain	Barley	n.a.	2.62	103	Lacasta Dutoit et al. (2005)
	Sunflower	n.a.	0.87	108	
Spain	Barley	1	3.50	100	Fernández-Ugalde et al. (2009)
	Barley	n.a.	1.00	200	

[a] Personal communication: J. Labreuche, 2011, Arvalis Institut du Végétal, Boigneville, France

Yields during wetter years are frequently reported to be lower especially on clay soils with poor drainage (Cannell et al. 1986). Interactions between crops, soil type and regional climate conditions with regard to the success of CA have often been observed throughout Europe. Under relatively cold soil conditions in spring, autumn-sown crops seem to perform comparatively better under CA than spring-sown crops, which can be attributed to delayed crop emergence (Anken et al. 2004) or deficient crop establishment, especially on wet clay soils (Carvalho and Basch 1994). In many cases, sandy soils were less suited to no-till than loams or clay loam soils, due to weak soil structure which tend to compact (Ehlers and Claupein 1994; Van Ouwerkerk and Perdok 1994). In other cases, some crops perform better when grown under CA on certain soil types. Under similar climate conditions, Tebrügge and Böhrnsen (1997a) found higher yields of NT sugar beet on loamy soil, but lower yields on a sandy Cambisol. Although rainfed sunflower should benefit from increased water availability under CA due to reduced evaporation losses, yields on Vertisols in South Portugal were lower under CA (Carvalho and Basch 1994). Basch et al. (1998), who found yield differences between tillage systems even under irrigated conditions, explain this through a reduced sunflower root development caused by a higher penetration resistance under NT and weak soil structural conditions.

Despite the wide difference in crop yields under different conditions when grown conventionally compared to CA, any possible initial yield reductions are overcome after the transition phase mainly due to improvements in soil structure and biopores, increased N and water availability in the soil and, not least, the farmer gaining practical experience with the CA system (Soane et al. 2012).

15.4.2 Soil Quality

Soil quality is usually assessed through physical, hydrological, chemical and biological parameters. Unlike other regions in the world, and with the exception of areas in the Mediterranean, most European cropland has been considered reasonable quality, showing low risk of degradation. However, at the very beginning of this century, a European Commission driven initiative called 'Soil Thematic Strategy' drew attention to major threats that 'apparently' European soils are also subject to. Although this initiative did not result in a European Soil Framework Directive, similar to other existing directives on Water, Air, Biodiversity, etc., it triggered action in the form of research, demonstration and support of soil conservation measures through changes in farming practices to combat the identified major soil threats, being erosion, loss of organic matter and loss of soil biodiversity (Van-Camp et al. 2004).

Over the last few decades, considerable research has been undertaken to assess the responses of soils to changes in their management, mainly soil tillage and soil cover, through either crop residues and/or cover crops. The results obtained allow anticipating the most important soil responses after a medium or long-term shift to CA. A more detailed compilation of the soil responses obtained mainly under European conditions is reported by Ball et al. (1998), Tebrügge (2003) and Imaz et al. (2010). Potential benefits and disadvantages of CA are summarized in Table 15.3.

With regard to soil physical properties, the gradual improvement of soil structure under CA and consequent higher aggregate stability was experienced under the most diverse climatic and soil conditions. Initial gains in bulk density and soil strength under NT were often compensated through a more vertically oriented

Table 15.3 Summary of the most frequently reported changes in soil properties after several years of no-till. (Adapted from Soane et al. 2012)

Benefits	Disadvantages
Increased aggregate stability, especially near surface	Increased bulk density at 0–25 cm depth can lead to poor aeration when wet
Increased organic matter content near surface	Increased moisture content near surface in spring in northern regions delaying drilling
Increased vertical and stable pore structure	Reduced soil surface temperature, especially in spring in northern regions delaying drilling
Increased biological activity, especially earthworms	Increased acidity near surface
Increased infiltration rate	Increased accumulation of P near surface with risks of loss in runoff
Increased hydraulic conductivity in subsoil on well structured soils	
Increased soil strength and load bearing capacity with reduced damage from traffic	

macroporosity with root channels and earthworm activity; contributing to soil aeration, water intake and moisture retention (Vogeler et al. 2009). After some years, however, and given that excessive traffic load under wet conditions is avoided, initial higher bulk densities may equal or even be less than those under conventional tillage. Still the benefits in terms of bearing capacity remain, though late harvests of summer crops under wet conditions may pose enormous challenges to soil structure under CA.

Changes in soil hydrology, after the adoption of CA, can be expected through the modification of soil structure, impact on infiltration rate, hydraulic conductivity and evaporation from the soil surface due to a higher rate of soil cover. The increase in infiltration rate over time after CA adoption has been well documented (Vogeler et al. 2009). In general terms, this is explained as the result of the raindrop energy-breaking mulch cover, better aggregate stability and higher topsoil SOC content (Lampurlanés and Cantero-Martínez 2006), as well as the vertically oriented macropore structure along the soil profile (Strudley et al. 2008).

However, changes in the hydraulic behaviour of the soil through CA adoption are not limited to water intake, drainage and evaporation. Carvalho and Basch (1995) observed a profound change in pore size distribution after 6 years of no-till on a vertic Cambisol (Fig. 15.2). The pore volume responsible for the retention of plant available water (50–0.2 µm) increased from 5.1 to 9.4% under no-till in the top 30 cm soil layer. The differences in water availability between no-till and ploughed land were very small resulting in identical crop yields under central European conditions (Vogeler et al. 2009), but in the semiarid northeast of Spain, barley yields doubled under no-till (Fernández-Ugalde et al. 2009).

Regarding chemical soil properties, the stratification of soil organic carbon and nutrients such as available P and K becomes more pronounced in the absence of soil tillage due to decomposition of crop residues and increased microbiological activity. Apparently, this accumulation near the soil surface does not interfere with

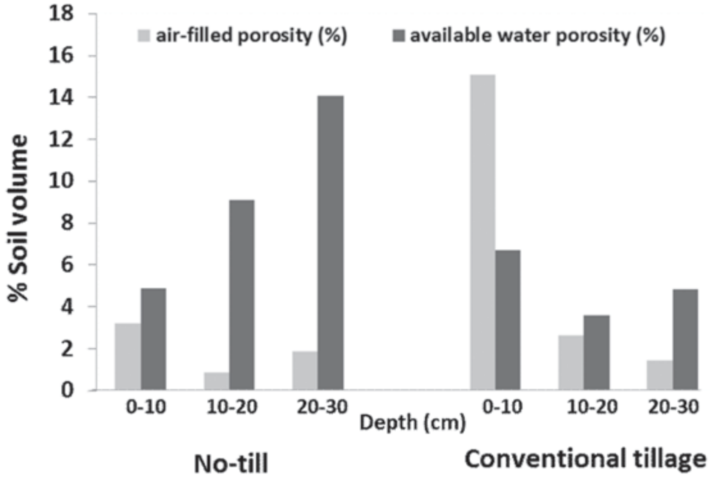


Fig. 15.2 Air-filled and available water porosity in the topsoil layers of a vertic Cambisol under conventional and no-tillage. (Adapted from Carvalho and Basch 1995)

plant nutrient uptake (Peigné et al. 2007). Other likely changes in chemical soil characteristics are increased soil acidity in the surface layer due to residue decomposition (organic acids) and nitrification of ammonium-based fertilizers (Ekeberg and Riley 1997), and increased enzymatic activity such as urease, which recommends avoiding the use of urea fertilizers (Rochette et al. 2009). After long-term application of no-till practices, Piovanelli et al. (2006) observed improved chemical fertility in the form of increased soil organic matter; whereas Mazzoncini et al. (2011) reported higher nitrogen contents, which agrees with the results of Carvalho et al. (2010) and Regina and Alakukku (2010).

The contribution of soil life to soil health and function is indisputable. Numerous European studies underpin the importance of minimal or no soil disturbance, and the food and shelter provided by crops including cover crops and their residues, for both diversity and number of soil organisms, and also above-ground wildlife. Increased numbers of earthworms in the absence of tillage and the presence of residues at the surface is the most frequently reported indicator for enhanced biological activity under CA (Peigné et al. 2009; Pelosi et al. 2009; Boguzas et al. 2006; Anken et al. 2004; Fortune 2003; Kladivko 2001; Ehlers and Claupein 1994). After 5 years of no-till on a Luvisol in South Portugal, the number of earthworms was almost threefold (39 vs. 129) and after 3 years of straw residue (0, 2000 and 4000 kg ha^{-1}), earthworm numbers increased from 100 to 122 and 136 individuals m^{-2} respectively. In addition, microbial activity and population, such as mycorrhizas (Brito et al. 2006), as well as other macro fauna and even ground-nesting birds that find more favourable habitats under CA, all contribute to the enriched biodiversity and food webs/chains below and above the ground surface.

15.4.3 Weeds, Diseases and Insect Pests

From scientific as well as practical experience, it is well known that the adoption of CA may cause changes in the incidence and type of weeds, insect pests and diseases. Some attempts to introduce CA have failed due to the unsuccessful or uneconomic control of these problems. Even the well-established no-till system in the UK was abandoned in the early 1980s after the straw burn ban, due to subsequent problems with weeds and volunteer cereals. The shift to no-till especially favours perennial grass weeds (e.g. *Agropyron repens*) but also some annual grass weeds such as sterile brome (*Bromus sterilis)*, black-grass (*Alopecurus mysuroides)* and annual meadow grass (*Poa annua*), and some broadleaved weeds like cleavers (*Gallium aparine*) and groundsel (*Senecio vulgaris*). Before the effective control by selective weedicides in cereal-based crop rotations, grass weed infestation meant a serious challenge to CA farmers, who in many situations adopted the stale seedbed technique to overcome weed infestation (Schutte et al. 2014). Many other weeds and overall weed numbers declined either due to effective chemical control, missing protection through seed burial or shading by crop residues acting as a physical barrier to weed seed emergence. Yet, volunteer cereals were a severe problem in a following no-till cereal crop in central and northern Europe (Melander 1998).

As a result of long and dry summers, the southern regions of Europe are challenged much less by perennial weeds as most of the weed species present are annual, with the exception of badly drained lowlands or continuously irrigated areas (Basch and Carvalho 1994). In rainfed conditions, the control of annual weeds under CA is facilitated in case the first wave of weeds is successfully controlled before the establishment of autumn-sown crops (Calado et al. 2010, Barros et al. 2008). Under no-till, these researchers observed a reduction in late re-infestation when compared to conventional tillage in which old weed seeds are brought up to soil layer from where they can germinate during the season. Barros et al. (2008) further stressed the importance of the higher soil-bearing capacity under no-till allowing for the correct timing of application of any necessary weed control measure. In general, in the more humid regions of Europe, grasses and some perennial weeds pose greater challenges to CA systems, while annual weeds seem to cause less problems throughout Europe.

The challenge posed by herbicide-resistant weeds has been known in Europe for a long time, but it is not limited to no-till or CA conditions. However, the more frequent use of non-lethal doses of glyphosate-based herbicides may carry a higher risk of developing resistant weeds in no-till systems. Problems with herbicide-resistant weeds could put at risk opportunities for wider adoption of no-till in Europe, calling therefore for complementary and effective integrated weed management measures that include permanent soil cover either through residues or cover crops where possible and, above all, crop rotations under CA conditions (Soane et al. 2012).

Slugs, whether seed hollowing or leaf damaging, present a potential threat to the successful establishment of crops under CA, especially under humid and high residue conditions (Hammond et al. 1999). Several strategies have been proposed to cope with this problem, ranging from the application of mulluscicides or calcium cyanamide that increase production costs and affect other beneficial soil organisms, to deeper seed placement and aggressive residue cultivation. In order to intervene in time, monitoring before and after seeding is recommended (Jordan et al. 1997, Glen et al. 1990). Other proposals to reduce undesirable initial slug incidence include avoidance of anti-slug treatments to favour higher populations of predator beetles and other natural enemies of slugs as shown by Symondson et al. (1996) under direct drilling. While the incidence of some insect pests such as springtails in sugar beet decreases under mulch conditions, others such as the European corn borer (Soane et al. 2012), lesion nematodes (Mota et al. 1997) and mice (Xavier et al. 2005) may increase due to the practice of no-till.

Pathogens contained in crop residues may bear a higher risk of disease infection of subsequent crops, especially in monocropping systems (Mikkola et al. 2005). However, the few studies available in Europe comparing the effects of conventional and CA-based cropping systems on the incidence of disease provide no clear evidence if one or the other practice favours or suppresses the occurrence of crop diseases. Bräutigam and Tebrügge (1997), for example, found no difference between ploughing and no-till in eyespot infestation in wheat after 3 years, but considerably higher infestations after 8 years when ploughing. In the Czech Republic, Matusinsky et al. (2009) found that soil management only had a limited effect on the incidence of stem-based diseases, whereas *Fusarium avenaceum* was more prevalent with tillage in 2007. In Norway, reduced incidence of clubroot (*Plasmodiophora brassicae*) in reduced and no-tilled brassica crops was observed by Ekeberg and Riley (1997), but Fortune et al. (2003) reported higher levels of infection of net blotch (*Pyrenophorateres*) and rhynchosporium (*Rhychosporium secalis*) under reduced tillage. Also, the incidence of barley yellow dwarf virus on no-till winter barley was considerably less when compared to ploughing (Jordan et al. 1997; Kendall et al. 1991).

15.4.4 Environmental Aspects of CA

Concerns about the environmental performance of farming practices rank high in Europe. Legislations and regulations govern the use and amount of many production inputs. It is therefore not astonishing that environmental impacts of CA or no-till have been investigated thoroughly in Europe and that there are many studies on the aspects of environmental behaviors of CA. The main concerns are related to erosion, nutrient and pesticide dispersal and, in the last two decades, emissions of greenhouse gases also (Holland 2004; Davies and Finney 2002).

For a long time in Europe, runoff and soil erosion have been underestimated as being a widespread problem not only with regard to the degradation of agricultural soils but also as an environmental problem affecting off-site ecosystems and water resources. Only in the twenty-first century has erosion been officially recognized as a major threat to agricultural soils and to the environment (Van-Camp et al. 2004). More evident and severe in some regions than in others, erosion is now a concern of almost all national and regional authorities in Europe. The Mediterranean regions, due to the concentration of rainfall in the winter months, are especially prone to severe erosion events (García-Ruiz 2010; Basch and Carvalho 1998), but also other regions in Europe are seriously threatened by soil erosion. Ploey et al. (1991) estimated this area to be around 25 Mha in western and central Europe, with an average annual soil loss of tens of Mg ha^{-1} on several million hectares. Others have estimated that the annual average soil erosion rate within the European Union is in the order of 17 Mg ha^{-1} (Troeh and Thompson 1993), and individual events may cause soil losses between 20 and 40 Mg ha^{-1} (Montanarella 2006).

Much evidence has been collected about the benefits of CA and no-till in effectively reducing soil erosion rates: improved soil structure, vertically oriented macropores and thus greater downward movement of water in the soil as well as the breakdown of the energy of raindrops through residues contributing to much less soil detachment and crust formation (Basch et al. 2012a) which are key processes that decrease soil losses by up to 95 % and surface runoff by up to 60 % under CA when compared to conventional soil management (Márquez et al. 2008; Ordóñez et al. 2001). Although less widespread—such as on sandy soils in the Netherlands (Van Ouwerkerk and Perdok 1994) and in East Germany—wind erosion has been effectively controlled by the adoption of CA (López and Arrúe 2005; IRENA 2005). However, under certain conditions, the absence of soil disturbance alone is not sufficient to keep runoff and erosion well below the rates found under conventional tillage management. In an experiment in olive groves in southern Spain, Gomez et al. (2009) obtained not only higher runoff coefficients in inter-rows kept weed-free but also higher erosion rates. Only the establishment of barley as a cover crop was able to reduce both runoff and erosion effectively.

Besides the impact on degradation of agricultural land, runoff and erosion contribute decisively to the off-site transport of nutrients and pesticides and thus to the environmental impact of farming. Both nutrients and pesticides can be transported in a dissolved form in runoff water, but the strong adsorption of many pesticides and phosphorous to soil particles make off-site transported sediments a major source for contamination and eutrophication of water bodies. Yet, the occurring soil stratification under CA and the consequent enrichment of the uppermost surface layer in SOM and the dissolved fraction of P may lead to higher concentrations of dissolved fractions in the runoff of no-till fields. Despite 70 % reduced off-site transport of particulate P under no-till, Puustinen et al. (2005) found almost four times more dissolved P in the runoff. Some authors attribute the higher availability of dissolved P at the surface of no-till fields also to the decay of weeds or cover crops and to surface-applied fertilizers (Ulén et al. 2010; Muukkonen et al. 2009). Further improvement of water infiltration by integrating the other two principles of CA to no-till farming may minimize the losses of dissolved P in runoff under no-till conditions.

Mechanisms for off-site transport of pesticides are similar to those of nutrients. Strongly soil-bound pesticides, such as glyphosate, the most widely used herbicide in CA systems, would only be a problem if considerable amounts of soil were lost by runoff. Several studies confirm that both the persistence of herbicides in soil and the amounts found in runoff from fields under no-till are reduced (Cuevas et al. 2001; Cox et al. 1999). Basch et al. (1995) attribute the lower persistence of pesticides in the soil under CA to the higher microbiological activity in the surface soil layer and the reduced concentration in the runoff to a stronger adsorption to higher amounts of SOM. With the exception of one first runoff event after application, these researchers found at different sites in southern Portugal that concentrations of atrazine and metolachlor in maize and isoproturon in winter wheat were lower in CA compared to conventional tillage. They also highlighted the importance of avoiding applications just before heavy rains, especially under CA conditions where weeds or crop residues retain considerable parts of the applied herbicide. Borin et al. (1997) confirmed similar results from other experimental sites in Italy and Germany, which also participated in the EU project on 'Effects of tillage systems on herbicide dissipation'.

Although nitrogen compounds may be transported in runoff, the main losses of nitrogen from agricultural fields occur in the form of nitrate leaching. The release of an EU Nitrates Directive and the classification by the EU of areas as 'nitrate vulnerable zones' indicate the severity of this problem in Europe. Farming practices are therefore scrutinized with regard to their impact to nitrate leaching (Hansen et al. 2010). However, as far as the practice of CA is concerned, results from several studies are inconclusive (Hansen et al. 2010; Oorts et al. 2007a). There is general agreement that the absence of tillage in autumn reduces mineralization and thus leaching of nitrate over winter (Hansen et al. 2010; Düring et al. 1998). In addition, Tebrügge (2003) argued that despite a greater percolation of water under no-till, there is no increase in nitrate leaching as most of the downward water movement occurs as bypass flow. He also concluded that the predominant form of nitrogen under no-till is organically bound nitrogen not subjected to vertical displacement as is the case with mineral nitrogen from fertilizer. Crop residues, especially those with higher C/N ratios will further tend to immobilize mineral nitrogen, thus reducing nitrate leaching (Morris et al. 2010).

Over the past 20 years, the analysis of the environmental impact of any economic activity has increasingly included its contribution to greenhouse gas (GHG) emissions. To obtain a full picture on the GHG footprint of any system change introduced, a complete life cycle assessment would be required. In agriculture, and apart from the well-known methane emission sources, which are flooded rice and ruminants, it is all the cultivated land that may contribute to the emission of GHG. According to Eurostat data from 2010 (Fellmann et al. 2012), agriculture in Europe contributed almost 10% to the total EU–27 GHG emissions deriving around one-third from enteric fermentation, one-sixth from manure management, and more than 50% from agricultural soils. Astonishingly, the JRC report (Fellmann et al. 2012) noted that 'emissions (and removals) of carbon dioxide (CO_2) from agricultural soils are not accounted for in the "agriculture" category. Whereas detailed statistics are available for the 27 member states on their agricultural share and evolution of methane and nitrous oxide emissions, no precise data are available on CO_2 emissions from agricultural soils'.

While analyzing the impact of different soil management practices on CO_2 fluxes from agricultural soil, short- and long-term effects must be considered. There is a broad consensus on the strong short-term increase of CO_2 emissions after conventional tillage when compared to CA, but in the longer term, not all researchers have found consistent reductions in CO_2 emissions under CA (Vinten et al. 2002), and under certain conditions some researchers even found higher CO_2 fluxes under no-till (Oorts et al. 2007b). Results from the measurement of CO_2 fluxes at a given moment, even if over a longer period of time, are strongly influenced by total C and N, but also by mineral N, water content, weather conditions and the amount and form of SOM (Regina and Alakukku 2010). Whether there is a long-term negative or positive balance with regard to CO_2 fluxes can be assessed to some extent by the evolution of SOM. Provided organic carbon inputs through biomass residues (above and below ground) are similar, the comparison of the evolution of SOM should provide a clear indication for the performance of different farming practices in terms of their carbon flux balance.

Although not linear over time (Freibauer et al. 2004), carbon sequestration has increased with the adoption of CA, especially under favourable conditions, i.e. under no-till and the retention of crop residues (Corsi et al. 2012; Basch et al. 2012b, 2010; Mazzoncini et al. 2011; Bhogal et al. 2007; Oorts et al. 2007c; Tebrügge 2003). According to the finding that SOM change was negatively correlated with initial SOM content (VandenBygaart et al. 2002), it also appears that the highly SOM-depleted soils in the Mediterranean region respond faster and with higher carbon sequestration rates to carbon-enhancing changes in soil management. However, in order to evaluate the full potential for carbon sequestration through changes in land use and soil management, excluding short-term effects of changes in soil biological processes, time scales of up to 100 years may be necessary under European conditions to reach a new equilibrium (Smith 2004). Several authors have used average carbon sequestration rates to highlight the importance and potential of widespread adoption of CA practices for the mitigation of anthropogenic CO_2 emissions at national and European levels (McConkey et al. 2000; Basch et al. 2002; Tebrügge 2002). Tebrügge (2002) estimated for EU-15, based on the assumption of no-till and conservation tillage adoption on 30 and 40 % of arable land, respectively, that a total emission reduction of CO_2 could be achieved by carbon sequestration in the soil. Together with an additional reduction of 5 $MtCO_2$ $year^{-1}$ through savings in fuel consumption, the total emission reduction could have accounted for around 39 % of the EU-15 commitment in terms of CO_2 emission reduction target within the Kyoto Protocol until 2012. These estimates also show that the mitigation potential of CO_2 emission through fuel savings using CA is far from that of carbon sequestration in the soil.

Concerning other GHGs, especially nitrous oxide, the results obtained for different soil management systems seem to be more controversial. It is well known that soil moisture and compaction, leading to less soil aeration, favour denitrification processes. Reduced aeration due to higher soil moisture under CA, especially on poorly drained soils, are therefore conditions where higher N_2O emissions are reported (Regina and Alakukku 2010; Ball et al. 2008; Oorts et al. 2007b). It seems however that with time, and the build-up of a favourable soil structure and porosity, the conditions under CA become less prone to the release of N_2O when compared to the conventional tillage (Six et al. 2004). Under well-aerated soil conditions similar (Rochette 2008) or even reduced N_2O emissions (Mutegi et al. 2010) were measured

Fig. 15.3 Evidence of increased incidence of above-ground vertebrate species (hares and Little Bustard) under CA. (Fotos: R. Freixial, left; AEAC/SV, right)

under no-till when compared to ploughing, and in the case of incorporation of leguminous crops through tillage, considerably higher N_2O emissions were detected when compared to no-till (Almaraz et al. 2009). The varying results regarding N_2O emissions while comparing soil management systems clearly indicate the need for further and continuous long-term research especially with regard to reduced mineral nitrogen fertilization requirements under improved soil fertility conditions with CA.

Under European conditions, little is known about the impact of soil tillage management on the emission or absorption of methane from soil. Ball et al. (1999) reported some increased methane emission under no-till, yet other authors did not find appreciable levels and differences between soil management systems (Regina and Alakukku 2010).

The decline in biodiversity has been considered by the Soil Thematic Strategy as an important threat to European soils (Van-Camp et al. 2004). Biodiversity as such can be looked at from the functional point of view affecting the productivity of soils but also from an environmental or ecological point of view as it goes much beyond interfering with the natural infrastructure and the soils' functions to provide ecosystem services. Today, it is evident from international scientific studies as well as from observational evidence from farmers' fields and agricultural landscapes that intensive soil tillage adversely affects soil biodiversity and health.

Besides the improvement of functional biodiversity through CA and no-till, already referred to in the section on soil quality, and including microfauna but especially meso- and macrofauna, there are below- and above-ground living vertebrate species such as birds and hares (Fig. 15.3) that benefit from no-till and the shelter that crop residues provide. Holland (2004) provided a comprehensive review on the environmental consequences of the adoption of CA in Europe.

15.4.5 Economic Aspects of CA

Initial uptake of no-tillage in Europe was voluntary and driven by the need to reduce crop establishment costs (Basch et al. 2008). More surprising is the fact that the declining economic viability through continuously increasing costs for inputs in the form of fuel, agrochemicals and labour but also through environmental restrictions did not lead to a breakthrough in terms of widespread adoption of CA systems. Economic returns almost throughout Europe have been highly favourable when applying the CA system. Calculating the profits of several crop rotations since the beginning of different long-term soil management systems at five different sites in Hessian/Germany, Tebrügge and Böhrnsen (1997a) obtained 17.8, 6.9, 15.7, 10.3 and 20.3 % higher profit, respectively, under no-till when compared to conventional ploughing, despite several years of smaller yield benefit at the beginning. Depending on the starting yield level and the market prices for the crops, and considering a 500-ha farm, they calculated 'acceptable' yield reductions (break even with the plough system) for no-till between 12 and 28 %. Under rainfed conditions in southern Portugal and for a 500-ha farm, Marques and Basch (2002) calculated a necessary level of wheat production to obtain a breakeven net margin of 1431 kg ha^{-1} for the plough system, whereas only 1130 kg ha^{-1} for the no-till system. These calculations, however, do not reflect other advantages of the no-till system that might translate into economic benefits, which are more days available for crop establishment and the better trafficability on no-till soil allowing the correct timing for top dressing or herbicide application even in wet winters (Basch et al. 1997), lower wear and tear costs on machinery and equipment as well as environmental and soil health benefits. In Finland, Mikkola et al. (2005) found that yield reductions up to 15 % under no-till were still economically tolerable.

In the final report of the European project on Sustainable Agriculture and Soil Conservation (SoCo 2009), the authors report cost savings with respect to labour in no-till systems of up to 50–75 % and up to 60 % of cost savings with fuel consumption. Although the adoption of CA may require some initial investment in machinery, mainly seeding equipment, the later reduction in overall machinery and respective costs for repair and replacement are significant, especially for larger farms. Freixial and Carvalho (2010) calculated a reduction in variable costs of around 80 % for the maintenance of tractors and seeding or tillage equipment after changing from conventional plough tillage to no-till cereal-based crop rotation on a farm of 350 ha in southern Portugal.

While the adequate timing of the application of agrochemicals may be a source of economic savings, improved soil fertility and better nutrient and water cycling and availability under CA are one of the most important economic benefits of CA. Besides the reduction of phosphorus losses through runoff and erosion (Soane et al. 2012), the possible reduction in mineral nitrogen inputs through higher total nitrogen contents in the SOM content could contribute to an improved nitrogen and water use efficiency and productivity of mineral fertilizer applied. In a nitrogen fertilization response trial, Carvalho et al. (2012) found a significant relationship between SOC content in the top 30 cm of the soil, level of nitrogen applied and wheat yield (Fig. 15.4).

On the same soil but with 2 % SOM content obtained after 11 years of no-till and crop residue retention, instead of 1 % SOM under conventional tillage and straw removal, the wheat crop yielded more with less nitrogen.

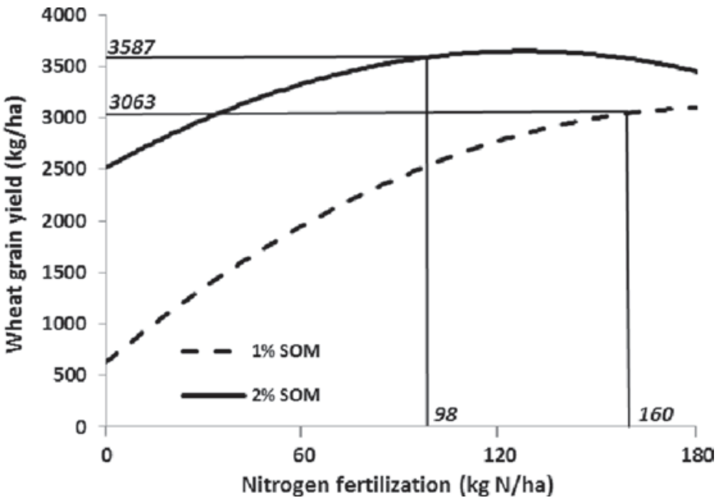


Fig. 15.4 Effect of soil organic carbon (SOC) content (0–30 cm depth) on the wheat response to nitrogen fertilization. The nitrogen level values (160 and 98 in *italic*) are relative to the most economical N level for each SOC value considered. The values for wheat grain yield (3063 and 3587 in *italic*) are relative to the respective predictable yields. (Adapted from Carvalho et al. 2012)

It is evident that the achievable cost savings through the implementation of CA systems far outweigh any potential small yield reductions that may occur in some instances, mainly in the transition phase from conventional tillage system to CA system. Still, the aforementioned examples do not account for the environmental costs or benefits that a change to CA may save or add to the system.

15.5 Challenges for CA in Europe

Bearing in mind the potential benefits that can be delivered through the application of CA as described in the previous sections, it raises the question ‘why is Europe lagging so far behind other regions in the adoption of CA?’ In an inquiry conducted in several European countries among two stakeholder groups, divided into practitioners (farmers) and experts (advisors, researchers, extensionists), Tebrügge and Böhrnsen (1997b) concluded that farmers who were applying CA had a positive attitude with regard to CA, highlighted the economic more than the ecological benefits, and complained about the lack of advice and applied research results. In contrast, experts were more sceptical, stressing the potential yield depressions as the main disadvantage of CA. In a study carried out in 2007 on behalf of the Spanish Ministry for Agriculture, 135 inquiries by Spanish CA farmers were analysed to find out more about the performance of CA practices (Veroz-González et al. 2008). The general conclusion was that despite a change in weed flora, CA does not increase weed control problems and the referred trends did not indicate any more or less problems with pests and diseases with CA. Production levels were reportedly maintained which together with reduced costs contributed to improved competitiveness of farms. The following sections discuss what makes European farmers reluctant to change.

15.5.1 Cultural and Economic Entrenchment of Tillage Agriculture

Even today, European farmers believe that by mechanically tilling and working the soil, they are doing good by burying any growing weeds and weed seeds, mineralizing nutrients, breaking soil compaction, aerating the soil and creating a 'suitably' loose seedbed for sowing a variety of crops. The perfect inversion of the upper soil layer that effectively controlled perennial grass weeds and provided a clean seedbed for sowing made the mouldboard plough the preferred tillage implement and the symbol of modern agriculture. Therefore, it is not surprising to still find ploughing contests all over Europe. Knowing the history of this implement, it is comprehensible why Europeans are the strongest defenders of the plough.

15.5.2 Favourable Natural Conditions and Yield Levels

In many regions of the world, the adoption of CA has been in response to adverse crop growing conditions caused by severe natural constraints, e.g. severe soil erosion, or the need to reduce costs due to high production risks or farming under marginal economic conditions. Despite the occurrence of less favourable conditions, such as low soil fertility (low soil organic matter), dry conditions and/or erratic rainfall distribution and poor soil structure, in some, mostly southern parts of Europe—the most important agricultural regions of Europe with the biggest influence on the definition of agricultural policies and on technological development—natural conditions for crop production and the financial support provided to farmers under the CAP agreement are favourable. Therefore, in most regions in Europe, the perception of the need to change and the drivers to search for better and sustainable solutions is insufficient.

Due to these favourable conditions, yield levels in many intensively cultivated regions in Europe are very high although difficult to sustain (Lin and Huybers 2012; Brisson et al. 2010; Petersen et al. 2010) and there is concern regarding possible yield losses as the result of a system change. In fact, some researchers have reported yield (not necessarily profit) reductions in the first year after CA adoption due to reasons outlined in Sect. 15.4.1. After the transition phase or under optimal conditions, crop yields are similar to or greater than those under conventional tillage right from the start. Still, in many cases, the performance of CA relative to plough tillage is measured on the basis of a crop yield and not on a profit or production cost per unit of grain basis.

15.5.3 Weed, Insect Pest and Disease Challenges

As referred to in Sect. 15.4.3, weeds, insect pests and diseases may pose serious problems to the prescriptive and ready-to-use application of CA principles. Certain weeds, mainly perennials and some grass weed species may become more abundant while overall weed numbers normally decline under CA. Successful weed control in CA means a change in timing of herbicide application and in the type of herbicides used, not necessarily higher amounts of chemicals applied. More persistent herbicides with residual effects are used less as they will not do their job effectively when retained in crop residues. Advanced CA farmers rely more and more on integrated weed control strategies based on the combination of crop rotation, cover crops and residue management. However, the general perception that no-till requires more herbicide applications to control weeds adequately remains one of the greatest obstacles for the acceptance of CA as a sustainable farming system.

With regard to insect pest and diseases, it is mainly slugs (Sect. 15.4.3.) and the increased incidence of head blight disease (*Fusarium* spp.) recorded in wheat that raised arguments against the uptake of CA. Whereas slugs may increasingly be controlled by higher numbers of predating beetles, under wet conditions, they may cause problems locally that need to be monitored carefully. The higher incidence of mycotoxins producing head blight under CA, reported mainly in Germany, France and Switzerland, may be suppressed by not following wheat after maize, and through adequate residue management and the use of resistant wheat varieties (Vogelgsang et al. 2005). In general terms, the inquiry conducted by Tebrügge and Böhrnsen (1997b) among 101 European farmers revealed that between 76 and 80 % of the participating CA farmers did not experience more problems with insect pests and diseases, respectively, after the change from conventional tillage to CA.

15.5.4 Crop Residues and Management

Within Europe, tremendous differences exist in terms of agro-ecological conditions with extremely high productivity levels and high input farming systems in the central and northern regions (and southern when irrigated) and rather extensive, rainfed agricultural systems in the Mediterranean region. The amount of crop residue the planters have to deal with varies from less than 2 Mg ha^{-1} to more than 10 Mg ha^{-1}. In regions with low productivity, crop residues and stubble (mainly cereals) are frequently used as fodder for livestock, whereas in high productivity regions, retention of crop residues in the field is common. Both situations present big challenges for the uptake and spread of CA, as high amounts of residue cause problems for drilling equipment and seed placement under wet conditions but also for warming and drying in spring, whereas low residue levels prevent the rapid improvement of soil conditions and water conservation under CA. Several solutions are used to deal with high residue levels, including improved chopping and distribution equipment on the combine harvester, high stubble cut, improved no-till drilling equipment, and even seeding by broadcasting small seeds like rape before the cereal harvest. Although the importance of crop residue retention for soil improvement and water availability in Mediterranean regions has been demonstrated (Basch et al. 2012b), it remains a challenge to guarantee adequate soil cover, especially under rainfed conditions, unless, as it happens in some countries or regions, payments for agri-environmental measures compensate for any loss of income.

15.5.5 Availability of Suitable Seeding and Planting Equipment and Inputs

One of the biggest challenges for the European farmer to adopt CA is the lack of adequate no-till drilling equipment. Under low residue conditions, most of the imported drilling machines from North and South America work considerably well, while on wet and clayey soils the management of high residue levels pose increased challenges for crop establishment. The low demand for adapted and specific drilling equipment did not encourage European manufacturers to develop machinery in this specific area compared to other regions where many solutions and options are available to cope with specific local conditions. It is not by chance that Finland has the highest percentage of arable land under CA. Despite about ten different brands of no-till seeders on the market, one Finnish manufacturer has more than a 50 % share of no-till drills sold in Finland. Some improvements have been noticed in the availability of chopping and distribution devices of harvest equipment.

Besides equipment, the availability or even the identification of crop varieties that respond to specific constraints when sown under CA conditions is still a challenge for breeders and seed companies in Europe. Varieties with improved germination under lower soil temperatures, more vigorous initial root development or a better response to different nutrient and water dynamics could make the difference for the success of CA, as well as specific, locally adapted mixtures of cover crops.

15.5.6 Problem-Oriented Research and Training in CA

Despite some intensive and long-term research carried out in several European countries in the field of CA, there seems to be no notable link between research and adoption by farmers. It also appears that the research was mainly driven by academic interest with little focus on practical and solution-oriented research. Only in regions where CA farmers organize farmers' groups, as it happened decades ago in South America, some bottom-up approach occurs, and researchers and extension workers whether public or private are called to provide solutions to further improve CA. In some countries or regions, such as Spain, the role of the national CA association has been decisive for a wider uptake of CA, mainly through training and technology transfer actions, organization of field days and exchange with experts, as well as through their efforts to guarantee support from the private sector and public institutions.

15.5.7 Common Agricultural Policy (CAP) and Economic Pressure

For almost 50 years, farming in Europe has been subjected to the strong influence of the CAP framework. The objectives of these policies changed substantially over this period; nonetheless, there was always and continues to exist strong financial support for the farming sector. Until more or less 10 years ago, subsidies were mostly production oriented favouring high productivity levels, obtained with massive external inputs, instead of promoting competitiveness and sustainability. The constant transfer of welfare from the consumer and taxpayer to the producer in the form of subsidies (named compensatory payments) prevented the necessary adaptation of European agriculture to the changes and new realities of a global agricultural market. Even with the tremendous fluctuations of commodity prices, European farmers do not yet fully perceive the need to lower productions costs and become economically sustainable, as much of the risk in farming is still covered by CAP subsidies. This dependence on subsidies has made most European farmers focus their activities towards maximization of subsidies rather than think and act in the long term and invest in soil fertility and health. It therefore seems that without financial incentives, new production methods will not be widely accepted, especially those referred to as being ‘knowledge and management intensive’ such as CA. Unless there is a clear change in the support policy for the agricultural sector, i.e. shifting away from unspecific, non-restrictive direct payments (1st Pillar of CAP) towards stronger support of overall sustainable productions systems through either conditioning 1st Pillar payments or agri-environmental measures supported through Rural Development Policy (2nd Pillar), little will change in the attitude of European farmers and EC policy makers regarding the mainstreaming of CA as a basis for sustainable production intensification. Although the new policy instrument of the 1st Pillar, the so-called Greening, is directed to the provision of environmental public goods, the measures proposed (maintenance of permanent grassland, ecological focus areas and crop diversification) are clearly insufficient to achieve the objectives explained in the CAP 2014–2020 reform proposal (Basch et al. 2012c).

15.6 Common and National Policies Affecting CA

In Europe as a whole, CA has received relatively little public support compared to other production methods. This support varies strongly from country to country and even between regions within Europe. In general, it is provided either through incentive for farmers to adopt certain management practices or, to a much smaller extent, through the promotion of mostly fundamental research with some relevance for CA.

15.6.1 Research Support

As mentioned in Sect. 15.2, even with some relevant research into the consequences of change in soil management practices, most research was focussed on conservation tillage and the comparison of the performance of different tillage systems, rather than on enhancing CA or other soil-improving management systems. From the scientific literature, there has been some research support at a national level in response to the increasing awareness of the seriousness of some of the later identified 'threats to European soils'. On a European level, an increasing concern with soil-related issues is noted with the start of the Fifth Framework for Research and Technological Development of the EU in 1998. Several research, technology transfer and knowledge dissemination projects have been put in place since then to close knowledge gaps and to create awareness of the need for soil conservation. In more recent years, several European transnational research projects such as 'Smartsoil', 'Ramsoil' and 'SoCo' have been funded to study ways to mitigate soil threats and to identify best management practices to achieve this mitigation. Similarly, in the next framework named Horizon 2020, calls are open to improve the insight into 'soil quality and functions' and 'sustainable crop production' and the 'assessment of soil-improving cropping systems', initially named 'assessment of CA systems'.

15.6.2 Soil Thematic Strategy Initiative and Rural Development Measures

The increasing awareness that sustainability of agricultural production can only be guaranteed if its most important resources are maintained or improved, gave rise to policy-driven initiatives towards soil protection both nationally and Europe-wide, with the Soil Thematic Strategy Initiative being the most visible attempt. Although the working groups established within this initiative clearly identified the major threats to European soils and proposed action that lead to the proposal of a European Soil Framework Directive, the ratification of this Directive was blocked by five-member states. Despite or most likely as a result of the failure of a European initiative, soil conservation became more and more an issue at national level and was encouraged by the possibility to support soil-protecting farming practices through so-called agri-environmental measures co-financed between the EU and member states through the Rural Development Program Funds (2nd Pillar of CAP). In some member states, this lead to the launch of support schemes for the uptake of CA either nationwide (Portugal) or limited to some regions (Spain, Germany, Italy). In Switzerland, it is in the Canton of Berne where a highly sophisticated support scheme to fight soil erosion started in 1993 (Schwarz et al. 2007). It is in this and three other cantons with similar support schemes where CA was practiced on around 5 % of arable land in 2006 (Ledermann and Schneider 2008).

The support schemes introduced and the respective levels of 'compensation' vary from country to country and even between regions. They can range from non-inversion conservation or mulch tillage (Saxony/Germany) to strip tillage on wide-row crops to pure no-till. Additional measures, such as those in place in Portugal during the past few years, should compensate the farmer in case he left high stubble or the entire straw on the field. In Spain, additional subsidies of up to 40 % of the costs of new no-till seeders were granted by several regional governments and governmental institutions. However, due to the economic crisis and the obligatory co-financing of the Rural Development measures through the member states or regional authorities, support and further uptake of CA measures have been seriously compromised.

15.7 Prospects for Up-Scaling CA in Europe

15.7.1 Effects of Climate Change

In Europe, climate change is a real concern for society and of major importance to farmers. Whether in Northern regions where winters are supposed to become milder and autumns and springs wetter, or in southern, central or eastern countries with expected increases in drought incidence in spring and summer, climate change will affect agriculture both in regard to adaptation strategies to be adopted and through its potential for mitigation. If winter climate conditions in northern Europe become wetter, possibly with more intense rainfall, widespread application of CA could limit the higher risk of water erosion and associated problems through off-site transport of sediments and agrochemicals. In regions where rainfall becomes less and more erratic, with longer summer droughts, no-till in combination with residue cover would improve soil water use efficiency to maintain or even improve yield levels (Basch et al. 2012b).

As referred to in Sect. 15.3.4, carbon sequestration in agricultural soils could contribute significantly to the mitigation of anthropogenic CO_2 emissions. The reversibility of this process if soils were submitted again to intensive soil tillage after years of SOM accumulation through CA makes very few decision makers believe in the long-term CO_2 emission mitigation potential of CA.

15.7.2 Soil and Crop Management-Related Policies

Probably more than elsewhere, soil and crop management practices in Europe are extremely scrutinized and regulated by the respective authorities with regard to their environmental performance, both at national and European level. Today, CA is recognized as a farming practice which can effectively reduce runoff and erosion, and even enhance SOM content. This is clearly demonstrated through the CA-promoting agri-environmental measures already in place in several European countries. The general acceptance of the conclusions of the Soil Thematic Strategy as a European Soil Framework Directive could have further positive impact on the adoption of CA, as it clearly addresses several of the identified soil threats.

On the other hand, more restrictive regulations for the use of herbicides as well as surface applied but not immediately incorporated slurry may pose increasing challenges to the use of CA systems based on no-till. Although the use of herbicides is not necessarily higher under CA when compared to conventional tillage, the perceived risk of not having the means to eventually handle weed problems may make farmers hesitate to adopt CA.

15.7.3 Evolution of Production Costs and Commodity Prices

At present, a considerable percentage of European farms are economically viable only due to the subsidies received in the form of the so-called Single Farm Payment. There is enormous pressure both from outside and inside the EU to reduce the direct payments and make support to farmers dependent on the verifiable delivery of public goods. More than in the past, the current CAP reform stresses the need for more competitiveness of European agriculture, as CAP expenditure within the EU budget has been maintained over the last 18 years despite the increase from 15 to 28 member states. The prospect of decreasing direct payments and the simultaneous increase of production costs, together with stagnating and extremely volatile agricultural commodity prices, will force farmers, also in Europe, to adopt farming methods that reduce overall production costs while maintaining productivity levels. As demonstrated in Sect. 15.4, CA will immediately reduce fuel costs and working time per unit area, reduce investment in machinery and maintenance costs, and, in the case of irrigation, result in less water and energy consumption. In the medium and long term, benefits from improved soil fertility are expected through lower levels of mineral fertilizer inputs. The concomitant improvement in the environmental and economic performance of farming through the application of ‘good’ CA has often been described as a win–win situation. The upward evolution of production costs and commodity prices, together with the reduction in subsidies will most probably be the fastest driver to have CA adopted on a much larger area, also in Europe.

15.8 Conclusions

In a few regions of Europe, CA has been well adopted while in others, this farming practice is almost unknown or regarded as exotic. The fact that CA is successfully applied under the most diverse pedo-climatic conditions (from the most southern regions in Spain up to Scandinavia) means that the reasons Europe lag far behind other regions in the world in the uptake of CA cannot be explained by less favourable soil or climate conditions or differences in cropping systems. There are two fundamental conditions that appear to make the difference when comparing with other regions of the world.

The use of agrochemicals in agriculture for weed and pest management in agriculture is a central issue both with regard to food safety and environmental impact. Consumers and society as a whole are receptive to arguments that justify the restriction of pesticides. Europe has probably one of the strongest regulations that control the release of plant protection products on the market (Regulation (EC) No 1107/2009) and the homologation of products must be obtained for each country. It therefore does not seem surprising that the alleged increased input of herbicides and other chemicals for disease and pest control is the main barrier to the full acceptance of CA as a sustainable crop production concept.

Less than a constraint, but more a missing driver for the adoption of CA, is the level of support European farmers still receive. Although subject to today's world market prices of commodities, the enormous transfer of welfare from consumers and taxpayers to the agricultural sector allows farmers to maintain less efficient and thus less competitive production systems.

There is no doubt that the change from conventional to conservation agriculture requires the acquisition of new knowledge, skills and a great deal of observation and learning capacity. However, farmers who wish to change do not find the necessary practical knowledge among extension workers and advisors, whether public or commercial. Despite some already existing farmer-to-farmer exchange, only the institutional promotion of education, capacity development and extension in CA-based sustainable soil management would help bridge the gap between the objectives of sustainable resource management recurrently proclaimed in the CAP and the implementation of real sustainable soil management. Lessons learned from other regions in the world, such as in Canada or Brazil, where the carbon offset potential of CA or its capacity to 'cultivate good water' (*Cultivando Água Boa*) are officially recognized and paid for as ecosystem services (Kassam et al. 2013), may teach European stakeholders and decision makers that the inclusion of the principles of CA in the CAP 'greening' measures of the 1st Pillar direct payments could reach a much larger area under sustainable management.

Regionally, there are other bottlenecks that may act as a deterrent to the wider uptake of CA, such as high crop residue amounts, specific weed problems, soil compaction or lack of adequate machinery. Persistent pioneer farmers, more than results from research, have demonstrated that CA does work in Europe, once it has adapted to the existing conditions. Research can help improve knowledge gaps and available technology, and obtain scientific evidence for the many benefits of CA in order for it to gain acceptance by the public. However, even if farmers were convinced and researchers were willing to help, in a Europe with agriculture driven by CAP and the respective authorities, it appears that it is up to the political decision makers and administrative stakeholders to set or change the course towards the right direction, bearing in mind the words of the former US President Roosevelt: 'A nation that destroys its soils, destroys itself'.

References

Alakukku L, Ristolainen A, Salo T (2009) Grain yield and nutrient balance of spring cereals in different tillage systems. Proceedings of the 18th ISTRO Conference, Paper T6-005, ISTRO, Izmir, 15–19 Jun 2009

Almaraz JJ, Zhou XM, Mabood F, Madramootoo C, Rochette P, Ma B-L, Smith DL (2009) Greenhouse gas fluxes associated with soybean production under two tillage systems in southwestern Quebec. Soil Tillage Res 104(1):134–139

Anken T, Weisskopf P, Zihlmann U, Forrer H, Jansa J, Perhacova K (2004) Long-term tillage system effects under moist cool conditions in Switzerland. Soil Tillage Res 78(2):171–183

Arvidsson J (2010) Direct drilling possible with a good preceding crop. Arvensis J Swedish Rural Econ Agric Soc 4:9–10 (Swedish)

Ball BC, Tebrügge F, Sartori L, Giráldez JV, González P (1998) Influence of no-tillage on physical, chemical and biological soil properties. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries, Final Report. Fachverlag Köhler, Giessen, pp 7–27

Ball BC, Scott A, Parker JP (1999) Field N(2)O, CO(2) and CH(4) fluxes in relation to tillage, compaction and soil quality in Scotland. Soil Tillage Res 53(1):29–39

Ball BC, Crichton I, Horgan GW (2008) Dynamics of upward and downward N2O and CO2 fluxes in ploughed or no-tilled soils in relation to water-filled pore space, compaction and crop presence. Soil Tillage Res 101(1–2):20–30

Barros JFC, Basch G, de Carvalho M (2008) Effect of reduced doses of a post-emergence graminicide to control Avena sterilis L. and Lolium rigidum G. in no-till wheat under Mediterranean environment. Crop Prot 27(6):1031–1037

Basch G (2002) Mobilização do solo e ambiente. In: Basch G, Teixeira F (eds) Mobilização de conservação do solo. Proceedings "1º Congresso Nacional de Mobilização de Conservação do Solo". APOSOLO, Évora, pp 51–61 (Portuguese)

Basch G, Carvalho M (1994) Conditions and feasibility of no-tillage in Portugal. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries. Proceedings EC-Workshop I. Wissenschaftlicher Fachverlag, Giessen, pp 93–104

Basch G, Carvalho M (1998) Effect of soil tillage on runoff and erosion under dryland and irrigated conditions on Mediterranean soils. Geoökodynamik XIX(3–4): 257–258

Basch G, Carvalho M, Düring R-A, Martins R (1995) Displacement of herbicides under different tillage systems. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries. Proceedings EC-Workshop II. Wissenschaftlicher Fachverlag, Giessen, pp 25–38

Basch G, Carvalho M, Marques F (1997) Economical considerations on no-tillage crop production in Portugal. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries. Proceedings EC-Workshop IV. Wissenschaftlicher Fachverlag, Giessen, pp 17–24

Basch G, Mendes JP, Carvalho M, Marques F, Santos MJ (1998) Influence of tillage system on water regime in irrigated and rainfed sunflower production. In: Pereira LS, Gowing JW (eds) Water and the environment-innovation issues in irrigation and drainage. E & FN Spon, London, pp 381–389

Basch G, Geraghty J, Streit B, Sturny WG (2008) No-tillage in Europe-state of the art: constraints and perspectives. In: Goddard T, Zoebisch M, Gan Y, Ellis W, Watson A, Sombatpanit S (eds) No-till farming systems, special publication No. 3. World Association of Soil and Water Conservation, Bangkok, pp 159–168

Basch G, Carvalho M, Barros JFC, Calado JMG (2010) The importance of crop residue management for carbon sequestration under no-till. In: ECAF (eds) Towards agro-environmental climate and energetic sustainability. Proceedings of the eur. congress on conservation agriculture. Ministerio de Medio Ambiente y Medio Rural y Marino, Madrid, pp 241–248

Basch G, Kassam A, Friedrich T, Santos FL, Gubiani PI, Calegari A, Reichert JM, Dos Santos DR (2012a) Sustainable soil water management systems. In: Lal R, Stewart BA (eds) Soil water and agronomic productivity, advances in soil science. CRC, Boca Raton, pp 229–289

Basch G, Calado JMG, Barros JFC, Carvalho M (2012b) Impact of soil tillage and land use on soil organic carbon decline under Mediterranean conditions. Agrociencia 16(3):175–182

Basch G, Kassam A, González-Sánchez EJ, Streit B (2012c) Making sustainable agriculture real in CAP 2020: the role of conservation agriculture. ECAF, Brussels, p 43. http://www.ecaf.org/docs/ecaf/ca%20and%20cap%202020.pdf

Bäumer K (1970) First experiences with direct drilling in Germany. Neth J Agric Sci-Papers on zero-tillage 18(4):283–292

Bhogal A, Chambers BJ, Whitmore AP, Powlson DS (2007) The effect of reduced tillage practices and organic matter additions on the carbon content of Arable soils. Scientific Report SP0561, Department of environment, food and rural affairs, London, p 47

Boguzas V, Kairyte D, Jodaugiene D, Lukosiunas K (2006) Effect of reduced and no-tillage, straw and green manure management on soil physical properties and earthworms. Proceedings of the 17th ISTRO Conference, ISTRO, Kiel, pp. 1566–1577

Boisgontier D, Bartholomy P, Lescar L (1994) Feasibility of minimum tillage practices in France. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries. Proceedings EC-Workshop IV. Wissenschaftlicher Fachverlag, Giessen, pp 81–91

Borin M, Sartori L, Guipponi C, Mazzoncini M, Düring R-A, Basch G (eds) (1997) Effects of tillage systems on herbicide dissipation—an experimental approach at field scale. Unipress, Padova

Bräutigam V, Tebrügge F (1997) Influence of long-termed no-tillage on soil borne plant pathogens and on weeds. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries. Proceedings EC-Workshop III. Wissenschaftlicher Fachverlag, Giessen, pp 17–29

Brisson N, Gate P, Gouache D, Charmet G, Oury F-X, Huard F (2010) Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. Field Crops Res 119(1):201–212

Brito I, Carvalho M, van Tuinen D, Goss M (2006) Effects of soil management on the arbuscular mycorrhizal fungi in fall-sown crops in Mediterranean climates. Proceedings of the 17th ISTRO Conference, ISTRO, Kiel, Aug 28–Sep 2 2006, pp 622–628

Calado JMG, Basch G, de Carvalho M (2010) Weed management in no-till winter wheat (*Triticum aestivum L.*). Crop Prot 29(1):1–6

Cannell RQ, Hawes JD (1994) Trends in tillage practices in relation to sustainable crop production with special reference to temperate climates. Soil Tillage Res 30(2–4):245–282

Cannell RQ, Christian DG, Henderson FKG (1986) A study of mole drainage with simplified cultivation for autumn-sown crops on a clay soil 4. A comparison of direct drilling and moldboard plowing on drained and undrained land on root and shoot growth, nutrient-uptake and yield. Soil Tillage Res 7(3):251–272

Cantero-Martínez C, Lampurlanés J, Vilardosa JM (1994) Effect of three different tillage systems on water use and root development of barley in a semiarid environment. Proceedings of the 3rd European society for agronomy congress, Abano, 18–22 Sept 1994, pp 660–661

Carvalho M, Basch G (1994) Experiences with direct drilling in Portugal. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries. Proceedings EC-Workshop I. Wissenschaftlicher Fachverlag, Giessen, pp. 105–110

Carvalho M, Basch G (1995) Effects of traditional and no-tillage on physical and chemical properties of a Vertisol. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries, Proceedings EC-Workshop II. Wissenschaftlicher Fachverlag, Giessen, pp 17–23

Carvalho M, Basch G, Barros J, Calado J, Freixial R, Santos F, Brandão M (2010) Strategies to improve soil organic matter under Mediterranean conditions and its consequences on the wheat response to nitrogen fertilization. In: ECAF (eds) Towards agro-environmental climate and energetic sustainability. Proceedings of the Eur. congress on conservation agriculture. Ministerio de Medio Ambiente y Medio Rural y Marino, Madrid, pp 303–308

Carvalho M, Basch G, Calado JMG, Barros JFC (2012) Long term effect of tillage system and crop residue management on soil carbon content of a Luvisol under rainfed Mediterranean conditions. Agrociencia 16(3):183–187

Christian DG (1994) Experience with direct drilling cereals and reduced cultivation in England. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries. Proceedings EC-Workshop I. Wissenschaftlicher Fachverlag, Giessen, pp 25–31

Christian DG, Ball BC (1994) Reduced cultivations and direct drilling for cereals in Great Britain. In: Carter MR (ed) Conservation tillage in temperate agroecosystems. Lewis, Boca Raton, pp 117–40

Corsi S, Friedrich T, Kassam A, Pisante M, Sá JCM (2012) Soil organic carbon accumulation and carbon budget in conservation agriculture: a review of evidence vol 16. FAO Integrated Crop Management, Rome

Cox L, Calderon MJ, Hermosin MC, Cornejo J (1999) Leaching of clopyralid and metamitron under conventional and reduced tillage systems. J Environ Qual 28(2):605–610

Cuevas MV, Calderón MJ, Fernández JE, Hermosín MC, Moreno F, Cornejo J (2001) Assessing herbicide leaching from field measurements and laboratory experiments. Acta Agrophys 57:15–25

Davies DB, Finney JB (2002) Reduced cultivations for cereals: research, development and advisory needs under changing economic circumstances. Home Grown Cereals Authority Research Review 48, London, p 57

Düring R-A, Basch G, Hummel HE (1998) Environmental aspects of no-tillage application-erosion and leaching of agrochemicals. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries, Final Report. Fachverlag Köhler, Giessen, pp 45–61

Ehlers W, Claupein W (1994) Approaches toward conservation tillage in Germany. In: Carter MR (eds) Conservation tillage in temperate agroecosystems. Lewis, Boca Raton, pp 141–165

Ekeberg E, Riley HCF (1997) Tillage intensity effects on soil properties and crop yields in a long-term trial on morainic loam soil in southeast Norway. Soil Tillage Res 42(4):277–293

FAO (2013a) What is CA? Conservation Agriculture Website of FAO. www.fao.org/ag/ca/1a.html. Accessed Dec 2013

FAO (2013b) CA Adoption Worldwide, FAO AQUASTAT database. www.fao.org/ag/ca/6c.html. Accessed Dec 2013

Fellmann T, Dominguez IP, Witzke HP, Jansson T, Oudendag D, Gocht A, Verhoog D (2012) Agricultural GHG emissions in the EU: an exploratory economic assessment of mitigation policy options. Institute for prospective and technological studies, Joint Research Centre. JRC-IPTS Working Papers JRC69817

Fernández-Quintanilla C (1997) Historia y evolución de los sistemas de laboreo. El laboreo de conservación. In: García-Torres L, González Fernández P, (eds) Agricultura de Conservación. Fundamentos Agronómicos, Medioambientales y Económicos (Spanish). Asociación Española de Laboreo de Conservación, Córdoba, pp 1–12

Fernández-Ugalde O, Virto I, Imaz MJ, Enrique A, Bescansa P (2009) Soil water retention characteristics and the effect on barley production under no-tillage in semi-arid conditions of the Ebro Valley (Spain). Proceedings of the 18th ISTRO Conference; Paper T1-008. 2009, ISTRO, Izmir, Turkey, June 15–19

Fortune T, Kennedy T, Mitchell B, Dunne B (2003, 29 Jan) Reduced cultivations-agronomic and environmental aspects. In: Teagasc (eds) Proceedings of the national tillage conference, Teagasc, Carlow, pp 70–82

Freibauer A, Rounsevell MDA, Smith P, Verhagen J (2004) Carbon sequestration in the agricultural soils of Europe. Geoderma 122(1):1–23

Freixial R, Carvalho M (2010) Aspectos prácticos fundamentales en la implantación de la Agricultura de Conservacion/Siembra Directa en el sur de Portugal. In: ECAF (eds) Towards agro-environmental climate and energetic sustainability. Proceedings of the Eur. congress on conservation agriculture. Ministerio de Medio Ambiente y Medio Rural y Marino, Madrid, pp 361-369 (Spanish)

Friedrich T, Kassam A, Corsi S (2014) Conservation agriculture in Europe. In: Jat RA, Sahrawat KL, Kassam A (eds) Conservation agriculture: global prospects and challenges. CABI, Wallingford, pp 127–179

García-Ruiz JM (2010) The effects of land uses on soil erosion in Spain: a review. Catena 81(1):1–11

Glen DM, Milsom NF, Wiltshire CW (1990) Effect of seed depth on slug damage to winter-wheat. Ann Appl Biol 117(3):693–701

Gomez JA, Sobrinho TA, Giraldez JV, Fereres E (2009) Soil management effects on runoff, erosion and soil properties in an olive grove of Southern Spain. Soil Tillage Res 102(1):5–13

González P, Giráldez JV, Ordóñez R, Laguna A, de Haro JM (1997) No tillage crop production in Spain. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries. Proceedings EC-Workshop IV. Wissenschaftlicher Fachverlag, Giessen, pp 155–165

Hammond RB, Beck T, Smith JA, Amos R, Barker J, Moore R et al (1999) Slugs in conservation tillage corn and soybeans in the eastern corn belt. J Entomol Sci 34(4):467–478

Hansen EM, Munkholm LJ, Melander B, Olesen JE (2010) Can non-inversion tillage and straw retainment reduce N leaching in cereal-based crop rotations? Soil Tillage Res 109(1):1–8

Hernánz JL, Sánchez-Girón V (1994) 13 años de ensayos en “El Encín”: Resultados a largo plazo. Conservar el Suelo. Monsanto España SA, Madrid, pp 16-17 (Spanish)

Holland JM (2004) The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric Ecosyst Environ 103(1):1–25

IAPAR (1981) Plantio direto no estado do Paraná. Fundação Instituto Agronómico do Paraná, Circular N° 23, Brasil, p 244

Imaz MJ, Virto I, Bescansa P, Enrique A, Fernandez-Ugalde O, Karlen DL (2010) Soil quality indicator response to tillage and residue management on semi-arid Mediterranean cropland. Soil Tillage Res 107(1):17–25

IRENA (2005) Indicator Fact Sheet. 14.2 Tillage systems. http://epp.eurostat.ec.europa.eu/portal/page/portal/agri_environmental_indicators/documents/IRENA%20IFS%2014%20%20Farm%20management%20practices_FINAL.pdf. p. 14

Jones CA, Basch G, Baylis AD, Bazzoni D, Biggs J, Bradbury RB, Chaney K, Deeks LK, Field R, Gomez JA, Jones RJA, Jordan VWL, Lane MCG, Leake A, Livermore M, Owens PN, Ritz K, Sturny W, Thomas F (2006) Conservation agriculture in Europe: an approach to sustainable crop production by protecting soil and water? SOWAP, Bracknell, p 109

Jordan VWL, Hutcheon JA, Donaldson GV, Farmer DP (1997) Research into and development of integrated farming systems for less-intensive arable crop production: experimental progress (1989–1994) and commercial implementation. Agric Ecosyst Environ 64(2):141–148

Känkänen H, Alakukku L, Salo Y, Pitkanen T (2011) Growth and yield of spring cereals during transition to zero tillage on clay soils. Eur J Agron 34(1):35–45

Kassam A, Basch G, Friedrich T, Shaxson F, Goddard T, Amado JCT, Crabtree B, Hongwen L, Mello I, Pisante M, Mkomwa S (2013) Sustainable soil management is more than what and how crops are grown. In: Lal R, Stewart BA (eds) Principles of sustainable soil management in agroecosystems, advances in soil science. CRC, Boca Raton, pp 337–399

Kendall DA, Chinn NE, Smith BD, Tidboald C, Winstone L, Western NM (1991) Effects of straw disposal and tillage on spread of barley yellow dwarf virus in winter barley. Ann Appl Biol 119(2):359–364

Kladivko EJ (2001) Tillage systems and soil ecology. Soil Tillage Res 61(1–2):61–76

Lacasta Dutoit C, Meco Murillo R, Maire N (2005, 9–11 Nov) Evolución de las producciones y de los parâmetros químicos y bioquímicos del suelo, en un agrosistema de cereales, sometidos a diferentes manejos de suelo durante 21 años. Proceedings Congreso Internacional sobre Agricultura de Conservación-El Reto de la Agricultura. el Medio Ambiente, la Energia y la Nueva Politica Agraria Común, Córdoba, pp 429–436 (Spanish)

Lampurlanes J, Cantero-Martinez C (2006) Hydraulic conductivity, residue cover and soil surface roughness under different tillage systems in semiarid conditions. Soil Tillage Res 85(1–2):13–26

Ledermann T, Schneider F (2008) Verbreitung der Direktsaat in der Schweiz. Agrarforschung 15(8):408–413 (German)

Lin M, Huybers P (2012) Reckoning wheat yield trends. Environ Res Lett 7(2):024016

Lopez MV, Arrue JL (2005) Soil tillage and wind erosion in fallow lands of Central Aragon, Spain: an overview. Sustain Use Manag Soils-Arid Semiarid Reg 36:93–102

Marques F, Basch G (2002) Comparação da viabilidade económica de quatro sistemas de mobilização do solo. In: Basch G, Teixeira F (eds) Mobilização de conservação do solo. Proceedings 1º Congresso Nacional de Mobilização de Conservação do Solo. APOSOLO, Évora, pp 283-298 (Portuguese)

Márquez F, Giráldez JV, Repullo M, Ordóñez R, Espejo AJ, Rodríguez A (2008) Eficiencia de las cubiertas vegetales como método de conservación de suelo y agua en olivar. In: Instituto Geológico y Minero de España (ed). Simposio del Agua en Andalucía. IGME, Madrid, pp 631-641 (Spanish)

Matusinsky P, Mikolasova R, Klem K, Spitzer T (2009) Eyespot infection risks on wheat with respect to climatic conditions and soil management. J Plant Pathol 91(1):93–101

Mazzoncini M, Sapkota TB, Barberi P, Antichi D, Risaliti R (2011) Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. Soil Tillage Res 114(2):165–174

McConkey B, Chang Liang B, Padbury G, Lindwall W (2000) Carbon sequestration and direct seeding. In: Saskatchewan soil conservation association (ed) Proceedings of direct seeding "Sustainable Farming in the new Millennium" 12th annual meeting of the Saskatchewan soil conservation association, SSCA, Saskatoon, 9–10 Feb 2000

Melander B (1998) A review of the major experiences with weeds in non-inversion tillage systems within the European Community (EEC). In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries, Final report. Fachverlag Köhler, Giessen, pp 63–68

Mikkola HJ, Alakukku L, Känkänen H, Jalli H, Lindroos M, Huusela-Veistola E, Nuutinen V, Lätti M, Puustinen M, Turtola E, Myllys M, Regina K (2005) Direct drilling in Finland, a review. Proceedings of the 4th international scientific and practical conference, ecology and agricultural machinery, vol 2. St Petersburg, 25–26 May 2005, pp 141–151

Montanarella L (2006) European soil protection strategies. Proceedings of the 17th ISTRO conference, ISTRO, Kiel, Aug 28–Sept 2 2006, pp 1586–1597

Morris NL, Miller PCH, Orson JH, Froud-Williams RJ (2010) The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment: a review. Soil Tillage Res 108(1–2):1–15

Mota MM, Carvalho M, Basch G, Mcgawley EC, Murcho DF (1997) Soil tillage and plant effects on nematode communities in Southern Portugal. J Nematol 29(4):595

Mutegi JK, Munkholm LJ, Petersen BM, Hansen EM, Petersen SO (2010) Nitrous oxide emissions and controls as influenced by tillage and crop residue management strategy. Soil Biol Biochem 42(10):1701–1711

Muukkonen P, Hartikainen H, Alakukku L (2009) Effect of soil structure disturbance on erosion and phosphorus losses from Finnish clay soil. Soil Tillage Res 103(1):84–91

Oorts K, Bossuyt H, Labreuche J, Merckx R, Nicolardot B (2007a) Carbon and nitrogen stocks in relation to organic matter fractions, aggregation and pore size distribution in no-tillage and conventional tillage in northern France. Eur J Soil Sci 58(1):248–259

Oorts K, Merckx R, Grehan E, Labreuche J, Nicolardot B (2007b) Determinants of annual fluxes of CO2 and N2O in long-term no-tillage and conventional tillage systems in northern France. Soil Tillage Res 95:133–148

Oorts K, Laurent F, Mary B, Thiebeau P, Labreuche J, Nicolardot B (2007c) Experimental and simulated soil mineral N dynamics for long-term tillage systems in northern France. Soil Tillage Res 94(2):441–456

Ordóñez R, González P, Perea F, Llanos I, Giráldez JV (2001) The protective role of stubble cover in dry-farming conservation-agriculture in Southwestern Spain. In: Garcia-Torres L, Benites J, Martinez-Vilela A (eds) Proceedings of the I World congress on conservation agriculture, vol II. Córdoba, 1–5 Oct 2001, pp 435–439

Peigné J, Ball BC, Roger-Estrade J, David C (2007) Is conservation tillage suitable for organic farming? A review. Soil Use Manag 23(2):129–144

Peigné J, Cannavaciuolo M, Gautronneau Y, Aveline A, Giteau JL, Cluzeau D (2009) Earthworm populations under different tillage systems in organic farming. Soil Tillage Res 104(2):207–214

Pelosi C, Bertrand M, Roger-Estrade J (2009) Earthworm community in conventional, organic and direct seeding with living mulch cropping systems. Agron Sustain Dev 29(2):287–295

Petersen J, Haastrup M, Knudsen L, Olesen JE (2010) Causes of yield stagnation in winter wheat in Denmark. DJF report plant science No. 147, Tjele, Nov 2010 (Dept. of Agroecology and Environment, Faculty of Agricultural Sciences, Aarhus University

Phillips ER, Phillips SH (eds) (1984) No-tillage agriculture, principles and practices. Van Nostrand Reinhold Co, New York, p 306

Piovanelli C, Gamba C, Brandi G, Simoncini S, Batistoni E (2006) Tillage choices affect biochemical properties in the soil profile. Soil Tillage Res 90(1–2):84–92

Ploey J, Imeson A, Oldeman LR (1991) Soil erosion, soil degradation and climatic change. Land use changes in Europe. The Geo Journal Library, vol 18. Springer, Netherlands, pp 275–292

Puustinen M, Koskiaho J, Peltonen K (2005) Influence of cultivation methods on suspended solids and phosphorus concentrations in surface runoff on clayey sloped fields in boreal climate. Agric Ecosyst Environ 105(4):565–579

Rasmussen KJ (1994) Experiments with no-inversion tillage systems in Scandinavia-impacts on crop yields, soil structure and fertilization. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries. Proceedings EC-workshop I. Wissenschaftlicher Fachverlag, Giessen, pp 39–48

Regina K, Alakukku L (2010) Greenhouse gas fluxes in varying soils types under conventional and no-tillage practices. Soil Tillage Res 109(2):144–152

Riley H, Børrensen T, Ekeberg E, Rydberg T (1994) Trends in reduced tillage research and practice in Scandinavia. In: Carter MR (ed) Conservation tillage in temperate agroecosystems. Lewis, Boca Raton, pp 23–45

Rochette P (2008) No-till only increases N2O emissions in poorly-aerated soils. Soil Tillage Res 101(1–2):97–100

Rochette P, Angers DA, Chantigny MH, MacDonald JD, Bissonnette N, Bertrand N (2009) Ammonia volatilization following surface application of urea to tilled and no-till soils: a laboratory comparison. Soil Tillage Res 103(2):310–315

Sartori L, Peruzzi P (1994) The evolution of no-tillage in Italy: a review of the scientific literature. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries. Proceedings EC-Workshop I. Wissenschaftlicher Fachverlag, Giessen, pp 119–129

Schjønning P, Høy JJ, Munkholm LJ (2010) Soil tillage effects on the development of winter wheat yields in Denmark. In: Petersen J, Haarstrup M, Knudsen L, Olesen JE (eds) Causes of yield stagnation in winter wheat in Denmark. DJF Report Plant Science No. 147. Aarhus University, Denmark, pp 105–119

Schutte BJ, Tomasek BJ, Davis AS, Andersson L, Benoit DL, Cirujeda A et al (2014) An investigation to enhance understanding of the stimulation of weed seedling emergence by soil disturbance. Weed Res 54(1):1–12

Schwarz R, Chervet A, Hofer P, Sturny WG, Zuber M (2007) Kanton Bern fördert Ressourcen schonenden Ackerbau. Agrarforschung 14(3):128–133 (German)

Six J, Ogle SM, Breidt FJ, Conant RT, Mosier AR, Paustian K (2004) The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Glob Change Biol 10(2):155–160

Smith P (2004) Carbon sequestration in croplands: the potential in Europe and the global context. Eur J Agron 20(3):229–236

Soane BD, Ball BC (1998) Review of management and conduct of long-term tillage studies with special reference to a 25-yr experiment on barley in Scotland. Soil Tillage Res 45(1–2):17–37

Soane BD, Ball BC, Arvidsson J, Basch G, Moreno F, Roger-Estrade J (2012) No-till in northern, western and south-western Europe: a review of problems and opportunities for crop production and the environment. Soil Tillage Res 118:66–87

SoCo Sustainable Agriculture and Soil Conservation. (2009) European commission directorate-general for agriculture and rural development. Final report. Luxemburg: EU23820EN

Strudley MW, Green TR, Ascough JC (2008) Tillage effects on soil hydraulic properties in space and time: state of the science. Soil Tillage Res 99(1):4–48

Symondson WOC, Glen DM, Wiltshire CW, Langdon CJ, Liddell JE (1996) Effects of cultivation techniques and methods of straw disposal on predation by Pterostichus melanarius (Coleoptera: Carabidae) upon slugs (Gastropoda: Pulmonata) in an arable field. J Appl Ecol 33(4):741–753

Tebrügge F (2002) Conservation tillage as a tool to improve soil-water and air quality In Proceeding 8th international congress mechanization and energy in agriculture, Kusadası, 15–17 Oct 2002, pp 83–86

Tebrügge F (2003) No-tillage visions-protection of soil, water and climate and influence on management and farm income. In: Garcia-Torres L, Benites J, Martinez-Vilela A, Holgado-Cabrera A (eds) Conservation agriculture: environment, farmers experiences, innovations, socio-economy, policy. Springer, Netherlands, pp 327–340

Tebrügge F, Böhrnsen A (1997a) Crop yields and economic aspects of no-tillage compared to plough tillage: results of long-term soil tillage field experiments in Germany. In: Tebrügge F, Böhrnsen A (eds). Experience with the applicability of no-tillage crop production in the West-European countries. Proceedings EC-workshop IV. Wissenschaftlicher Fachverlag, Giessen, pp 25–43

Tebrügge F, Böhrnsen A (1997b) Results and conclusions on the surveys on No-Tillage. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries. Proceedings EC-workshop IV. Wissenschaftlicher Fachverlag, Giessen, pp 54–153

Troeh FR, Thompson LM (1993) Soils and soil fertility, 5th edn. Oxford University, New York

Ulen B, Aronsson H, Bechmann M, Krogstad T, Oygarden L, Stenberg M (2010) Soil tillage methods to control phosphorus loss and potential side-effects: a Scandinavian review. Soil Use Manag 26(2):94–107

Van Ouwerkerk C, Perdok UD (1994) Experiences with minimum and no-tillage practices in the Netherlands. I: 1962–1971. In: Tebrügge F, Böhrnsen A (eds) Experience with the applicability of no-tillage crop production in the West-European countries. Proceedings EC-Workshop I. Wissenschaftlicher Fachverlag, Giessen, pp 93–104

Van-Camp L, Bujarrabal B, Gentile A-R, Jones RJA, Montanarella L, Olazabal C, Selvaradjou S-K (2004) Reports of the technical working groups established under the thematic strategy for soil protection. Office for official publications of the European communities; 2004 EUR 21319 EN/1, Luxembourg, p 872

VandenBygaart AJ, Yang XM, Kay BD, Aspinall JD (2002) Variability in carbon sequestration potential in no-till soil landscapes of southern Ontario. Soil Tillage Res 65(2):231–241

Veroz-González O, Sánchez CS, Sánchez Ruíz F (2008) Estudio estadístico de encuestas dirigidas a agricultores que aplican técnicas de Agricultura de Conservación. In: Gil Ribes J, Ordóñez Fernández R, Ayuso González J, Veroz-González O, González Sánchez EJ (eds) Métodos de Producción Agraria compatibles con el Medio Ambiente: Lucha contra la Erosión y Agricultura de Conservación. Informe Final, p 113–202 (Spanish)

Vinten AJA, Ball BC, O'Sullivan MF, Henshall JK (2002) The effects of cultivation method, fertilizer input and previous sward-type on organic C and N storage and gaseous losses under spring and-winter barley following long-term leys. J Agr Sci 139:231–243

Vogeler I, Rogasik J, Funder U, Panten K, Schnug E (2009) Effect of tillage systems and P-fertilization on soil physical and chemical properties, crop yield and nutrient uptake. Soil Tillage Res 103(1):137–143

Vogelgsang S, Hecker A, Forrer HR (2005) Fusarium head blight and mycotoxins in cereals: potential control strategies under conservation tillage. Poster at the 4th Canadian workshop on Fusarium Head Blight, Ottawa, Canada, 1–3 Nov 2005

Xavier MA, Nogueira A, Brás A, Basch G (2005) Estudo das pragas da cultura do milho forrageiro em função do sistema de mobilização do solo. In: Escola Superior Agrária de Coimbra (eds) A Produção Integrada e a Qualidade e Segurança Alimentar vol. I. Proceedings "VII Encontro Nacional de Protecção Integrada". Edições IPC, Coimbra, pp 327–334 (Portuguese)

Chapter 16
Conservation Agriculture in Latin America

A. Speratti, M.-S. Turmel, A. Calegari, C.F. Araujo-Junior, A. Violic, P. Wall and B. Govaerts

Abstract Conservation agriculture (CA) has been widely successful in the Southern Cone region of South America. A leader in the development of CA practices and technology, Brazil has encouraged the spread of CA throughout the region through an effective and innovative network of farmers and their associations, private and public partnerships. The benefits of CA in Latin America include soil conservation, reduced production costs, and increased soil biodiversity, which enhances environmental equilibrium, improves crop water balance, and increases yields. In other regions of Latin America, however, such as Central America and the Andean region, CA adoption has proven more difficult. A review of case studies in Latin America suggests that CA adoption is limited by socioeconomic constraints, access to appropriate machinery, crop-residue trade-offs, lack of adaptation of the technology to farmer's agronomic constraints, and uncoordinated efforts of stakeholders. The development of effective CA innovation systems in countries such as Brazil and Mexico has been instrumental in overcoming factors limiting CA adoption and reflects the importance of collaboration between public and private sectors, including machinery manufacturers, as well as the need for positive incentives and low-interest loans to make technology affordable for farmers. In addition, CA education, information dissemination through extension agents and farmers, and greater policy support and social capital, can help change attitudes and conventional farming practices.

Keywords No-till · Brazil · Mexico · Southern Cone · Central America · Andean region · Direct seeding · Innovation systems

---

B. Govaerts (✉) · M.-S. Turmel · P. Wall
International Maize and Wheat Improvement Centre (CIMMYT), Apdo. Postal 6–641, 06600
Mexico, DF, Mexico
e-mail: b.govaerts@cgiar.org

A. Speratti
Institute for Resources, Environment and Sustainability, University of British Columbia,
Vancouver, BC, Canada

A. Calegari · C. F. Araujo-Junior
Agricultural Research Institute of Paraná (IAPAR), Londrina, Paraná, Brazil

A. Violic
Chilean Academy of Agricultural Sciences, Santiago, Chile

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_16

16.1 Introduction

Conservation agriculture (CA) has been introduced and promoted in more than 40 countries, yet its massive adoption has only occurred in a few regions (Ekboir 2002; Derpsch et al. 2010). Latin America, particularly the Southern Cone of South America, has had the highest rate of CA adoption. The success of CA in this region has been attributed to close collaboration between industry, government, research centers, extension services, and farmer associations (Busscher et al. 1996) and the rise of "networks that used participatory research and extension methods" (Ekboir 2003). CA is commonly referred to as no-till, or no-tillage, and describes systems with direct seeding into untilled soil with minimum soil disturbance, permanent soil cover with growing crops and/or crop residue, and crop rotation (Kassam et al. 2009). No-tillage can be used synonymously with the terms "direct seeding" or "direct drilling" which denotes the process of sowing the seed into soil not previously tilled. In the Southern Cone region (Argentina, Brazil, Chile, Paraguay, Uruguay), the term direct seeding (*siembra directa* in Spanish, *plantio direto* or *semeadura direta* in Portuguese) is most often used; worldwide, however, the term CA has been more widely accepted as it encompasses the idea of a production system rather than concentrating solely on the tillage component, and is therefore used in this chapter.

The development of CA in Latin America originated from the need to address extensive soil degradation, especially soil erosion, evident by the mid-20th century. This soil degradation mainly resulted from the transfer of agricultural practices and technology from European colonists. Plowing worked well for European soils, but as conventional plow-based tillage expanded, it proved inefficient for tropical soils low in soil organic matter (Derpsch 1998). The reduction in production costs and evident reduction in soil erosion were the main drivers that encouraged the adoption of CA first in Brazil, then throughout the region (Machado and Silva 2001). CA has since then become the main agricultural system in southern Latin America, implemented on 60 % of cropland (Kassam et al. 2009). In this chapter, the origins and impacts of CA in different regions of Latin America are described. Factors limiting its adoption and innovations and strategies developed in some countries to overcome these limitations are also discussed.

16.2 Origins of CA in Latin America

CA originated in the USA around 1945, where it was further developed during the 1950s into the CA we know today. Up until then, conventional agriculture consisted of tillage systems (Friedrich and Kassam 2009; Kassam et al. 2009). The use of a plow to till the soil was developed in Europe in the 18th and 19th centuries, where tillage continues to be the most common land preparation practice. During the age of colonization, the European powers transferred their agricultural knowledge and practices to their new colonies, but after some decades these resulted in problems of soil erosion and degradation in the hotter and more humid tropical and subtropical regions (Derpsch 1998). Although agriculturally driven soil erosion is not a recent problem, as evidenced through historical records of regions, such as the Mediterranean during the Roman era, the widespread erosion and degradation observed today with conventional agricultural practices is a major threat to world food security, considering the importance of soil fertility for sustaining high yields of food, feed, and fiber (Constantinesco 1976).

In South America, Brazil became the first country to adopt CA practices in response to severe erosion and soil degradation rates. Implementation of no-tillage systems began in 1972 and according to Ekboir (2003), no-tillage "is the most important agricultural technology adopted in Brazil in the past 50 years." Although the environmental benefits of using CA were quickly evident, the main driver for the widespread adoption was economics (Derpsch 2003). When first converting to CA, costs may increase due to the purchase of new equipment, especially direct seeders, and increased herbicide use, but in the long term the costs are significantly lower compared to conventional tillage (CT; Ekboir 2003). Beginning in the 1960s and up until the 1990s, agricultural expansion in the South, Center-West and North of Brazil was heavily encouraged by the federal government. Soybean production intensified, leading to wider use of CT which, combined with rainfall and hilly terrain, caused extensive soil erosion. Looking for ways to control soil degradation and prevent financial losses by a forced switch to cattle raising or forestry, large-scale farmers began looking into conservation practices (Ekboir 2002).

Southern Brazil led the way for no-tillage research beginning in 1971, with no-till field trials headed by the Meridional Agricultural Research Institute (IPEAME) carried out by German researcher, Rolf Derpsch, and a Brazilian farmer of German origin, Herbert Bartz. Bartz bought a no-till planter from the USA and began cultivating soybean continuously under no-till. The first few years without tillage were difficult and some neighboring farmers who adopted the new system reverted back to CT after struggling to control weeds (Derpsch 1998). This exemplified the need to continuously adapt CA systems and find solutions to emerging problems rather than simply reverting to soil degrading practices. After the initial trials, major actions were taken by the Agricultural Research Institute of Paraná (IAPAR) for the dissemination of CA techniques. Efforts from this research institute included the development of direct-seeding machinery, herbicide testing, and the selection of cover crops based on adaptation to different soils, climates, and their effects on soil properties (IAPAR 1981).

Like Brazil, research into no-till practices began in Argentina in the 1970s. However, it was not until 1986 with the creation of the nonprofit Argentine Association of Direct Seeding Farmers (AAPRESID) that the use of CA really began and spread. Since its beginnings as a small group of no-till farmers, AAPRESID has grown tremendously, organizing conferences, encouraging knowledge-sharing among agricultural producers, participating in field trials, lobbying with the central government, and collaborating with public and private organizations both nationally and internationally to support the spread of CA (Aapresid 2013). In 2009, there were reportedly about 25 million ha under CA in Argentina (FAO 2012). However, not all of this land was under strict CA, but rather under a direct-seeded soybean monoculture, which leaves little durable crop residue for soil protection so these systems still lead to soil degradation. Thus, less than half of the direct-seeded area in Argentina is under complete CA practices including crop rotations (Friedrich et al. 2012). Yet, once Argentinian farmers switch to CA they tend to continue with the system permanently. The success of no-tillage in Argentina is mainly due to relatively cheap herbicides and accessibility to direct-seeding equipment. There are numerous manufacturers of no-till equipment in the country, with some exporting their machinery abroad (Derpsch et al. 2010).

In Uruguay, about 655,000 ha are under direct seeding (FAO 2012), but, as in Argentina, not all can be considered a complete CA system. The problem is being addressed through stronger regulations regarding use of cover crops, specifically in soybean systems, and subsidies to encourage proper CA in general. In Paraguay, successful application of CA began in 1983 through the efforts of a Japanese immigrant, Akinobu Fukumi, director of the farmers' cooperative, Colonia Yguazú. With the help of the Japan International Cooperation Agency (JICA), no-tillage was being practiced by all the cooperative's farmers within 10 years. No-till systems expanded in Paraguay, thanks to the support of the German Technical Cooperation (GTZ; Derpsch et al. 2010) and by 2008, there were 2.4 million ha under CA in Paraguay (FAO 2012). The successful adoption of CA by small farmers in Paraguay was mostly due to grants provided by the Ministry of Agriculture and the GTZ with the KfW (the German Reconstruction Credit Institute) to buy direct-seeding equipment. In addition, yield increases of manioc (*Manihot utilissima*), a staple crop in Paraguay—previously considered inappropriate for CA because of the soil disturbance associated with its harvest—have encouraged continued use of CA practices by small farmers (Derpsch et al. 2010).

In the 1980s, some local large-scale farmers started no-till activities in Bolivia. No-till with crop rotation has a positive effect on wheat production in the dry winters. Large-scale farmers found that no-till machinery reduced production costs, mainly equipment and fuel costs, and extended the planting period from 3 days to as many as 12 days (Ekboir 2002; Wall 2002). Since the late 1990s, CA in Bolivia has been used mainly in soybean cultivation in the eastern lowlands (150–700 masl; Derpsch et al. 2010), with 706,000 ha under CA management by 2007 (FAO 2012). Up to 2001, most formal no-till research was carried out by the International Maize and Wheat Improvement Centre (CIMMYT) and the Centre for Tropical Agricultural Research, a state nonprofit research center in Santa Cruz de la Sierra, in collaboration with the National Association of Oilseed and Wheat Producers (ANAPO), Fundacruz (a farmer-funded research foundation), agrochemical companies, and farmers (Ekboir 2002).

In Chile, a farmer in the southern region, Carlos Crovetto, began developing no-tillage practices in 1978 and has promoted CA practices in the country ever since (Derpsch et al. 2010). Crovetto has published books (e.g., *Agricultura de Conservación y Rastrojos sobre el Suelo*) based on his experiences and the science underlying CA. Though the government has done little to encourage CA in Chile, about 180,000 ha were under CA in 2008 (FAO 2012).

Research on no-till with residue cover in Mexico began in the 1950s through the national agricultural research organization, Instituto Nacional de Investigaciones Agrícolas (INIA, today INIFAP), but was soon abandoned due to poor results. In 1973, CIMMYT began research on no-till maize, encouraging researchers from INIA and another agricultural research organization, the Fideicomisos Instituidos en Relación con la Agricultura (Rural Development Trust Funds, FIRA), to start their own CA programs. FIRA provided no-till training for farmers, organized conferences and, most importantly, purchased necessary equipment. Research and promotion by these two organizations continued into the 1980s and 1990s, joined by the Colegio de Posgraduados whose CA research was mainly carried out by postgraduate students. Although all three institutions conducted similar research, interaction and communication between them was scarce and farmer adoption of CA was minimal. During this time, private companies (e.g., John Deere, Monsanto) also promoted minimum tillage and no-till (Ekboir 2002).

In 2001, the Agricultura Sostenible Basada en la Siembra Directa (ASOSID) project was initiated in the Bajío and irrigated double-crop region of central Mexico. ASOSID aimed to assemble an interinstitutional platform project including farmers and their associations (irrigation districts, groups of tube well users, marketing groups), federal and state government agencies located in the region (FIRA, INIFAP), regional, national, and international research institutions (CIMMYT and the Centre de Coopération Internationale en Recherche Agronomique pour le Développement, CIRAD), and private companies. The project employed a participatory technology development and training approach that involved close interaction with farmers, extension agents, and researchers and promoted farmer-to-farmer extension. As of 2014, ASOSID continues to play an important role in promoting CA in the region. Farmers in the Bajío region have continued to experiment with components of CA and currently more than half of the farmers are practicing a system of no-till during the spring/summer season. However, many of these farmers practice CT in the autumn/winter season (M.-S. Turmel, personal observation, 2014).

In 2011, CIMMYT partnered with the Mexican Secretariat of Agriculture to carry out a project called the Sustainable Modernization of Traditional Agriculture, better known as MasAgro. The objective of MasAgro is to strengthen innovation systems with multiple stakeholders to address factors limiting the productivity of Mexico's maize and wheat production systems. CA is the basis of the modernized production system promoted by CIMMYT because of its demonstrated benefits of improving soil quality, retaining soil moisture, and reducing production costs in the varied agroecological regions of Mexico. The MasAgro project has continued previous efforts by CIMMYT and other institutions in the Bajío, the Central valley, the Northwest, and the Chiapas regions, and seeks to unify the efforts of stakeholders at the regional and national levels (CIMMYT 2012).

A common agricultural system used by indigenous peoples in Mexico and other parts of Central America since pre-Hispanic times is the slash–mulch system. Different forms of this system have been observed in southeastern Mexico, Guatemala, Honduras, Nicaragua, and Costa Rica (Kettler 1997). The slash–mulch system can be considered a resource-conserving technology and a step towards

Table 16.1 CA in selected Latin American countries. (Source: FAO 2012)

Country	Land under CA (ha)
Argentina	25,553,000 (2009)
Brazil	25,502,000 (2006)
Paraguay	2,400,000 (2008)
Bolivia	706,000 (2007)
Uruguay	655,100 (2008)
Venezuela	300,000 (2005)
Chile	180,000 (2008)
Colombia	127,000 (2011)
Mexico	41,000 (2011)

CA conservation agriculture

CA systems, in some cases following all three principles of CA (Pulleman and Flores 2008). A common slash–mulch system used in this region, called "abonera" or "frijol de abono," incorporates the legume mucuna, also called velvet bean (*Mucuna* spp.), in maize crop rotations. Originally from Asia, mucuna has spread throughout the Americas where farmers have adapted it to their own needs. Unlike the traditional slash-and-burn methods of growing maize in both the dry and rainy seasons for 2 years and then leaving the land fallow for 4 or more years, the maize–mucuna system consists of planting mucuna in the dry season in between maize rows. After maize harvest, the mucuna continues to grow through the wet season, at the end of which it is slashed (cut down) and then maize is planted directly into the mucuna residues at the start of the next dry season (Neill and Lee 1999). In the past few decades, thousands of farmers in Honduras, southern Mexico, and Guatemala have adopted the slash–mulch maize–mucuna system (Buckles et al. 1999).

In some regions of Central America, where CA-type practices have been abandoned, efforts to reintroduce its principles to reduce rates of soil erosion have been made. For example in Panama's Azuero Peninsula, the Agricultural Research Institute of Panama (IDIAP), along with CIMMYT and the Regional Maize Program (PRM), began a research program in the 1980s examining the major soil erosion problem in this maize-producing region. The main causes were land preparation and maize-sowing practices, both linked to high production costs. IDIAP began recommending the use of no-till (now CA) to replace the conventional practice of preparing the soil with a disk plow up to 15 cm in depth, followed by harrow passes. By 1994, farmers in the region were using three forms of land preparation: no-tillage (17 %), minimum tillage (by reducing the number of harrow passes; 48 %), and CT (36 %; Pereira de Herrera and Sain 1999).

Information on the development of CA systems in other countries in Latin America is scarce, and more research and monitoring are necessary to determine the progress of, and challenges to, CA adoption particularly in Central America and the Andean region. Table 16.1 provides a summary of the latest available data on area under CA systems in Latin American countries.

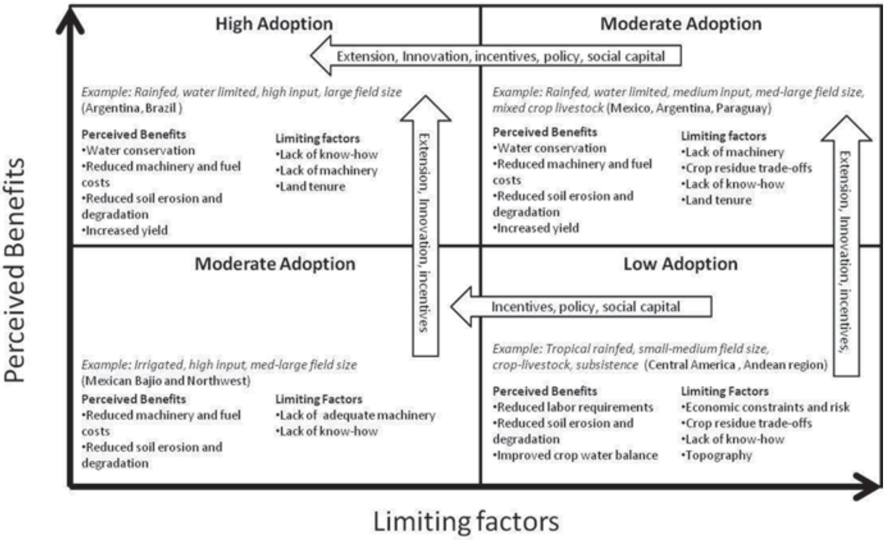


Fig. 16.1 Perceived benefits and limiting factors to the adoption of conservation agriculture and examples of regions of Latin America with different levels of adoption

16.3 Impacts of CA in Latin America

Since post-Columbian times, some form of soil tillage has been used in Latin America with the belief that turning the soil before planting is beneficial. More recently, CT often involves the initial use of moldboard plowing followed by harrowing or field cultivating. This form of tillage buries all remaining superficial crop residues (Tisdale et al. 1985), which can help to incorporate organic matter in the soil, as well as temporarily enhance porosity and control weeds (Hillel 1982). However, tillage causes high rates of soil erosion and breaks down the natural soil structure, leading to loss of soil organic matter by oxidation and erosion (Hillel 1982; Montgomery 2007). Deterioration of soil quality worldwide, especially in tropical and subtropical regions, has been observed over the past few decades due to tillage-based management practices (Arshad and Martin 2002).

Developed in response to the degradation, CA is a system based on integrated management of soil, water, and agricultural resources. Its main objective is economical, ecological, and socially sustainable agricultural production (Fig. 16.1) allowing soil regeneration and preventing soil degradation (Govaerts et al. 2009b; Derpsch et al. 2010; FAO 2012). CA practices achieve these objectives by reducing soil erosion, improving water conservation, reducing costs and, over time, generally increasing soil organic matter, soil microbiota, soil fertility, and crop yields (Verhulst et al. 2010a; Calegari et al. 2013). Minimum soil disturbance, combined with a mulch layer on the soil surface, is critical to sustainable and productive agriculture. In addition, crop rotations can reduce the need for applied nutrients (especially nitrogen) and the incidence of pests and diseases. The maintenance of surface cover either with crop residues or growing crops, including green-manure cover crops (GMCC, incorporated into the system specifically for soil cover production and improved nutrition), is particularly important in warm and wet environments such as the tropics where heavy rainfall causes severe erosion, microbial activity and nutrient leaching is high, and weeds can grow quickly throughout the year as long as moisture is available. Understanding how different crop residues, crops, and GMCC influence soil nutrient cycling and chemical properties is essential to optimize the system (Govaerts et al. 2009b).

With crop rotations, including the use of GMCC, and careful planning, Brazilian farmers have been able to keep the soil continuously covered under a variety of soil and climatic conditions and a range of farm sizes. The resulting CA systems have led to decreased soil erosion, increased soil organic matter, and breakdown of compacted soil layers, while at the same time permitting integration of livestock into the system and reducing the reliance on agrochemicals. Lime requirements to manage the highly acidic soils have been reduced, and regular (usually annual) applications of small amounts of lime and gypsum have replaced the heavy applications every 5 years or so. Among the leading CA nations, Brazil has substantial areas of CA in the tropics, including considerable adoption by small landholders. In both the subtropical and savannah (Cerrado) regions of Brazil, CA practices have not only increased crop yield but also conserved and maintained soil fertility, and decreased the incidence of insect pests and/or diseases, representing a promising strategy for sustainable soil–water crop management (Basch et al. 2012). Reported benefits of CA for small landholders include reduced labor demands and drudgery, increased income, crop and labor productivity, and reduced erosion (Calegari 2010).

In Mexico, an improved crop moisture balance is one of the main benefits of leaving surface residue cover, which results in increased crop yield, especially in rainfed climates where crop production is limited by soil moisture. Residue retention protects the soil surface from the impact of raindrops, increases water infiltration into the soil, thereby reducing runoff and erosion, and reduces evaporation, contributing to greater soil water content and resilience in drought-prone areas (Verhulst et al. 2011b). In a 15-year study in the semiarid, subtropical highlands of central Mexico, Verhulst et al. (2011b) observed that soils under no-tillage with surface residues retained (CA) had higher soil moisture content than those under CT with or without residue retention or no-tillage without surface residues. Average maize yields over the course of the study were higher and more stable in CA compared to both CT and no-tillage without residue retention, reflecting more crop resilience to drought stress.

Besides increased moisture retention, CA practices also improve soil structure through the combined effects of reduced tillage and increased superficial soil organic matter. In the irrigated Yaqui valley in the state of Sonora, Mexico, surface residues are traditionally used for animal feed or incorporated into the soil (now that burning is not permitted). Irrigation water is becoming scarce and water-efficient gravity-irrigated systems are increasingly required. Here a CA system has been developed with permanent raised beds, where the furrows between the beds are used for irrigation. The tops of the beds are never tilled, but furrows are re-shaped between seasons as necessary and some soil moved back onto the top of the beds. Comparing CT and no-tillage under full and reduced irrigation, both with residue retention, Verhulst et al. (2011a) noted increased soil aggregate stability in the 0–5-cm layer in permanent raised beds compared to conventionally tilled beds due to increased soil-surface protection with residues. Leaving residues on the soil protects surface aggregates from raindrop impact and thus overcomes surface crust formation. In tilled soils, the weakened soil aggregates at the surface are broken down by raindrops and the loosened soil particles block the surface pores, creating an impervious soil layer that restricts water infiltration, increasing runoff and erosion. When this layer dries, it forms a surface crust that can reduce or impede crop germination leading to reduced plant populations.

Soil compaction is caused by tillage implements or wheel traffic on crop fields, especially when the soil is moist or wet. Compaction is exacerbated when soil structure is weak, such as those with reduced organic matter content or recently tilled soils. In CA, both tillage and traffic are reduced, and any compaction is superficial where it is readily overcome by surface biological activity associated with residue breakdown. However, with tillage, a sub-surface plow pan or tillage pan is common, reducing root growth and water infiltration. In northwestern Mexico, penetration resistance was highest in soils with no-tillage and burnt crop residue compared to tilled soils and CA (Verhulst et al. 2010b). With residues left on the surface, however, higher infiltration rates under CA were recorded compared to no-tillage without residue retention (Govaerts et al. 2009a), indicating that surface residue retention is important for soil health.

In addition to soil conservation, studies on the economic impact of adoption of CA practices often show higher net returns compared to CT practices (Knowler and Bradshaw 2007), due to a reduction in labor and fuel costs associated with machinery operation and have been a main driving factor for adoption. For example, economic studies of CA systems in the Yaqui valley and the central highlands of Mexico found that CA systems were more profitable due to a combination of higher yields and lower production costs (Table 16.2; Romero-Perezgrovas et al. 2014; Sayre and Govaerts 2012). In Brazil and Paraguay, after the initial investment in no-till machinery on farm, costs decreased over time (Ekboir 2003) and net revenue increased substantially with CA compared to CT (Sorrenson et al. 1997; Table 16.2).

The economic benefits of CA are not limited to large-scale mechanized farms, but have also been found in small-scale subsistence systems. In Central America, the slash–mulch mucuna–maize or abonera systems have been found to reduce manual labor requirements for land preparation and weeding. The extensive cover of the mucuna plants suppresses weed growth and, since it is a legume, the mucuna mulch reduces the need for fertilizer applications (Sain et al. 1994; Neill and Lee 1999). In Honduras, several studies have explored the benefits of the abonera system in the country's Atlantic coastal region (Flores and Licona 1985; Buckles et al. 1993, 1999; Sain et al. 1994; Neill and Lee 1999). Through farm surveys, Sain et al. (1994) examined the short-term and long-term economic advantages of the abonera system compared to the traditional system (maize–fallow rotation without abonera) during its expansion in the 1980s. They found that after the third year of setting up

Table 16.2 Economic analyses of CA compared to conventional tillage (CT) in selected case studies in Latin America

Case study description	Location	Year	Net returns (USD)		Observations	Source
			CA	CT		
On-farm comparison of maize under CA and CT under severe drought conditions in the central highlands, Mexico, 2009–2010	Hidalgo, Mexico	2009	320/ha		Positive effect of CA compared to CT, indicating CT resulted in lower net return	Romero-Perezgrovas et al. 2014
		2010	165/ha		Negative effect for both CA and CT in average rainfall year 2010	
CA trial on irrigated wheat systems, Yaqui valley, Sonora, Mexico, 1993–2006	Yaqui valley, Mexico	13-year average	304	495	Reduction in production costs	Sayre and Govaerts 2012
Cost difference between no-tillage (CA) and CT for the rotation soybean–maize–wheat in southern Brazil, 1999	S. Brazil	1st year	550	532	Costs may increase the first year under CA, but fall with time	Ekboir 2003
		10th year	371			
Financial performance simulated for a typical large-scale farm based on data collected from 18 farms using various no-tillage/crop rotations in the regions of Itapua and San Pedro, Paraguay, 1993	Itapua, Paraguay	1st year	73/ha	54/ha	Declining crop yields in CT Increasing crop yields, higher cropping intensity and savings in crop production in CA	Sorrenson et al. 1997
		10th year	250/ha	8/ha		
	San Pedro, Paraguay	1st year	64/ha	36/ha		
		10th year	230/ha	-22/ha		
Profitability of maize rotation with abonera system over 6 years in the region of Atlántida, Honduras, the 1980s	Atlántida, Honduras	1st year	25/ha	44/ha	Reduction in weed control labor	Sain et al. 1994
		6th year	34/ha	24/ha		

CA conservation agriculture

the mucuna rotation, the abonera system had higher maize yields than the traditional system. Using the net present value, production costs were much lower after the second year in the abonera system, since land preparation was no longer required after the initial mucuna planting. For farmers renting cropland for only 1 year (two growing seasons), switching to the abonera system would be less attractive; however, for landowners it would be advantageous in the long term. In fact, Sain et al. (1994) observed that in a complete 6-year cycle, the abonera system reduced labor requirements. After 6 years, the profitability of the abonera system was greater than that of the traditional system (Table 16.2), increasing the value of land on the Honduran Atlantic coast as producers were willing to pay higher prices for productive land under abonera. A review by Erenstein (2003) described similar environmental and economic benefits of slash–mulch systems for small landholders in tropical and subtropical countries around the world.

16.4 Overcoming Factors Limiting the Adoption of CA: Case Studies from Latin America

The environmental and economic benefits of CA are evident in many regions of Latin America; yet its success and adoption is closely tied to the socioeconomic issues of each country and region. The importance of perceived benefits of CA including soil conservation, reduced production costs and labor requirements, improved soil water retention, and increased yields depend on the agroecological and socioeconomic conditions (Fig. 16.1). The adaptation and adoption of CA principles have been more successful in the temperate regions of South America (e.g., the Southern Cone), while remaining more challenging for resource-poor farmers in tropical regions (Fig. 16.1).

Several papers have reviewed factors that influence adoption of CA around the world (e.g., Ekboir 2002; Knowler and Bradshaw 2007; Wall 2007; Friedrich and Kassam 2009; Erenstein et al. 2012). The main factors that appear to limit the adoption of CA by farmers in different regions of Latin America include:

- Socioeconomic constraints (limited access to financial capital and credit opportunities, inability to take risks, short-term priorities, land tenure)
- Lack of machinery and tools (reliance on manual labor, lack of locally available mechanization solutions)
- Crop-residue trade-offs (mixed crop–livestock systems)
- Agronomic constraints and lack of CA knowledge (poor extension capacity, adaptation of CA principles to different agroecological and socioeconomic conditions)

CA has mainly been addressed through two perspectives: soil conservation and increased production and profitability. Since ultimately it is the farmers who decide how to manage their land, it is necessary to “alleviate some productivity concerns before, or in addition to, conservation concerns, with the soil conservation measures imposing only moderate additional costs on the user” (Erenstein 1997). Thus, not surprisingly, some of the main factors limiting the adoption of CA in Latin America pertain to the economic realities of farmers as well as preconceptions, attitudes, and traditional practices.

Adoption rates in different regions of Latin America are essentially reflected in the balance of perceived benefits and limiting factors (Fig. 16.1). For example, high adoption rates are found in rainfed high-input systems of the Southern Cone where the perceived benefits of CA are high and the limiting factors are few and relatively easy to overcome. However, in small tropical non-mechanized mixed crop–livestock systems such as in Central America and southern Mexico, many complex limitations exist and the perceived benefits of CA adoption are relatively low. Regions with moderate adoption include areas where limiting factors are low, but with fewer perceived benefits, such as the irrigated systems of northwest Mexico where CA may reduce production costs, but is unlikely to increase crop productivity, at least in the short term. Moderate adoption is also found in rainfed mixed crop–livestock systems of the Southern Cone and Mexico where the perceived benefits in terms of water and soil conservation and increased productivity are high, although adoption is limited strongly by residue trade-offs. Adoption can be increased by increasing perceived benefits and reducing limiting factors through a combination of innovation, extension, positive incentives, policy, and social capital (Fig. 16.1).

The combination of bottom-up and top-down efforts is essential in the success of CA adoption. In most cases, there are multiple factors limiting CA adoption, thus the adaptation and adoption of CA requires the participation of diverse stakeholders working in cooperation to eliminate these limiting factors (Fig. 16.1). Below we provide examples of the main limiting factors to CA adoption in Latin America and, where ever possible, case studies identifying how these limiting factors were overcome.

16.4.1 Socioeconomic Constraints

Socioeconomic constraints can be a major factor preventing farmers from adopting CA practices especially in small-scale subsistence farms in Central America and the Andean region. Although the benefits of CA in terms of soil conservation have been clearly demonstrated, the adoption of CA by small-scale farmers in both rainfed and irrigated regions has remained minimal due to economic constraints. For example, in Belize, socioeconomic constraints prevent indigenous Mayan communities in particular from adopting more sustainable agricultural practices. Traditionally, farmers use slash-and-burn agriculture which works well if there is a balance between land availability and population growth. In the past few decades, however, the high population growth rate has increased pressure on land availability, leading to more forest clearing for agriculture and shorter fallow periods. In the Mayan community of San José in the Toledo district, the main factors impacting the population and agricultural production were: (1) decreasing availability of fertile agricultural land, (2) no national government representation (as of 1997), (3) the land tenure system (most of the land is owned by the state), (4) minimum agricultural support, and (5) limited markets for their crops (Levasseur and Olivier 2000). Farmers have the potential to intensify agricultural production in existing agricultural land rather than clearing more forest to address problems of land reduction. However, sustainable intensification through the adoption of CA practices would require more institutional support (Levasseur and Olivier 2000).

Land tenure can also limit the implementation of sustainable soil management practices. Whether the land is owned or rented can determine how much importance the farmer places on soil conservation, as those who rent will focus mainly on the short-term outcome (Pereira de Herrera and Sain 1999). In Honduras, the slash–mulch system expanded rapidly among small-scale farmers in the 1980s (Buckles et al. 1993), with land tenure being one of the factors promoting adoption of the abonera system. Since positive results of the practice are not noticeable until after a few years, adopting the practice is less risky for those that own their land (Buckles et al. 1992). By 1997, however, it was reported that 45 % of the farmers surveyed had abandoned the abonera system and only 39 % were still using it, while16 % had never adopted it (Neill and Lee 1999). Considering its economic benefits, as described above, and its previously widespread acceptance, Neill and Lee (1999) sought to explain what caused the sudden abandoning of the abonera system in the 1990s. Three main categories of factors were suggested: external, environmental, and management. External factors included: “changes in land markets, distribution and tenure; the expansion of the cattle industry; and modernization of the infrastructure of Northern Honduras” (Neill and Lee 1999). In order to benefit, the abonera system requires several years to build up organic matter and nitrogen levels to produce better yields. Therefore, long-term land security is necessary. In addition, land area is important, with the abonera system requiring a minimum of 2–3 ha because one or two additional plots are needed for the main maize crop during the wet season while the other plot(s) are planted with mucuna. However, since the 1970s, farm size has decreased and in the 1980s the government’s new land-titling program and the Agricultural Modernization Law made landowners less likely to sell their land and made it harder for subsistence farmers to enter in informal land agreements with landowners. This suggests that policy that governs farmer land tenure or the ability to enter into long-term rental agreements significantly impacts the adoption of sustainable land management practices such as CA.

Soil conservation practices provide important ecosystem services such as reduced erosion and its multiple negative downstream effects and the prevention of landslides. However, for many small farmers, adopting new practices may not be economically viable or involves too much risk. A study begun in 2012 through the United States Agency for International Development (USAID)-sponsored Sustainable Agriculture and Natural Resource Management Collaborative Research Support Program (SANREM-CRSP) examined the benefits of CA in the poorest region of Ecuador, the province of Bolivar. Subsistence farmers in the province are faced with food insecurity and environmental constraints related to inconsistent rainfall and steep topography. Landslides have left many areas bare, forcing farmers to grow crops on low-quality soils on slopes, thus leading to further soil erosion, low yields, and cropland expansion (Nguema et al. 2013). Nguema et al. (2013) reported economic benefits of using CA in two distinct regions of Bolivar: the higher elevation sub-watershed of Illangama and the lower elevation sub-watershed of Alumbre. Due to elevation, these sub-watersheds have different cropping systems. In Alumbre, reduced tillage and a corn–oats/vetch–bean rotation without incorporation of the cover crop into the soil had larger returns than CT. In Illangama, however, the current practices of CT with removal or incorporation of the crop cover and a crop–fallow rotation for the main crops (faba beans and potatoes) was economically more advantageous than converting to reduced tillage and thus there was little incentive to adopt soil conserving practices. Further participatory research is required to adapt the principles of CA to the conditions of Illangama in such a way that the system is productive and economically viable (Nguema et al. 2013). In regions where converting to CA may not be initially economically viable, but the potential benefits to society in terms of soil conservation and ecosystem services are high, incentive programs may be used to promote adoption of soil-conserving practices.

Socioeconomic constraints to CA adoption have been overcome in other regions through institutional support, incentive programs, and social capital. To promote CA in southern Mexico, since the 1970s, information dissemination has mainly been carried out by research centers and national institutions, including the Secretaría de Agricultura y Recursos Hidráulicos (SARH), the Secretaría de Desarrollo Rural y Ecología (SDRyE), FIRA, INIFAP, and CIMMYT. CIMMYT and INIFAP began a collaborative research program in Chiapas in the 1980s. A survey of 181 farmers conducted in 1992, with support from SARH, examined factors limiting maize production and factors promoting CA adoption in La Fraylesca, Chiapas, Mexico (van Nieuwkoop et al. 1994). The main problems limiting agricultural production were high soil erosion and low fertility caused by environmental factors, CT, and residue burning. van Nieuwkoop et al. (1994) found that 3 years before their survey, adoption of CA practices grew rapidly, largely due to local incentive programs. Beginning in 1990, FIRA provided free backpack sprayers and herbicides to those who did not burn their field residues. SARH and SDRyE also initiated CA support programs and provided free equipment. In addition, information obtained through these incentive and promotion programs, together with field demonstrations and conversations with contacts outside the farm played a role in enhancing CA adoption (van Nieuwkoop et al. 1994).

In the Peruvian Altiplano, the mountainous terrain not only increases the susceptibility to soil erosion but also limits the land available for agriculture and accessibility to markets. In addition, reduced government aid to farmers and funding for agricultural research in the mid-1980s and 1990s coincided with mass migration from rural communities to urban centers. Combining a conceptual behavioral model and data from a 1999 farm survey in the Peruvian Altiplano, Swinton (2000) suggested that social capital may be a useful tool in developing more sustainable agricultural practices. Based on the results, the author postulated that alternative solutions to public programs and market incentives are needed to motivate farmers to use agricultural practices that reduce soil erosion and ensure long-term soil conservation. Thus, “Social capital in the form of shared norms and/or fellow feeling among community members has the potential to motivate individuals to act for the collective good. Where community organizations exist, social capital may further help individuals overcome resource barriers to conservation, by providing collective capital and labor" (Swinton 2000).

16.4.2 Access to Machinery

Lack of or insufficient access to machinery for planting, fertilizing, and spraying pesticides, due both to economic and local technological constraints, often limits the adoption of CA (Fig. 16.1). In areas with fewer technological constraints such as Brazil, Argentina, regions of Paraguay and Bolivia, changing seed drills happened very quickly. Generally, farmers bought a small grain drill that they could use for wheat and soybean, or they adapted their conventional equipment for direct seeding. Later, as they grew accustomed to the system, they bought more specialized precision drills for maize and soybean. However, in other regions, suitable machinery for CA may not exist locally or is relatively more expensive (Pereira de Herrera and Sain 1999). For small-scale farmers in the Bolivian lowlands, for example, adopting no-till practices was difficult because no-tillage machinery suitable for farm sizes smaller than 150 ha was not locally available (Ekboir 2002). In La Fraylesca, Chiapas, Mexico, with few direct seeders in the region, many farmers who own CT and seeding equipment prefer minimum tillage or CT, incorporating crop residues, over replacing their conventional machinery (van Nieuwkoop et al. 1994). Machinery constraints have been overcome through innovation and adaptation of existing machinery, promotion of local machinery developers to create CA designs, and incentives to make new machinery more accessible.

Private industry innovation has played an important role in machinery development and CA promotion. As Brazilian farmers began experimenting with no-tillage in the 1970s, the British agrochemical company, Imperial Chemical Industries (ICI), transferred its no-till research to Brazil in 1972 and began investing in the development of direct-seeding machinery. Collaborating with IAPAR, Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) and a then-small manufacturing company, Semeato, ICI imported a planter for researchers, farmers, and manufacturers to use (Ekboir 2003). Semeato is now the "largest manufacturer of no-till planters outside the US" (Ekboir 2002) and continues to promote CA practices in Brazil (Semeato 2013).

The development of machinery for small farmers, including animal-drawn planters (e.g., Fig. 16.2), has been instrumental in the adoption of CA by farmers. In the southern state of Paraná, Brazil, the state government's family agriculture support policy implemented in the early 1980s resulted in the development of animal-powered direct-seeding machines. In the 1990s, the main no-tillage technologies were validated on small farms and, in later years, were responsible for the wide adoption of the system and the appearance of small, manual, and animal-powered equipment manufacturers, mainly in the states of Santa Catarina and Rio Grande

Fig. 16.2 An animal-powered no-till seeder. (Source: Casão-Junior et al. 2012)

Fig. 16.3 Knife roller used on a black oat cover crop before the cash crop is seeded. Agronomic Institute of Paraná (IAPAR), Londrina, State of Paraná, Brazil

do Sul. This encouraged the change to CA systems on small farms in southern Brazil (Casão-Junior et al. 2012; Calegari et al. 2013). Figures 16.3 and 16.4 show examples of no-tillage machinery used in this region.

Providing finance and incentives for investing in CA machinery has been another key factor in improving access to CA machinery. In Brazil, after 1995, agricultural financing started to have lower and fixed interest rates which increased machinery acquisition throughout the country. In addition, agricultural machinery fairs, usually with dynamic exhibitions of direct-seeding machines, proliferated and provided reference points to launch new machine models by the industry and linked farmers to suppliers (Casão-Junior et al. 2012; Calegari et al. 2013).

Modification of conventional equipment to no-tillage equipment and to local conditions has also permitted CA adoption by small-scale farmers. This was particularly effective for small-scale farmers in Paraguay who could adapt CA tools at home and start using them before investing in specialized equipment (Lange and Meza 2004). In the Bolivian highlands, small-scale farmers had difficulty operating heavy animal-drawn direct seeders imported from Brazil, which were designed for maize and beans. Through a joint project between CIMMYT, the Universidad Mayor de San Simón, and the Bolivian research institute, Instituto Boliviano de

Fig. 16.4 Big farm seeder for direct seeding in crop residues. Floresta, State of Paraná, Brazil

Tecnología Agropecuaria (IBTA), animal-drawn direct seeders for small grains were developed for local conditions and tested by farmers. Based on wheat yield increase under direct seeding with Brazilian seeders, researchers and extension staff were confident that results would be positive with the adapted seeders, as long as enough straw cover could be retained on the surface (Wall 1999). However, since the early 2000s, funds for research and extension to continue this work with farmers have not been available and efforts were largely suspended (P. Wall, personal communication, 2014). In Mexico, CIMMYT imported prototypes of machines from Argentina, Bangladesh, Brazil, China, India, and Nepal ranging from large tractor-drawn planters to animal-drawn seeders and hand planters, in order to develop and adapt them to local conditions. They are working with local machine shops to encourage local production of machinery to increase accessibility for farmers (CIMMYT 2012).

16.4.3 Crop-Residue Trade-offs

Crop residues are commonly used as animal feed, albeit of relatively low quality. The trade-offs involved in leaving crop residues on the surface for soil conservation are important, especially for smallholder farmers, who often manage mixed crop–livestock systems. These systems become more intense in marginal areas with low system productivity, leading to intense competition for residues and limited CA adoption (Fig. 16.1). For example, in Panama, maize residue is highly coveted as livestock feed, particularly during the dry season. Most maize farmers also manage mixed crop–livestock systems. Over 85 % of landowners use maize residue to feed their livestock; those who do not have livestock sell their crop residues or grazing rights; and those who rent land from cattle producers must leave crop residues on the surface for livestock to graze (Pereira de Herrera and Sain 1999). Similarly, in Bolivia one of the biggest challenges for leaving crop residue on the surface was that it was usually removed for threshing, used for livestock feed, or allowed to be grazed (Wall 1999).

In many areas of Mexico, the use of crop residues for animal fodder is a major constraint to adopting full CA. Since there is high demand for residues as animal feed, farmers prefer to supplement their income than leave residues on the ground for soil conservation; moreover, even if they left it on the surface, traditional practices of burning and communal grazing make it difficult to retain residue on the soil (Ekboir 2002). In La Fraylesca, Chiapas, Mexico, a factor determining whether or not farmers adopted CA in the 1980s was the use of crop residue for animal feed. Chances of CA adoption decreased according to the availability of pasture, the number of cattle owned relative to farm size, and the local importance of communal grazing rights (van Nieuwkoop et al. 1994). Leaving residues on the surface is an essential part of CA especially in soils susceptible to surface compaction and crusting (Verhulst et al. 2010b). However, communities practicing communal livestock grazing find it difficult to apply the residue retention component of CA. After several years of continued on-farm training and demonstration events conducted through the MasAgro project, Mexican farmers in the central highlands have begun to see the value of retaining residues on the surface in terms of water infiltration and soil moisture retention. Farmers have started to raise awareness of this value in their communities by communicating with their neighbors. As of 2013, the communities have started to respect individual farmers' intentions to retain crop residues and not allow their animals to graze on their land (M.-S. Turmel, personal observation, 2013).

Strategies to reduce animal grazing of surface residues have included restricting animal access, measures to make residues unpalatable or growing pasture species for grazing in fallowed areas (Wall 1999). In addition, adopting CA practices in water-limited environments usually results in greater crop yields that leave more biomass residue after harvest, enabling some residues to be used for animal feed (or other purposes) and the remainder for soil cover (Lal 1995; Ekboir 2002; Govaerts et al. 2005). A potential compromise to the residue trade-off is only removing a part of the residue for fodder and leaving a part for soil cover. Farmers can cut stalks higher to leave them as standing stubble that is more difficult for goats to eat. Another solution is growing fodder crops or dual-purpose (grain and fodder) crops (Reyes-Muro et al. 2013). Triticale has been promoted as an alternative forage crop for the central highlands that can be grown on a small portion of the farmer's land and is more nutritious than maize residue**.**

The feed–soil cover trade-off may be one of the most difficult obstacles to overcome for CA adoption. However, solutions can be found through a combination of participatory research on potential solutions and by changing perceptions of the importance of soil degradation and the value of residue for soil cover (Reyes-Muro et al. 2013).

16.4.4 Adaptation of CA to Overcome Local Agronomic Constraints

A widespread limitation to the adoption of CA is its complexity and the need to adapt the system to local conditions (Erenstein et al. 2012). CA is a knowledge- intensive system; in addition to changing tillage and residue management practices, adoption of CA can require many other agronomic changes such as weed and pest management and crop rotation. CA practices efficient in one region may not be applicable to another location given the agronomic and socioeconomic context of that region. A shift from conventional practices to CA requires learning and innovation and multiple changes in agricultural systems.

A major agronomic constraint to CA adoption worth discussing is the control of weeds without tillage, especially for smallholder farmers with limited access to herbicides. In the state of Veracruz, Mexico, for example, research carried out by CIMMYT in the 1970s observed that the main challenge to high maize yields for small-scale farmers was weed control. Weed removal was mostly done by using the machete and hoe. Some farmers would contract a tractor to assist in seedbed preparation, but few tractors were usually available and the sticky, clay vertisols of the area made it difficult for mechanical tilling and hoeing. For these reasons, the use of herbicides together with no-tillage and surface residue retention was recommended, and farmers in the region still use these practices (Violic et al. 1989). Cover crops are also a viable option for reducing weed infestation and herbicide costs (Teasdale et al. 2007), reducing diseases and pests, and producing permanent cover needed in a direct-seeding system to increase the organic matter content of soil (Derpsch 2003). In perennial crops like coffee plantations, cover crops can provide good soil cover and protect the soil against water erosion and surface crusting (Araujo-Junior et al. 2013). Araujo-Junior et al. (2013) noted that GMCC reduced weed density and diversity, both between coffee rows and under the canopy, which promoted reduced production costs through less weed control by hand hoeing.

The impact of herbicides on the spread of CA is worth noting. In 1955, ICI discovered the desiccant herbicide, paraquat. Seeing that it could be used to control weeds prior to crop establishment in untilled fields, ICI began investing in research to develop a new agricultural technology package. However, paraquat only controlled annual weeds, and problems with increasing perennial weed populations led to many farmers abandoning the system. By the end of the 1970s, an alternative herbicide, glyphosate, arrived on the market, allowing for a complete no-tillage package for farmers (Ekboir 2002). Yet, the price of Roundup®, Monsanto's patented glyphosate herbicide, was very high which restricted its use, thus spawning many new crop-spraying technologies and techniques to reduce herbicide use. The drop in glyphosate prices after the end of the Monsanto patent in Brazil in 1985, coupled with the availability of no-till machinery adapted for different soils, led to a rapid expansion of CA practices nationally (Casão-Junior et al. 2012).

In regions with hot and wet climates, surface residues degrade rapidly making permanent soil cover difficult to achieve. Cover crops can provide living soil cover and more mulch. In the state of Paraná, Brazil, for example, black oats (*Avena strigosa*) alone or mixed with vetch (*Vicia* spp.) is used as a cover crop that is laid (rolled) onto the soil surface to complement the residue of the main crops, which degrade quickly under the warm, wet conditions, or crops such as soybean that do not produce much residue (K. Sayre, personal communication, 2013). The use of cover crops in CA is widespread in all main production areas of Brazil, from the south to the Cerrado, where they also provide mulch for no-till cash crops used as intercrops in perennial crops (coffee, rubber tree, citrus, and other perennial fruit) or for horticultural crops (potatoes, carrots, tomatoes, onion, garlic, cabbage, etc.; Teasdale et al. 2007). Besides providing mulch and weed suppression, cover crops can also be a source of nutrients, especially nitrogen, and animal fodder (Calegari 2009).

16.4.5 Innovation Systems and Coordination of Stakeholders

In most cases, the adoption of CA is not limited by one single factor, but rather several factors that must be overcome to facilitate adoption. Innovation systems that engage farmers, agronomists, researchers, extension agents, input and credit suppliers, produce purchasers, policy makers, and other members of the principal value chains are essential to overcome complex agronomic and socioeconomic constraints to CA adoption. In Brazil, adaptation required problem solving and innovation which developed through the formation of groups of large-scale and small-scale farmers and support from government agencies, universities, industries, and international organizations (Kassam et al. 2009). According to Casão-Junior et al. (2012), the common goal of these innovations in the 1970s was to develop agricultural guidelines for tropical and semitropical regions of Brazil since there was little knowledge from other tropical regions with similar conditions. Most land management practices had come from temperate European countries from which many Brazilian immigrants had originated. Through the work produced by innovation systems adapted to local conditions, Brazil has become a pioneer in CA, with its development of new no-till technology, making it a worldwide leader in CA particularly in the field of agricultural machinery (Casão-Junior et al. 2012).

In the past, most small landholders in Brazil did not have easy access to credit and information about agricultural technologies. In recent years, this has changed and, as a result of a combination of government support (municipal, state, and federal), farmers' associations, public extension service, and participatory research has focused on developing sustainable soil and water management practices. This has been done mainly by supporting CA practices, including use of cover crops, crop rotation, and options for grain, livestock, and agroforestry. In addition, strategies that improve local markets for inputs and outputs, support agroindustry to add value to their products, and develop locally adapted soil and water conservation systems, have been promoted in various agricultural regions of Brazil (Casão-Junior et al. 2012).

Examples of the successful development of innovation systems are evident in southern Brazil (the states of Paraná, Santa Catarina, and Rio Grande do Sul), which in the 1970s and 1980s was facing extensive soil erosion. In Paraná, forest cover went from 87 to 10% in a 50-year period. To address this issue, organizations in Paraná such as farmers' cooperatives, research institutions and professional associations assembled to develop soil conservation programs which were subsequently supported by state legislature. Mainly led by local farmers, with financial support from conservation programs, several actions were carried out to control soil erosion by water and promote CA conservation practices, including "training and capacity development of technicians and farmers through lectures, field days, courses, regional and state meetings on soil management and the publication of technical manuals" (Casão-Junior et al. 2012). In Rio Grande do Sul, a project involving five public and private institutions began in 1993 to support research and extension to facilitate small landowners' access to no-tillage packages. Among other activities, they allowed for the adjustment of cover crop and fertilizer management to local needs, provided cost-effective kits to convert conventional planters to no-till planters, and provided training for extension agents. Similarly in the state of Santa Catarina, development of soil management practices based on research and farmers' experience led to massive adoption of CA; by 1999, 80 % of the grain produced in the state was under no-tillage (Ekboir 2002).

As in Brazil, support from research institutions, international organizations (e.g., JICA, GTZ, CIMMYT) and farmers' organizations (e.g., AAPRESID) has been the key for promoting adoption in Argentina and Paraguay. In addition, active information exchange exists between farmers' associations in Brazil, Argentina, and Paraguay (Ekboir 2002) and through the regional organization, CAAPAS, the Confederación Americana de Asociaciones de Productores para una Agricultura Sustentable (American Confederation of Associations in Sustainable Agriculture).

The collaboration between multiple stakeholders to align interests towards promotion of sustainable soil management has been instrumental in the promotion of CA in Mexico. The increase in productivity will, in part, be achieved through adoption of CA in areas where water is the limiting factor. In 2 years, the strategy increased the area under CA adoption by 23,000 ha nationally (B. Govaerts, unpublished data, 2012). CIMMYT has played a catalytic role in improving the collaboration and coordination among stakeholders including farmers and their organizations, research institutes, extension services, national, state, and local government, and the private sector. Most notably, MasAgro has played an important role in orienting federal and state government incentive programs to promote CA and reactivating the national extension program for maize, Programa de Incentivos para Productores de Maiz y Frijol (PIMAF), through training in CA and sustainable management practices, and strengthening linkages between farmers and research institutes (CIMMYT 2012).

Sharing CA know-how between farmers has been vital for the expansion of CA practices in Latin America and should be maximized in CA extension programs. In Atlántida, Honduras, the expansion of the abonera system during the 1970s and 1980s attracted a great deal of attention among researchers as its spread was mostly farmer-to-farmer, rather than through government or researcher intervention. Farmers using this system innovated and shared new and improved practices with their neighbors (Neill and Lee 1999). An effective way to continue promotion is for extension agents to focus on farmer communication networks and facilitate information exchange between farmers (Buckles et al. 1992). Indeed, in their review on factors affecting CA adoption, Knowler and Bradshaw (2007) noted that "Without knowledge of the practices associated with CA via some [effective] information or communication channel, adoption is improbable." CA has been more readily embraced by farmers who have better linkages to information systems, and are more engaged in farmers' associations, as seen in Argentina and Brazil. Organized farmers' unions and associations are important as they can assist not only in disseminating information among peers but also in pooling resources for the purchase of machinery and other inputs, reducing economic barriers, and improving accessibility to technology.

16.5 Summary and Conclusions

The greatest success of CA adoption has been in the southern South American region. In Brazil, CA knowledge and technology developed first in the southern temperate region has spread to the more tropical north and central-west regions. Areas of Argentina, Paraguay, and Bolivia with similar agroclimatic characteristics also benefited from knowledge and technology exchange with Brazil. No-till machinery, ranging from manual planters and small animal-drawn planters designed for hilly regions, to extremely wide planters for expansive, flat regions such as the Brazilian Cerrado have been developed. The fact that CA has spread throughout the vast landscape of Brazil reflects the widespread applicability of the principles of CA to different climates and topography. However, the techniques used to apply these principles have been diverse, depending on local farming systems and the socioeconomic situations of farmers. In Central America, for example, many communities have adopted the slash–mulch system which follows the principles of CA. This practice was developed by indigenous farmers and can be considered a bottom-up approach for soil conservation and food security which, especially when combined with institutional and policy support, led to rapid adoption. A number of global networks of sustainable agriculture collaboration exist, through which ideas and innovations from one region can be exported to others and can then be adapted to local conditions. Component technologies and techniques implemented, for instance in the Southern Cone of South America, can be adapted to other regions where CA has caught on more slowly.

Since it appears that CA has the potential to be adapted to any agroclimatic zone, one may suggest that constraints to the adoption of CA practices in other regions are not so much related to environmental factors but related rather mainly to socioeconomic and political issues. Of the limitations outlined above, most were related to economic constraints, lack of incentives, access to information, crop-residue trade-offs, and traditional practices and beliefs. In Central America, institutional support for research on CA and information dissemination has been limited. Though benefits in terms of reduced labor, soil conservation, and increased yields have been demonstrated, small-scale farmers still have limited access to technology due to economic constraints and lack of know-how. Competition for crop residues between animals and soil cover in Central America and the Andean region, as well as in many other regions worldwide, especially rainfed cropping regions, is closely linked to the potential of CA adoption. Future research using participatory methods should aim to find solutions to crop-residue trade-off issues and to make CA more economically viable for small holders.

Future research directions should thus focus on strengthening innovation systems and collaboration among research institutions, NGOs, farmers and farmers' associations, policy makers, input and output market agents, machinery suppliers, etc., in order to create the enabling environment for CA innovation and adoption. Farmer-to-farmer knowledge dissemination has proven most effective suggesting that technology extension efforts should concentrate on facilitating farmer-to-farmer information exchange. Increased knowledge sharing on CA between similar regions of Latin America and the rest of the world could help to accelerate rates of adoption. Adoption of CA, leading to sustainable and soil-conserving farming systems, can become more widespread in Latin America, but will require increased collaboration of stakeholders and attention to socioeconomic, political, and agronomic factors that currently impede adoption.

References

Aapresid (2013) ¿Qué es Aapresid? http://www.aapresid.org.ar/aapresid-2/. Accessed 19 July 2013

Araujo-Junior CF, Rodrigues BN, Chaves JCD, Yada-Junior GM (2013) Soil physical quality and carbon stocks related to weed control and cover crops in a Brazilian Oxisol. In: Soloneski S, Larramendy M (eds) Weed and pest control-conventional and new challenges. InTech, Rijeka, pp 181–205

Arshad MA, Martin S (2002) Identifying critical limits for soil quality indicators in agro-ecosystems. Agric Ecosyst Environ 88:153–160

Basch G, Kassam A, Friedrich T, Santos FL, Gubiani PI, Calegari A, Reichert JM, dos Santos DR (2012) Sustainable soil water management systems. In: Rattan L, Stewart BA (eds) Soil water and agronomic productivity. Boca Raton, CRC, pp 229–288

Buckles D, Ponce I, Sain G, Medina G (1992) Tierra cobarde se vuelve valiente: uso y difusión del frijol de abono (*Mucuna deeringianum*) en las laderas del Litoral Atlántico de Honduras. CIMMYT, Texcoco, pp 1–41

Buckles D, Ponce I, Sain G, Medina G (1993) Uso y difusión del frijol de abono (*Mucuna deeringianum*) en las laderas del Litoral Atlántico de Honduras. Agron Mesoam 4:15–29

Buckles D, Triomphe B, Sain G (1999) Los cultivos de cobertura en la agricultura en laderas. CIMMYT, Texcoco

Busscher WJ, Reeves W, Kochann RA, Bauer PJ, Mullins GL, Clapham WM, Kemper WD, Galerani PR (1996) Conservation farming in southern Brazil: using cover crops to decrease erosion and increase infiltration. J Soil Water Conserv 51:188–192

Calegari A (2009) Alternative land uses and farm diversification strategies to strengthen CA. Lead papers-4th World Congress on Conservation agriculture on innovations for improving efficiency, equity and environment, New Delhi, India, pp 117–121

Calegari A (2010) No-till in southern Brazil. In: Crabtree B (ed) Search for sustainability with No-Till Bill in dry land agriculture. Crabtree Agricultural Consulting, Beckenham, pp 162–178

Calegari A, de Araújo AG, Costa A, Fuentes Lanillo R, Casão Junior R, dos Santos DR (2013) Conservation agriculture in Brazil. In: Jat RA, Sahrawat KL, Kassam AH (eds) Conservation agriculture: global prospects and challenges. CABI, Reading, pp 54–88

Casão-Junior R, de Araújo AG, Llanillo RF (2012) No-till agriculture in southern Brazil: factors that facilitated the evolution of the system and the development of the mechanization of conservation farming. FAO and IAPAR, Rome

CIMMYT (2012) MasAgro. Reporte de Actividades 2011-2012. http://masagro.mx/index.php/es/2012-06-21-17-47-58/documentos

Constantinesco I (1976) Soil conservation for developing countries. FAO, Rome

Derpsch R (1998) Historical review of no-tillage cultivation of crops. JIRCAS working report No. 13. Proceedings of the 1st JIRCAS seminar on soybean research-no-tillage cultivation and future research needs, 5–6 March, Iguassu Falls, Brazil, pp 1–18

Derpsch R (2003) Why and how to use green manure cover crops in a no-till system: experiences from Latin America. South Dakota No-Till Association Conference, 4–5 February, Sioux Falls, SD, pp 43–50

Derpsch R, Friedrich T, Kassam A, Hongwen L (2010) Current status of adoption of no-till farming in the world and some of its main benefits. Int J Agric Biol Eng 3:1–26

Ekboir JM (2002) CIMMYT 2000-2001 World wheat overview and outlook: developing no-till packages for small-scale farmers. CIMMYT, Texcoco

Ekboir JM (2003) Research and technology policies in innovation systems: zero tillage in Brazil. Res Policy 32:573–586

Erenstein O (1997) Are productivity enhancing, resource conserving technologies a viable "win-win" approach in the tropics? The case of conservation tillage in Mexico. CIMMYT, Texcoco, pp 313–322

Erenstein O (2003) Smallholder conservation farming in the tropics and sub-tropics: a guide to the development and dissemination of mulching with crop residues and cover crops. Agric Ecosyst Environ 100:17–37

Erenstein O, Sayre K, Wall P, Hellin J, Dixon J (2012) Conservation agriculture in maize- and wheat-based systems in the (sub)tropics: lessons from adaptation initiatives in South Asia, Mexico, and southern Africa. J Sustain Agric 36:180–206

FAO (2012) CA adoption worldwide. http://www.fao.org/ag/ca/6c.html. Accessed 4 Sep 2013

Flores G, Licona H (1985) Investigación agrícola en campos de agricultores. El caso de Jutiapa, Honduras. Memoria XXXI Reunión Anual del Programa Cooperativo Centroamericano para el Mejoramiento de Cultivos y Animales (PCCMCA), San Pedro Sula, Honduras

Friedrich T, Kassam A (2009) Adoption of conservation agriculture technologies: constraints and opportunities. ICAR, New Delhi, pp 1–14

Friedrich T, Derpsch R, Kassam A (2012) Overview of the global spread of conservation agriculture. FAST Reports Special Issue 1–7

Govaerts B, Sayre KD, Deckers J (2005) Stable high yields with zero tillage and permanent bed planting? Field Crop Res 94:33–42

Govaerts B, Sayre KD, Goudeseune B, De Corte P, Lichter K, Dendooven L, Deckers J (2009a) Conservation agriculture as a sustainable option for the central Mexican highlands. Soil Till Res 103:222–230

Govaerts B, Verhulst N, Castellanos-Navarrete A, Sayre KD, Dixon J, Dendooven L (2009b) Conservation agriculture and soil carbon sequestration: between myth and farmer reality. Crit Rev Plant Sci 28:97–122

Hillel D (1982) Introduction to soil physics. Academic, San Diego

IAPAR (1981) Plantio direto no Estado do Paraná Circular IAPAR, 23. Fundação Instituto Agronômico do Paraná, Londrina, pp 11–17

Kassam A, Friedrich T, Shaxson F, Pretty J (2009) The spread of conservation agriculture: justification, sustainability and uptake. Int J Agric Sustain 7:292–320

Kettler JS (1997) Fallow enrichment of a traditional slash/mulch system in southern Costa Rica: comparisons of biomass production and crop yield. Agrofor Syst 35:165–176

Knowler D, Bradshaw B (2007) Farmers' adoption of conservation agriculture: a review and synthesis of recent research. Food Policy 32:25–48

Lal R (1995) Tillage and mulching effects on maize yield for seventeen consecutive seasons on a tropical Alfisol. J Sustain Agric 5:79–93

Lange D, Meza M (2004) You can do it! Innovative homemade equipment by/for smallholder farmers in conservation agriculture. FAO/GTZ/MAG-Paraguay, Asunción

Levasseur V, Olivier A (2000) The farming system and traditional agroforestry systems in the Maya community of San Jose, Belize. Agrofor Syst 49:275–288

Machado PLOA, Silva CA (2001) Soil management under no-tillage systems in the tropics with special reference to Brazil. Nutr Cycl Agroecosyst 61:119–130

Montgomery DR (2007) Soil erosion and agricultural sustainability. Proc Natl Acad Sci U S A 104:13268–13272

Neill SP, Lee DR (1999) Explaining the adoption and disadoption of sustainable agriculture: the case of cover crops in northern Honduras. Department of Agricultural, Resource, and Managerial Economics, Cornell University, Ithaca, pp 1–27

Nguema A, Norton GW, Alwang J, Taylor DB, Barrera V, Bertelsen M (2013) Farm-level economic impacts of conservation agriculture in Ecuador. Exp Agric 49:134–147

Pereira de Herrera A, Sain G (1999) Adoption of maize conservation tillage in Azuero, Panama. CIMMYT Working Paper No 99-01, CIMMYT, Mexico pp 1–30

Pulleman M, Flores D (2008) Promotion, research and adoption of resource conserving technologies in La Fraylesca, Chiapas, 1980–2008. Report for the CA-CCER, Region Southeast Mexico. CIMMYT, Texcoco

Reyes-Muro L, Camacho-Villa TC, Guevara-Hernández F (2013) Rastrojos: manejo, uso y mercado en el centro y sur de México. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Pabellón de Arteaga, Aguascalientes, México

Romero-Perezgrovas R, Verhulst N, de la Rosa D, Hernández V, Maertens M, Deckers J, Govaerts B (2014) Effects of tillage and crop residue management on maize yields and net returns in the Central Mexican Highlands under drought conditions. Pedosphere 24:476–486

Sain G, Ponce I, Borbón E (1994) Rentabilidad del sistema de abonera en el litoral Atlántico de Honduras. Agron Mesoam 5:30–49

Sayre K, Govaerts B (2012) The principles of conservation agriculture. In: Reynolds MP, Pask AJD, Mullan DM (eds) Physiological breeding I: interdisciplinary approaches to improve crop adaptation. CIMMYT, Texcoco, pp 164–174

Semeato (2013) No Title. http://www.semeato.com.br/home. Accessed 21 Sep 2013

Sorrenson W, Lopez Portillo J, Derpsch R, Nunez M (1997)Economics of no-tillage and crop rotations compared to conventional cultivation cropping systems in Paraguay. 14th ISTRO Conference, agroecological and economical aspects of soil tillage, 27 July–1 Aug, Pulawy, Poland

Swinton SM (2000) More social capital, less erosion: evidence from Peru's Altiplano. Department of Agricultural Economics, Michigan State University, East Lansing, pp 1–19

Teasdale JR, Brandsaeter LO, Calegari A, Skora Neto F (2007) Cover crops and weed management. In: Upadhyaya MK, Blackshaw RE (eds) Non-chemical weed management: principles, concepts and technology. CABI, Reading, pp 49–64

Tisdale SL, Nelson WL, Beaton JD (1985) Soil fertility and fertilizers, 4th edn. Macmillan, New York

van Nieuwkoop M, López Báez W, Zamarripa Morán A, Constantino R, Cruz Chavez FJ, Camas Gómez R, López Martínez J (1994) La adopción de las tecnologías de labranza de conservación en La Fraylesca, Chiapas. CIMMYT, Texcoco

Verhulst N, Govaerts B, Verachtert E, Mezzalama M, Wall PC, Chocobar A, Deckers J, Sayre KD (2010a) Conservation agriculture, improving soil quality for sustainable production systems? In: Lal R, Stewart BA (eds) Advances in soil science: food security and soil quality. CRC, Boca Raton, pp 137–208

Verhulst N, Kienle F, Sayre KD, Deckers J, Raes D, Limon-Ortega A, Tijerina-Chavez L, Govaerts B (2010b) Soil quality as affected by tillage-residue management in a wheat-maize irrigated bed planting system. Plant Soil 340:453–466

Verhulst N, Carrillo-García A, Moeller C, Trethowan R, Sayre KD, Govaerts B (2011a) Conservation agriculture for wheat-based cropping systems under gravity irrigation: increasing resilience through improved soil quality. Plant Soil 340:467–479

Verhulst N, Nelissen V, Jespers N, Haven H, Sayre KD, Raes D, Deckers J, Govaerts B (2011b) Soil water content, maize yield and its stability as affected by tillage and crop residue management in rainfed semi-arid highlands. Plant Soil 124:347–356

Violic AD, Palmer AFE, Kocher F (1989) Experiencias del CIMMYT en labranza de conservación en el trópico bajo de Veracruz, México. In: Barreto H, Raab R, Tasistro A, Violic AD (eds) XI Seminario, Labranza de Conservación en Maíz. PROCIANDINO, El Batán, p 195

Wall PC (1999) Experiences with crop residue cover and direct seeding in the Bolivian highlands. Mt Res Dev 19:313–317

Wall P (2002) Extending the use of zero tillage agriculture: the case of Bolivia. International workshop on conservation agriculture for sustainable wheat production in rotation with cotton in limited water resource areas, 13–18 October, Tashkent, Uzbekistan

Wall PC (2007) Tailoring conservation agriculture to the needs of small farmers in developing countries. J Crop Improv 19:137–155

Chapter 17
Conservation Agriculture in North America

N. C. Hansen, S. Tubbs, F. Fernandez, S. Green, N. E. Hansen and W. B. Stevens

Abstract Conservation agriculture (CA) is a production paradigm that groups reduced tillage, mulching with crop residues or cover crops, and diversified crop rotations, especially those that incorporate leguminous crops. In North America, reduced tillage is the most widely adopted practice that seeks the ideals of CA and adoption rates are increasing. Cover crops are used on a low percentage of cultivated land in North America, but recent efforts to promote the value of cover cropping have resulted in increased adoption rates. Developing cropping systems that use biomass for biofuel systems has potential for expanding the cultivation of cover crops. This chapter illustrates the diversity in CA adoption in North America by describing CA adoption in contrasting production regions with variations in climate, soil types, and cropping systems. Zero-till adoption has been more popular in regions where growing seasons are not limited by cold conditions and with moderate levels of crop residue. Zero-till adoption has been limited by difficulties in seeding and the development of weed resistance to common herbicides. Strip tillage has evolved as an alternative conservation tillage practice and is being adopted widely across North America. Future CA systems will allow for conservation practices, such as tillage intensity, to be applied in a spatially variable way that matches conservation costs and benefits with specific conditions in fields and watersheds.

Keywords Cover crops · Cropping systems · Dryland agriculture · Great Plains · Watersheds

---

N. C. Hansen (✉)
Brigham Young University, 4105 LSB, Provo, UT 84602, USA
e-mail: neil_hansen@byu.edu

S. Tubbs
University of Georgia, P.O. Box 478, Tifton, GA 31794, USA

F. Fernandez
University of Minnesota, Minneapolis, MN 55455, USA

S. Green
Arkansas State University, P.O. Box 1080, Jonesboro, AR 72467, USA

N. E. Hansen
Brigham Young University, Benson 265, Rexburg, ID 83460, USA

W. B. Stevens
USDA-ARS, Sidney Montana, MT 59270, USA

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_17

17.1 Introduction

Conservation agriculture (CA) is a production paradigm that groups reduced tillage, mulching with crop residues or cover crops, and diversified crop rotations, especially those that incorporate leguminous crops. The use and adoption of these practices varies widely throughout North America, but the grouping of these three management systems is not commonly referred to as CA by producers, conservationists, or researchers. The variability in adoption of CA in North America is a function of climate, cropping system, soil type, and socio-economic factors (Pannell et al. 2014). In North America, reduced tillage is the most widely adopted practice that seeks the ideals of CA. For example, maize (*Zea mays* L.) is produced on more than 10,000,000 ha in the USA and about 20 % of the area sown to maize is zero-till (Horowitz et al. 2010). However, the adoption of zero-till varies widely among maize regions in North America. For example, in the Great Plains region, zero-till is practiced on about half of the total maize area in the US state of Kansas (Horowitz et al. 2010). In this semiarid region, zero-till has been beneficial in improving water use in rainfed systems. By contrast, in the US state of Minnesota, maize is extensively cultivated but zero-till adoption is less than 1 % of the sown area (Horowitz et al. 2010). As with other parts of the Upper Mississippi River Basin, cold climate and short growing seasons limit the adoption of zero-till. Conservation tillage, including zero-till, has been widely promoted in the USA by federal government conservation agencies and no-till adoption rates are increasing overall at an estimated rate of about 1.5 % per year (Horowitz et al. 2010).

Cover crops are an increasingly important conservation practice in North America. In the USA, there are currently about 0.8 million ha planted to cover crops. While this is a small percentage of the total cropland, this area experienced about a fivefold increase in the USA between 2008 and 2013 (Werblow and Watts 2013). Organic crop producers have successfully demonstrated how cover crops can be used to suppress weeds, fix nitrogen, and cycle nutrients. The success in organic systems has been a catalyst for adoption in conventional crop production. Federal incentive programs in the USA are currently emphasizing the use of cover crops as an approach to reduce soil erosion and improve overall soil health.

To illustrate the diversity in CA adoption in North America, this chapter provides an overview of several contrasting production regions (Fig. 17.1). For each region, the climate and soil types are described and the typical cropping systems are outlined. An explanation of how CA practices are adopted is given and barriers to further adoption are explained.

17.2 History and Present Status of CA in North America

There has been an evolution of common tillage approaches in North America. In the early twentieth century, most soils were subjected to intense tillage with the moldboard plow as the primary tillage approach. However, reducing fuel use, minimizing

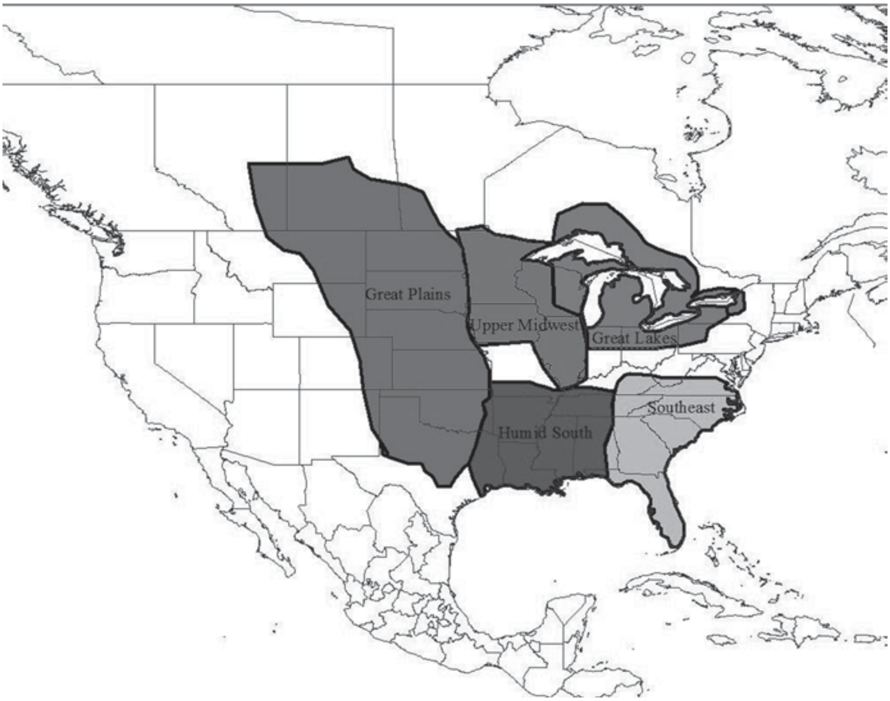


Fig. 17.1 Selected Regions of North America where conservation agriculture is practiced

soil erosion, and improving soil quality have motivated adoption of reduced tillage practices. Conservation tillage systems have been promoted as a component of best management practices for reducing water runoff, soil erosion, and enhancing soil quality (Unger 1990; Hatfield et al. 2001; Holland 2004). Conservation tillage can increase water infiltration rate (Truman et al. 2005; Sullivan et al. 2007), soil water content (Phillips et al. 1980), crop water productivity (Blevins and Frye 1993; Hatfield et al. 2001), soil organic matter (Franzluebbers 2002), and microbial activity (Six et al. 1999) compared to conventional tillage.

Early in the history of no-till and conservation tillage, the major stumbling blocks to adoption of these practices were concerns over weed and pest control limitations of planting equipment to handle crop residues. Technology has evolved to address these concerns, including advancements in herbicide and pesticide technologies as well as improvements in field equipment and plant genetics. As adoption of conservation tillage has grown, weed resistance to common herbicide modes-of-action has increased as a concern for crop producers (Lyon et al. 1996). In addition, insect and pathogens can be more difficult to control as crop producers reduce tillage or discontinue tillage operations in favor of soil conservation and reduced tillage. Other stumbling blocks to adoption of no-till or other conservation tillage practices are prominent in colder climates and are related to planting delays, poor crop establishment, and slow crop growth, which often results in substantial yield reductions

(Buman et al. 2004). This concern is especially important for maize production or high-crop residue rotations, such as continuous maize. As soil and water conservation continue to be a high priority, innovation and technology are needed to address factors that limit adoption of sustainable practices such as CA.

17.3 Regional Experiences with Conservation Agriculture

17.3.1 Dryland Cropping Systems in the Semiarid Great Plains

The US Great Plains is a semiarid agricultural region in a native prairie and steppe landscape. Irrigation is widely practiced when there is access to water resources, but dryland crop production is also extensive. The region extends from Canada in the north to the US state of Texas in the south and is bound by the Rocky Mountains to the west and higher rainfall zones to the east (Fig. 17.1). Most cultivated soils in the Great Plains were formed from loess parent materials, have textures of silt loam, silty clay, and loamy sands (Stewart et al. 2010), and are classified as Mollisols, Entisols, Aridisols, Vertisols, and Alfisols (Aandahl 1982). Annual precipitation increases sharply from west to east, ranging from just 300 mm east of the Rocky Mountains to more than 500 mm on the eastern boundary of the semiarid zone. A major challenge for crop production in this region is the frequency of in-season and long-term droughts, with annual precipitation varying more than 100 % from year to year. While precipitation increases from west to east, there is also a strong increase in potential evapotranspiration (PET) from north to south. Annual precipitation nearly equals annual PET in the northern Great Plains, but PET is nearly four-times greater than annual precipitation in the southern Great Plains. The geographic variation in precipitation and PET strongly influences cropping practices and adoption of CA over the region.

The principle dryland crop in the Great Plains is wheat (*Triticum aestivum* L.). Because of limited and unpredictable rainfall, the traditional rotation is wheat–summer fallow (WF). The WF rotation produces one crop every 2 years, employing a summer fallow to capture and store precipitation. For the southern and central Great Plains, winter wheat is grown and the cropping period is 9 months followed by 15 months of fallow. In the northern Great Plains, spring wheat is grown with the fallow period as long as 21 months. These extended fallow periods, referred to as summer fallow, have been the traditional system for wheat production in the Great Plains since early in the twentieth century. Although WF produces only one crop every 2 years, this rotation gained favor over annual cropping because the summer fallow stabilized yields, reduced crop failure, and improved the annualized grain yield at some locations (Greb et al. 1970; Baumhardt and Anderson 2006).

While summer fallow minimizes the risk of crop failure, there are many sustainability problems associated with extensive fallowing including poor precipitation use efficiency, increased soil erosion, decreased soil organic C and N, and fragile economic returns (Black et al. 1981; Janzen 1987; Campbell et al. 1990; Wienhold et al. 2006). Precipitation storage efficiency during fallow is poor, ranging from approximately 15 to 40 % (Black and Power 1965; Tanaka and Aase 1987; Peterson et al. 1996), with reduced and no-till systems accounting for the higher reported values. To address these problems, there has been an evolution of tillage and residue management practices for dryland cropping systems in the Great Plains that has reduced the number and type of tillage operations (Lyon et al. 2004). Specific tillage methods used in WF rotations vary, but a common approach is to use multiple, shallow tillage passes using wide blades or sweeps to control weeds during summer fallow and chisels or disks for seedbed preparation. The development of cost-effective herbicides and good planting equipment has facilitated the adoption of zero-till systems by an increasing number of producers. Zero-till systems eliminate all soil disturbing operations other than planting, increase precipitation capture and storage, and allow intensification of the crop rotation. Thus, zero-till adoption is the first step towards developing a CA system in the Great Plains environments.

Intensified dryland crop rotations employed with zero-till in the Great Plains reduce the frequency and change the timing of fallow periods. The adoption of these CA systems varies regionally in the Great Plains. In the northern Great Plains, zero-till increased from less than 5 % of total dryland in 1989 to nearly 25 % in 2004 (Fig. 17.2; CTIC 2011) to nearly 60 % in recent years (Hansen et al. 2012). Adoption of no-till practices has been less in the higher PET areas of the central and southern Great Plains where there is less flexibility in crop choice and crop rotation. In the central Great Plains, no-till has increased from 5 % of the dryland areas in the early 1990s to more than 20 % in recent years (Hansen et al. 2012; Fig. 17.2). In parts of the southern Great Plains, adoption of no-till is less than 5 % of the dryland area (Hansen et al. 2012). In these southern areas, biomass production in dryland

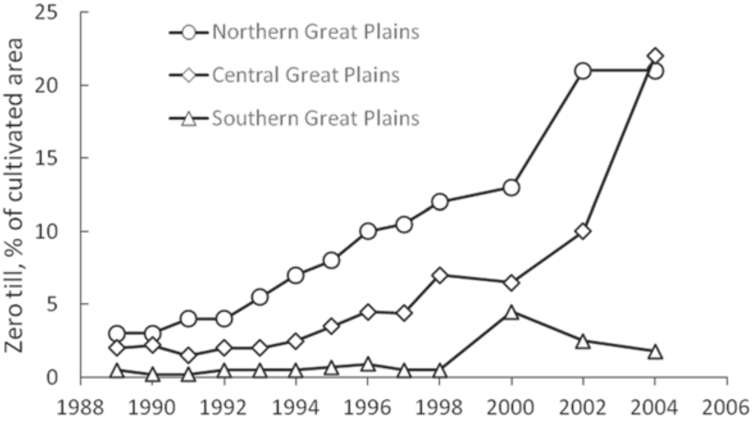


Fig. 17.2 Zero-till adoption in the northern, central, and southern Great Plains in the USA from 1989 to 2004. (Source: Conservation Tillage Information Center, Purdue University, West Lafayette, IN)

areas can be so limited that there is not enough crop residue to conserve soil water under no-till practices. Further, grazing of winter annual forage crops is typical in the southern region, which can lead to soil compaction that requires tillage to alleviate the problem. These regional differences clearly illustrate how climate factors influence the potential adoption of CA.

Intensification of the WF rotations has accompanied adoption of zero-till due to improved soil water capture and storage (Aase and Siddoway 1980; Aase and Reitz 1989; Cochran et al. 2006). In the northern Great Plains, zero-till farmers have converted the traditional WF to annual crop rotations without a summer fallow period. The most common CA rotations in the northern regions replace the summer fallow period with pulse and oilseed crops (Zentner et al. 2002). In the central Great Plains, CA rotations have not eliminated summer fallow, but have reduced fallow frequency to every third or fourth year. A typical 3-year CA rotation is winter wheat–summer crop–summer fallow with maize, sorghum (*Sorghum bicolor* [L.] Moench ssp. bicolor), sunflower (*Helianthus annuus* L.), and proso millet being common summer crops. There has been little success incorporating a pulse crop in the central Great Plains, but current efforts are exploring options. In the hotter and drier southern Great Plains, the most common CA crop rotation is wheat-sorghum summer fallow.

Use of green manures and cover crops in CA systems has been limited in dryland systems of the Great Plains. The greatest adoption of green manures and cover crops has been in the northern Great Plains, where leguminous green manures have been used to reduce fertilizer N requirements (Pikul et al. 1997; Zentner et al. 2004; Miller et al. 2006). In the central and southern regions, the competition for soil water by cover crops has limited their adoption. Research in these areas has shown that cover crops in lieu of fallow can adversely affect subsequent wheat yields due to soil water depletion (Vigil and Nielsen 1998; Nielsen and Vigil 2005).

CA systems have increased the productivity of dryland cropping systems in the Great Plains. Zero-tillage increases water use efficiency of spring wheat (Cutforth and McConkey 1997), oilseeds (Cutforth et al. 2006), and pulse crops (Cutforth et al. 2002). Cochran et al. (2000) found that the total production of continuous spring wheat was about 25 % greater than a spring wheat–summer fallow rotation in a long-term study in NE Montana initiated in 1984. Wheat-based rotations with crops like pea (*Pisum sativum* L.) or lentil (*Lens culinaris* Medic) increased the wheat yield by 25 % compared with continuous wheat (Allen et al. 2010; Miller et al. 2003). In the central Great Plains, intensifying the cropping systems using CA has increased annualized grain yield by more than 75 % relative to the yield of the WF system (Peterson and Westfall 2004). These yield increases have translated into 25–40 % gains in net income for farmers (Kaan et al. 2002). CA systems have had positive impacts on soil physical and chemical properties including decreased bulk density of the surface soil layer, increased total porosity, and increased effective pore space (Shaver et al. 2002). In a long-term study, Sainju et al. (2009) reported that zero-till annual cropping systems for spring wheat reduced the potential for soil erosion, improved soil quality, and increased soil organic matter compared to conventionally tilled spring wheat–summer fallow.

17.3.2 Irrigated Cropping Systems in the Semiarid Great Plains

Irrigated crop production systems are highly developed in the semiarid climate of the Great Plains. Irrigation substantially increases crop yield potential and decreases the risk of crop failure during periods of drought, especially for full-season crops such as maize and alfalfa (*Medicago sativa* L.) or relatively high-value crops such as potato (*Solanum tuberosum* L.) or sugar beet (*Beta vulgaris* L.). Irrigation, however, depends on the availability of surface or subsurface water resources, which are scarce in the semiarid Great Plains. As a result, irrigation is practiced on only about 7 million ha in this region (NASS 2012). Principal sources of irrigation water are (1) the upper Missouri River, (2) the Platte River, (3) the Arkansas River, and the High Plains (Ogallala) Aquifer. Soils under irrigation are usually highly productive, but their characteristics vary widely, ranging from loess or glacial till in upland areas to mixed alluvium in the river valleys.

Maize is the most common irrigated crop in the semiarid Great Plains and is grown on more than 2.4 million ha. Alfalfa and other hay crops, wheat, grain sorghum, cotton (*Gossypium hirsutum* L.), soybean (*Glycine max* [L.] Merr.), sugar beet, malt barley (*Hordeum vulgare* L.), potato, dry edible bean (*Phaseolus vulgaris* L.), and many other minor crops are also grown with irrigation. Rotation diversity varies throughout the region from continuous maize or perennial hay crops to 3- or 4-year rotations including combinations of the previously listed crops. Often, when a single crop with relatively high economic return is grown in an area, producers will grow that crop as often as possible to maximize economic return, with maize produced for grain as the most common crop in continuous rotations. While economic factors often favor continuous maize production, it is well established that most crops benefit from rotation diversity. It is often attractive for producers to diversify their rotations by adding annual legume crops such as dry bean or soybean to maize rotations. Further, rising costs and environmental risks associated with commercial N fertilizers make it attractive to adopt practices that utilize nonfertilizer sources of N and it is well-documented that including legumes in rotation with nonlegume crops reduces the commercial fertilizer N requirement (Burgess et al. 2012).

There is ample opportunity to implement principles of CA in irrigated cropping systems of the semiarid Great Plains. The earliest development of irrigation in the Great Plains used surface water that was spurred by construction of water storage reservoirs and distribution canals beginning in the late nineteenth and early twentieth century. Most early irrigation projects involved surface irrigation practices (furrow, flood, etc.) that were not conducive to CA. Beginning in the 1930s, pumping and sprinkler irrigation technology advanced and more sprinkler systems were installed and the most extensive irrigation in the Great Plains is center-pivot sprinklers fed by water pumped from the High Plains Aquifer. Sprinkler irrigation now makes up more than 70 % of the irrigated land in the Great Plains.

A current factor driving adoption of CA is water scarcity. Increased irrigation in the semiarid Great Plains has led to declining groundwater supplies. For example, irrigation wells in the central and southern Great Plains of the USA that tap the High

Plains Aquifer have led to declining water levels in the aquifer. While the overall decline is less than 10% of the original water storage, there are some southern areas of the aquifer where only about half of the original saturated thickness remains, leading to an estimated 35% of the southern High Plains unable to economically pump water for irrigation within 30 years (Scanlon et al. 2012). Further, competition for surface and groundwater among agriculture, municipalities, industries, recreation, and environmental uses is driving scarcity and the need for improvements in water use efficiency. CA is being implemented to maintain crop residues at the soil surface, leading to more efficient capture and use of precipitation, thus reducing the demand for irrigation water. Similarly, crop rotations that reduce the frequency of high water use crops such as maize and alfalfa (*Medicago sativa* L.) are becoming more common.

No-till innovation and adoption has been fostered through local organizations that bring together producers, equipment companies, and scientists that work together to solve challenges associated with no-till. For example, the organization called *No-till on the Plains* demonstrates consistency with the principles of CA, stating their purpose to education of "several key components including high-quality continuous no-tillage with invisible sowing methods, undisturbed previous crop residue or growing a living mulch between cash crops, and diverse crop rotations along with planned, managed grazing of livestock (www.notill.org)." The organization hosts an annual conference and trade show, symposia, and field day events, publishes a trade-oriented magazine, and maintains a website (www.notill.org). Other organizations with similar goals are instrumental in promoting CA in the Great Plains (Table 17.1) and throughout North America. Most of the organizations are led by a board of volunteers who are committed to forwarding soil conservation and sustaining agriculture.

While zero-till adoption has increased, many irrigated producers have been reluctant to adopt no-till due to challenges associated with high levels of residue, weeds, disease, and insect pressure. Abundant crop residues produced by some crops (e.g., maize) under irrigation may interfere with planting operations or may inhibit seedling emergence due to reduced springtime soil temperatures or physical interference. Some farmers remove crop residues in order to address these and other concerns.

Strip tillage is a conservation tillage system that is gaining popularity as an alternative to zero-till in the Great Plains. Strip till seeks to combine attributes of both conventional tillage and zero-till. In this system, a narrow band of soil (15–25 cm) is tilled to a depth of about 10–20 cm where the row crop will be established while the soil and crop residue in the inter-rows (50–60 cm) remains in a no-till condition (Farmaha et al. 2011). The system provides soil and water conservation similar to a zero-till approach, and also overcomes some of the seedbed limitations associated with zero-till (Vyn and Raimbault 1992; Jones et al. 1994; Morrison 2002; Randall and Vetsch 2008; Farmaha et al. 2012; Fernández and White 2012). Strip till is often used to subsurface apply nutrients such as phosphorus and potassium, which otherwise tend to accumulate in the soil surface in no-till fields (Holanda et al. 1998; Fernández and Schaefer 2012). Strip till requires specialized equipment and greater operator skills, not only to till the strips, but to match the strip with the planter and

Table 17.1 Organizations in the US Great Plains region that promote the adoption of conservation tillage practices with their mission statements and activities

Organization	Mission statements and activities	Website
Colorado Conservation Tillage Association	Mission: "To facilitate the exchange of ideas to preserve our agricultural soil and water resources for generations by providing a system which drastically reduces soil erosion, conserves soil moisture, and builds organic matter"	www.highplainsnotill.com
	Regular activities: Annual conference, newsletter	
No-till on the Plains	Mission: "To provide education and networking on agricultural production systems that model nature"	www.notill.org
	Regular activities: Annual conference, symposia, magazine	
Panhandle No-till Partnership	Mission: "To help arm producers with educational support, knowledge, and practical use techniques for continuous no-tillage cropping practices"	www.panhandlenotill.org
	Regular activities: Annual conference, field day events	
Manitoba-North Dakota Zero-Till Farmer's Association	Mission: "To preserve our agricultural soil resource for future generations by promoting a system of crop production which drastically reduces soil erosion and builds up organic matter"	www.mandakzerotill.org
	Regular activities: Field tours, workshops	
South Dakota No-Till Association	Mission: "To promote, advance, and improve agriculture through the utilization of no-till farming methods"	www.sdnotill.com
	Regular activities: workshops, soil health challenge	

other field equipment. It has been most successfully adopted in association with precise global positioning system-based guidance mechanisms. In the Great Plains, strip till has recently been applied successfully to sugar beet production (Overstreet 2009; Evans et al. 2010). Jabro et al. (2011) reported that bulk density was lower and infiltration greater in sugar beet grown with strip tillage than when grown with conventional tillage. This difference was attributed to differences in soil compaction resulting from vehicular traffic, which can be five to seven times greater with conventional tillage than with strip tillage.

17.3.3 Rainfed Cropping Systems in the Upper Minnesota River Basin

The Upper Minnesota River Basin is an important agricultural region in North America and a major part of the region known as the US corn belt. The region is primarily comprised of land in four US states, Illinois, Iowa, Minnesota, and western Wisconsin (Fig. 17.1). Most cultivated soils in this region formed from loess or glacial till parent material, and soil textures in agricultural fields range from sand in the central part of Minnesota to silt loam and silty clay loam in most of Illinois, Iowa, southern Minnesota and western Wisconsin. One of the most distinctive characteristics of the region is the prevailing deep and fertile soils with high organic matter content in a relatively level landscape. The dominant soil orders in agricultural production areas are Mollisols and Alfisols. The southern third of Illinois is characterized by older soils that were not affected by the last glaciation (Wisconsinan glaciation) approximately 11,000 years ago and have lower productivity and a subsurface claypan that makes them less permeable. In general, soils become more alkaline from east to west as calcium carbonate concentrations increase. The region has a substantial precipitation gradient that decreases from south to north and from east to west. Mean annual precipitation in southern Illinois is above 1200 mm and in northwestern Minnesota is about 450 mm. Annual mean temperatures also decrease from south to north with approximately 14 °C in southern Illinois to less than 2 °C in northern Minnesota. The temperature variation has a large influence on the adoption of CA, with much less adoption of zero-till practices in the colder zones. In general for the region, wet and cool soil conditions in early spring become increasingly predominant from south to north. The adoption of zero-till for maize production follows this pattern, decreasing from south to north reflecting the challenge for zero-till maize production under wet and cool soil conditions.

The two most-extensively cultivated crops in the Upper Mississippi River basin are maize and soybean, representing 89 % of all cropland. The most common crop rotation is a 2-year rotation of maize and soybean. In recent years, mostly induced by favorable maize prices and increasing maize demands for ethanol production, there has been an increase in continuous maize or 2 years of maize followed by 1 year of soybean. Lesser crops in the region are wheat and alfalfa. In southern areas of this region, where wheat harvest is sufficiently early in the growing season, a second crop of soybean is often produced in the same growing season.

Among the CA practices, conservation tillage has been the most widely adopted practice in this region. Reducing soil erosion by water has been the primary motivation for adoption of conservation tillage practices. Another important reason for implementation of conservation tillage practices in the region is the benefit of reduced labor and equipment costs associated with these practices. Although conservation tillage approaches are common, adoption of continuous zero-tillage in the upper Mississippi basin is only 13 % of cultivated land (Horowitz et al. 2010). The primary limitation to the adoption of zero-tillage is that crop residues create an insulation layer and greater albedo of crop residue compared to tilled soil, which reduces water evaporation and warming of the soil (Horton et al. 1996). These are important concerns in this region where soils are cool and normally saturated with water early in the spring. Reduced water evaporation can delay field operations for planting and wet soils are slower to warm up in the spring, which can cause problems with seed germination and root development. Further, cool soils can slow down important processes of sulfur and nitrogen mineralization from the soil organic matter and reduce their availability to the crop. In general for the region, wet and cool soil conditions in early spring become increasingly predominant from south to north. The adoption of zero-till for maize production follows this pattern, decreasing from south to north reflecting the challenge for zero-till maize production under wet and cool soil conditions. Most maize is planted after primary tillage with chisel plowing in the fall followed by secondary shallow tillage, such as field cultivation, to prepare the seedbed in the spring. In most cases, this approach is still classified as conservation tillage because the fall chisel plow leaves a rough surface and sufficient crop residue on the soil surface to reduce soil erosion concerns. Maize grain yield is affected by tillage system, but the effect varies according to soil and climate factors. Typically, maize yield tends to be equal or slightly higher in no-till than conventional tillage systems in well-drained soils, soils with considerable slope (5 % or greater), soils with low organic matter, or when dry conditions develop during the growing season. The yield advantage is mostly the result of water conservation benefits with zero-till. On the other hand, maize yields tend to reduce with no-till relative to tilled fields in the predominant soils of the region: poorly drained fine-textured soils with high organic matter content and minimal slope (Simmons and Nafziger 2009). In contrast to maize, soybean is often planted directly on the maize residue, and is often referred to as zero-till soybean. While soybean is planted without tillage, the maize–soybean rotation is not a zero-till system. The reason soybean is often planted directly without prior tillage operations is that this crop is planted later in the spring relative to maize, so the soils are normally drier and warmer than when maize is planted. However, recent research also indicates that there might be seed yield advantages for early soybean planting (De Bruin and Pedersen 2008). It is possible that similar concerns to those for maize production exist for early-planted soybeans in no-till or conservation tillage systems.

Strip tillage is also emerging as an alternative to zero-till in the Upper Mississippi River Basin (Farmaha et al. 2011; Fernández and White 2012). In contrast to the semiarid Great Plains region, strip tillage in this region is best when done in the fall rather than spring because soil conditions tend to be drier and there is less concern for sidewall smearing in the soil or formation of large clods. Fall tillage also exposes soil in the tilled strip to the freezing and thawing, which is perceived to create a more “mellow” seedbed. A significant limitation for strip tillage in the Upper Mississippi River Basin is the common rolling topography. Strip tillage is best suited for flat fields as tillage strips in the direction of the slope can create a channel for water to flow and cause substantial soil erosion.

17.3.4 Rainfed Cropping Systems in the Great Lakes Region

Situated at the border of the USA and Canada are five large, fresh water lakes (Lakes Superior, Erie, Huron, Michigan, and Ontario) collectively referred to as the Great Lakes region, which encompass parts of eight US states and the Ontario province of Canada (Fig. 17.1). The region has a subhumid, temperate climate. Annual precipitation varies from 840 mm in the northwest to 1100 mm in the southeast

(Harstene 1991), which is similar to the wetter parts of the Upper Mississippi River Basin. In most years, precipitation is sufficient to meet crop water requirements of rainfed agronomic crops. Irrigation is used to support some fruit and vegetable crops, which are more sensitive to lack of soil moisture than agronomic crops. One distinguishing feature of this region is in winter when dry cool air masses from Canada's northwest pick up heat and moisture when passing over the ice free lakes. The moisture precipitates as snow over the downwind land masses and can lead to significant snowfall in areas known as the Snowbelt (USEPA 1995). Further, annual temperatures are moderated by the latent heat of the massive freshwater bodies, which extend the frost-free periods and provide a climate conducive for some crops that otherwise could not persist at these northern latitudes, such as grapes (Dami et al. 2005). Soil genesis in the Great Lakes region is strongly affected by glacial activity during past ice ages (USEPA 1995). Several soil orders can be found in the region, but Alfisols dominate followed by Mollisols.

In the Great Lakes region, maize, soybean, hay crops, and wheat are planted on the majority of cropland (OMAFRA 2013; USDA 2009). A variety of other economically important field and vegetable crops are produced, but on much less area. Similar to the Upper Minnesota River Basin, a maize–soybean rotation is commonly practiced throughout the region. Soybeans may be planted as a double crop after wheat is harvested if the growing conditions are favorable. Forage crops are significant in the region and include alfalfa and silage maize. A developing forage practice is to plant winter cereal grains (i.e., wheat, triticale) after maize silage as a double-cropping system. The winter cereals are harvested as forage in late fall or spring as supplemental feed for the operation (Dustin Ramsier, personal communication, 29 January 2014).

One factor motivating the need for CA is the loss of sediment and nutrients in runoff from cropland and the resulting water quality degradation. Erosion is most likely to occur during winter and spring months when soils are either bare or covered with decomposing crop residue rather than summer or fall when cropland is covered by growing plants or recent crop residues (Richards et al. 2007). In the late 1970s, Wall et al. (1982) reported that cropped land contributed 70–100 % of sediment loads in basins in southern Ontario resulting in an estimated 5.9×10^5 Mg year^{-1} of sediment to the Great Lakes. Since then, adoption of conservation tillage and other erosion control practices has been widely promoted in this region. In northwest Ohio, sediment loading of Lake Erie declined during a 30-year period ending in 2005 (Richards et al. 2007).

Subsurface and surface losses of nitrogen and surface losses of phosphorus from cropland in the Great Lakes drainage basin are also of major concern. Improved surface and subsurface drainage systems increase the transport of nutrients from cropland to streams that drain into the Great Lakes (Gilliam et al. 1999). Addition of phosphorus to the Great Lakes has caused considerable negative impacts in the past. Historically and in recent years, Lake Erie has been severely impacted by eutrophication due to phosphorus loads in agricultural runoff (Kleinman 2012). Phosphorus loading to Lake Erie declined as crop producers shifted from conventional to conservation tillage practices and reduced total phosphorus in runoff (Sharpley et al.

2013). However, one challenge associated with reduced tillage is the stratification of applied phosphorus in the surface soil horizons, which can increase the risk of dissolved phosphorus loss in runoff to the Great Lakes.

Adoption of conservation and reduced tillage practices varies by region and crop. In the more southern parts of the region, no-till adoption represents 47 % of cropland, while in the more northern areas, no-till is about 20 % of cropland. The more broadly defined conservation tillage represents 60 and 30 % of cropland for the same areas, respectively (Horowitz et al. 2010). When the same data are considered over the entire region by crop, zero-till is used on 20 % of maize and 65 % of soybean. Similar to the observations for the Upper Mississippi River Basin, these statistics clearly do not illustrate zero-till over the full crop rotation.

Less data are available about the adoption of cover crops, but in general they are used on a small percentage of cropland. When used, cover crops are most often planted between maize and soybean in the 2-year rotation. Generally, crop producers appear to prefer planting a single species, which may be winter cereal grains, legumes, brassicas, and annual grasses in decreasing order of preference (Werblow and Watts 2013). Less than 20 % of crop producers are planting two or more species in a cover crop mix.

Maize and soybean crop yields are slightly lower when crop producers practice CA in the Great Lakes region compared to conventional tillage practices (DeFelice et al.). The yield reduction is greater in poorly drained soils than well-drained soils. Yet, the benefit of zero-till management is the reduction in overland flow, sediment, and chemical transport from cropland (DeLaune and Sij 2012). Crop producers are less likely to contribute nonpoint pollutants to streams and lakes when erosion and runoff are minimized through conservation tillage practices. The benefits of cover crops in CA systems continue to be reported. Cover crops are grown to secure the soil during winter and spring months, reduce nutrient loss, and provide forage for animals. Fae et al. (2009) reported that cover crops planted after silage maize in Ohio did not negatively affect the following maize yield, and crop producers harvested the crop as supplemental forage. Similarly, many researchers find that cover crops do not negatively affect yields in the following crops in this region (Heatherly and Elmore 2004; Wortman et al. 2012). The benefits of cover crops are reduced surface runoff, increased infiltration and percolation of precipitation, increased soil organic carbon, improved soil structure, secured nutrients, and addition of nitrogen to soils when a legume is used (Frye et al. 1988).

In a survey of crop producers in Ohio, Sundermeier et al. (2009) evaluated how producers make decisions about farming practices. They reported crop producers adopted conservation practices based on observing other crop producers and reading popular press publications. Nearly 75 % of those surveyed who have adopted conservation tillage identified decreased inputs (time, labor, expense) as their primary reason for adopting CA and about 67 % also indicated protection against erosion as a motivating factor. In addition, the justification for adopting CA systems may need to focus on the financial implications of conservation practices rather than focusing on ecological impacts or values (Long 2003).

17.3.5 Rainfed Cropping Systems in the Humid Southeast

The south and southeastern regions of the USA consists of vast land areas of forests, woodlands, agricultural lands, and urban areas. The vast agricultural land area is diverse in soil types and agricultural commodities produced. From fruits and vegetables to timber, grazing and row crop production, the southern region is a productive agricultural region. The southern USA has a warm and humid climate that allows diversity of production as well as a mild winter allowing production of various crops in the winter season as well as the summer season. CA in the southeastern USA has been adopted mostly in row crop production. Summer agronomic crops such as maize, cotton, peanut (*Arachis hypogaea* L.), and soybean are the most widely grown. The traditional tillage practice in this region is based on soil inversion with a moldboard plow. Plowing is still a common practice. Heavy rainfall events can occur in spring in this region, which can cause fields to washout and erode drastically when a cover crop is not in place. CA systems that minimize soil erosion save time and operation costs associated with preparing land for planting. Severe erosion is a serious concern for the long-term sustainability of farming where soils are plowed. Additionally, plowing can create hardpans in the coarse-textured, sandy soils common in the region. Hardpans typically form immediately below the impact point where the bottom of the plow glides across the soil profile, usually 25–30 cm depth. Downward pressure from the weight of the implement forces the soil to compact at that depth, which becomes very difficult for roots to penetrate.

CA systems for row crops in this region of the USA emphasize the use of conservation or zero-till systems. Adoption of zero-tillage has been quite limited, but there has been better adoption of other forms of conservation tillage. In cotton, for example, zero-till is rare but strip tillage has been widely adopted. In a strip-till-based CA system, a winter cover crop is established in the fall (September through November). Common cover crops are rye (*Secale cereale* L.) and wheat, or crimson clover (*Trifolium incarnatum* L.) if a leguminous cover crop is preferred. Vetch (*Vicia villosa* L.) is another legume that has increased in popularity in recent years. Grass cover crops are most common because of more rapid growth in the fall prior to cold temperatures, providing better surface cover for weed suppression and erosion prevention into the winter. Crimson clover has gained some popularity preceding maize or cotton because of the added benefit of supplemental nitrogen. Strip tillage is performed, typically to a depth of 30–45 cm deep. This often results in around 10–30 % disruption of the soil surface and the rest of the surface is not tilled. Strip tilling uses a subsoil shank that is deeper than typical compaction layers and can fracture through a hardpan, allowing easier root penetration for exploration of water and nutrients through the soil profile. A deeper root system also reduces the chance of lodging with taller, upright growing crops like maize and cotton. Zero-till is more common in soybean production than for cotton and is practiced on about half of the cultivated land in the state of North Carolina. In recent years, herbicide-tolerant weeds have emerged as a significant problem in this area, leading to more tillage.

In addition to improved root penetration, there are numerous benefits to zero-till or conservation tillage systems in this region. These include improved soil organic matter and tilth, reduced mechanical power demand and fuel costs, and reduced labor expenses. Other benefits are often unseen and overlooked and include erosion control and more diverse agroecosystems. For peanut, there can be both advantages and disadvantages to using either conservation or conventional tillage. Some benefits gained from turning the soil include physical weed control of emerged seedlings, warming the seedbed for quicker crop germination, and burial of surface residues containing pathogens and other pests. Negative impacts include soil erosion as previously discussed, new weed seed brought to the soil surface, and rapid drying of the soil. One of the greatest in-season benefits of strip till is the fact that the surface residue from a cover crop disrupts the feeding behavior of thrips on peanut foliage, which also reduces infection of tomato spotted wilt virus (TSWV). However, the release of some highly resistant cultivars to TSWV has minimized this benefit compared to more susceptible varieties. Therefore, tillage operations should be evaluated consistently. There are some long-term benefits from using strip till (especially when considering rotations and cropping systems as a whole) that may outweigh the immediate gains of using conventional tillage (greater seed–soil contact and warmer soil temperatures at planting, raised beds for easier digging, etc.). If the same yields and grades can be achieved with fewer inputs, then both the producer and sustainability of the environment will benefit from reduced tillage systems.

Although this humid region has high annual precipitation (1000–2000 mm), there are key times during the growing season when dry conditions can prevail. The most common argument against using cover crops in CA systems in the southeastern USA is that there is not adequate soil moisture available to the seed during planting of the summer crop in nonirrigated growing conditions. The use of available water in the soil profile throughout winter by growing cover crops can deplete the soil during a time when it is most crucial for moisture to be present. However, if a crop can be established with timely rainfall or irrigation, then the cover crop residue on the soil surface helps to retain soil moisture throughout the remainder of the growing season by reducing evaporation and capturing and holding more water in the soil.

Some producers have experimented with growing a winter grain crop to gain the advantages of a cover crop and an additional grain harvest. However, since wheat harvest is not usually completed until mid- to late May and most of the high-value summer crops have ideal planting times around that time or earlier, there is a time constraint for getting fields prepared rapidly for double cropping. Most farmers prefer to optimize timing of their primary cash crop (the summer crop) rather than risk late planting in order to complete a preceding winter grain crop. In some cases, a planted wheat crop originally designed for carrying to grain harvest may be terminated and used as a cover crop in order to allow for earlier planting of the summer crop, especially true in nonirrigated systems.

An example of a successful CA system in southeastern US cropping systems is an integrated sod-based-row-crop rotation. Perennial pasture grasses grown for high biomass yield make up the sod component of the rotation. Bahiagrass (*Paspalum notatum* Flüggé) is extensively grown in the southeast because of its adaptability to a wide range of soils and climatic conditions, ease of establishment and termination, and low-maintenance management because of characteristics like low fertility requirement, tolerance to drought and close grazing, and minimal concern of disease and insect infestation. It functions well in rotation with most row crops in the southeast since it is a nonhost for most pathogens that affect the major row crops. The rooting of bahiagrass aids in water infiltration, development of soil organic matter, and increasing earthworm populations. Row crops in this CA rotation have reduced early and late leaf spot (*Cercospora arachidicola* and *Cercosporidium personatum*, respectively) diseases in peanut, decreased southern blight/stem rot/white mold (*Sclerotium rolfsii*) in peanuts and cotton, and reduced thrips (*Flankliniella fusca*), leading to less TSWV (*Tospovirus*) in peanuts and tobacco. In addition, it is reported that peanut and soybean root-knot nematode (*Meloidogyne* spp.), reniform nematode (*Rotylenchulus reniformis*), and soybean cyst nematode (*Heterodera glycines Ichinohe*) infestations may decline following bahiagrass since it is a nonhost to these pests (Johnson et al. 2000; Katsvairo et al. 2006). Collectively, these factors can result in savings from reduced inputs such as a less frequent need for irrigation, elimination of one or more fungicide spray events, and potentially reduced applications of expensive specialty herbicides due to bahiagrass outcompeting weeds.

17.3.6 Bioenergy Cropping Systems in the Humid South

The southern USA has a humid climate much like that described for the southeast region of the country. Many crop production practices related to CA are similar, as are the challenges such as soil erosion and degradation. For many years, agricultural soils in the region have provided food, feed, and fiber. More recently, there has been an interest for these soils to provide feedstocks for the production of biofuel, both for co-firing and for liquid transportation fuels. While many traditional summer annual crops, such as maize and soybean, have been used in bioenergy production, the focus here is to illustrate how winter bioenergy crops and perennial bioenergy crops can be integrated with traditional row crops in a CA system. Bioenergy cropping systems can provide many conservation benefits while providing farm revenue.

Both perennial biomass crops and winter annual bioenergy crops can provide some conservation benefits in a CA system that may otherwise leave fields fallow in the winter. Table 17.2 contains a list of examples of bioenergy crops being explored in the south and southeast regions of the USA. The crops are presented in categories of perennial biomass, winter annual oilseed, and winter annual sugar. Bioenergy crops provide an opportunity not only to diversify the energy portfolio but also to diversify crops and crop rotations.

Winter annual crops can provide some of the same benefits as cover crops, yet provide a harvestable product. Some advantages of growing crops over the winter include physical protection of the soil, growing roots that provide microorganism habitat, break-up of compaction layers by roots of different depth/morphology than the summer crop, and addition of organic matter from the winter crop residues. The combination of these plant growth activities improves aggregate stability, enhances

Table 17.2 Bioenergy crops being evaluated for production in CA systems in the US south and southeast regions

Energy crop	Reported yield	Citations
Perennial biomass crops	*Dry biomass yield (Mg ha^{-1})*	
Switchgrass (*Panicum virgatum*)	5–18	Angima et al. 2009; Heggenstaller et al. 2009
Miscanthus (*Miscanthus* x *giganteus*)	15–25	Lewandowski et al. 2000
Eastern gamagrass (*Tripsacum dactyloides*)	5–10	Angima et al. 2009; Heggenstaller et al. 2009
Big bluestem (*Andropogon gerardii*)	6–12	Angima et al. 2009; Hall et al. 1982; Heggenstaller et al. 2009
Little bluestem (*Schizachyrium scoparium*)	6	Angima et al. 2009
Indian grass (*Sorghastrum nutans*)	7–18	Angima et al. 2009; Heggenstaller et al. 2009
Reed canarygrass (*Phalaris arundinacea*)	9–16	Cherney et al. 2003; Lamb et al. 2005
Winter oilseed crops	*Seed yield (kg ha^{-1})*	
Camelina (*Camelina sativa*)	675–1700	Gesch and Archer 2013
Rapeseed (*Brassica napus*)	2200–3900	Gascho et al. 2001; Slaton et al. 2011
Winter sugar crops	*Wet yield (Mg ha^{-1})*	
Energy beet (*Beta vulgaris*)	128	Scully and Webster 2012

CA conservation agriculture

natural nutrient cycling and infiltration, and overall maintains a healthy soil. Two winter oilseed crops gaining interest in the south for bioenergy production are camelina (*Camelina sativa* L. Crantz) and rapeseed (*Brassica napus* L.), both in the Brassicaceae family. Both of these winter crops are cold tolerant and, in most years, can be grown successfully in the southern region over winter, whereas in northern climates, these are summer crops. The oil from these crops can be used to produce biodiesel and other specialty lubricants. These crops, when drilled with narrow row spacing, provide good groundcover over the winter months. The seed germinates quickly, can be planted into late fall, and has a growth pattern that provides good soil coverage even early in the growing season. When cold weather commences, the plants remain relatively dormant in the rosette stage, until the early warming when the plants begin growing again. They grow additional leaves in the rosette and then bolt, flower, and put on seeds in a relatively short time period. Both camelina and rapeseed can be planted in zero-till CA systems. After harvest, the crop residue is easily planted with the summer crop, as early as May, in the case of camelina and June for rapeseed in the mid-south region. The potential delay in planting the summer crop is one of the barriers to adoption of the bioenergy CA system.

Another winter bioenergy crop beginning to emerge in the southern USA is energy beet. Preliminary data suggest that energy beets can be grown in the humid south as a winter crop, providing potential for both revenue and soil protection.

The leaves of energy beets provide good canopy cover and the roots take up excess nutrients, thus protecting the soil from raindrop impact as well as reducing water quality impairment from leaching. A study in Georgia produced up to 128 Mg ha^{-1} of raw energy beets (Scully and Webster 2012).

Perhaps the most promising CA bioenergy systems come from the production of biomass crops. These crops, including but not limited to switchgrass, big bluestem, eastern gamagrass, and Indiangrass are historical mainstays of conservation plantings. These crops are native, warm-season perennials of the southern prairies. They are deep rooted (> 1.5 m), bunch grasses developing dense stands that produce high biomass (switchgrass yielded up to 23 Mg ha^{-1} in a Tennessee study (Mooney et al. 2009) and 26 Mg ha^{-1} in an Alabama study (Bransby and Sladden 1991), grow rapidly, are drought tolerant, and very adaptable to the variations of climatic conditions in the south (Sanderson et al. 1996). These native warm-season grasses can provide excellent habitat for nesting birds (Meehan et al. 2010, Robertson et al. 2011). These biomass grasses provide excellent erosion control. When drilled at planting, these biomass plantations provide dense strips of bunch grasses in narrow rows that expand their coverage over the years. Even when harvested as biomass in the late fall, early winter, 10–15 cm tall stems remain to protect the soil in addition to a substantial mat of leaves that senesce prior to harvest. Studies have also shown that perennial warm-season grasses such as switchgrass work as a carbon sink (Adler et al. 2007). Whereas many cropping practices are sources of greenhouse gases, long-term perennial grass cropping systems can sequester carbon and offset other greenhouse gases due to the low inputs and high above- and below-ground biomass production (Adler et al. 2007).

In addition to the physical protection provided by the plant material, soil health is enhanced by these perennial crops. Research in northeast Arkansas has shown that aggregate stability of a silt loam soil under native warm-season grasses, including switchgrass and eastern gamagrass, was significantly greater than that of high biomass sorghum (47 % greater), a summer annual with minimum tillage and a winter wheat cover crop. A Missouri soil increased in hydraulic conductivity and soil porosity and reduced bulk density (Udawatta et al. 2008). In Texas, soils under warm-season grasses had more water stable aggregates and lower bulk density than soils under row crops (Acosta Martinez et al. 2004). Perennial warm-season bioenergy crops also aid tremendously in controlling erosion on susceptible lands. Hohenstein and Wright (1994) estimated a reduction in erosion of up to 95 % for switchgrass compared to summer annual crops like maize and soybean.

Another warm-season grass, though not native to North America, has taken root in parts of the humid south. *Miscanthus* x *giganteus* has many of the same conservation attributes as the native warm-season grasses: deep rooting, high aboveground biomass, thick stands, perennial, erosion control, etc. (Heaton et al. 2004a). It produces high biomass, returns substantial organic matter to the soil system, and uses soil nutrients efficiently, especially nitrogen (Anderson et al. 2011). Its aboveground biomass is often greater than that of switchgrass (22.4 Mg ha^{-1} for *Miscanthus* vs. 10.3 Mg ha^{-1} for switchgrass in an analysis of 21 different studies; Heaton et al. 2004b). In northeast Arkansas, more than 2600 ha of *Miscanthus* have been planted specifically for bioenergy production (with a goal of 20,000 ha in northeast Arkansas). These bioenergy plantations have been planted on marginal land that would likely have been planted to row crops where erosion, nutrient leaching, and runoff would have been probable. Studies in Illinois have shown the positive impact of land use change from cultivated agriculture to perennial bioenergy cropping with *Miscanthus* (Anderson-Teixeira et al. 2009; Davis et al. 2010).

Growing bioenergy crops in the south provides many benefits to conservation as well as maintaining potential for farm revenue. Whether the bioenergy CA system is based on winter annuals that act similarly to a cover crop or are perennial grasses that provide permanent cover, managing bioenergy crops in the south has the potential to have many agricultural conservation benefits.

17.4 Challenges for Increased Uptake of CA in North America

The challenges for increased adoption of CA in North America have been highlighted in the regional examples. They are diverse and depend on specific cropping systems and climates. The following list summarizes the primary challenges, many of which are being addressed through research and development in public and private sectors.

Principle challenges for increased adoption of CA are:

- Delayed planting and emergence associated with zero-till in cold climates
- Competition by cover crops for limited water in dry climates
- Management of diseases and pests harbored in crop residues
- Development of herbicide tolerance in weeds
- Development of crop varieties and hybrids best suited to CA systems
- Application of conservation tillage in surface-irrigated systems

17.5 National Policies Affecting CA in North America

There are numerous national policies in both the USA and Canada that encourage the application of management practices consistent with the principles of CA. A few key examples are detailed here. In the USA, soil conservation has been a national priority since the 1930s, when a national-scale drought triggered serious wind erosion. Within the US Department of Agriculture, the Natural Resources Conservation Service (NRCS) is the principle agency promoting the adoption of conservation practices. The philosophy of the NRCS is to use incentive programs to encourage farmer participation. The NRCS has widely promoted conservation practices under the slogan "Core 4." The NRCS "Core 4" are principles similar to CA that embody a wide range of practices that can be applied in a site-specific way. The four principles are (1) conservation tillage, (2) crop nutrient management, (3) conservation buffers, and (4) pest management. The NRCS has outlined the details of these practices in a published technical document (USDA-NRCS 1999) and uses this information to direct conservation incentive programs. The NRCS is currently emphasizing soil health and is widely promoting the use of cover crops.

Conservation research and development is also widely sponsored by the USA and Canada. In the USA, a major national funding program is the Sustainable Agriculture Research and Education (SARE) program, which has grant programs for researchers and innovative producers. SARE has widely promoted the development of cover crop practices and has published a useful reference book on the topic (Bowman et al. 2007), which is available at no cost on-line. SARE has also developed a cover crop decision tool to help producers identify ideal cover crop species for their application and they host a national Cover Crops and Soil Health conference.

17.6 Future Direction and Trends

Perhaps one of the most influential technologies affecting agriculture in modern times is the development of precision agriculture. Elements of precision agriculture, such as the use of tractor guidance systems, precision nutrient management, and precision seeding have become common practice in much of North America and the world. The technologies are now being explored in the realm of precision conservation. Since many farmers have or will have the needed tools and technologies for precision farming; these resources can be applied towards precision conservation. Future CA systems will allow for conservation practices, such as tillage intensity, to be applied in a spatially variable way that matches conservation costs and benefits with specific conditions in fields and watersheds. Remote sensing technologies can be used for real-time assessment of soil and climate factors that affect not only crop production but also soil and water conservation. Much research is currently needed on how to obtain and interpret data from remote sensing and apply it for creation of precision conservation recommendations.

The emergence of strip till as a system that seeks the advantages of zero-till while overcoming some of its limitations has resulted in increased adoption of conservation tillage. Similar developments that overcome barriers while capturing benefits are needed. The application of plant breeding and biotechnology tools has potential for improved function and adoption of CA. For example, development of crop varieties that perform well in zero-tillage has not been a priority in most seed development programs. Similarly, development of crops with properties that enhance the function of residues for soil protection holds potential.

Among the most pressing threats to modern agriculture and growing global food needs is the issue of water scarcity. Expanding the water conservation aspects of CA is critical for sustainability. One of the most important ways to reduce the stress on surface and ground water resources used for irrigation is to improve the water productivity of rainfed and dryland cropping systems. A key step is developing a paradigm of assessing crop water productivity then comparing with potential water-limited yields as a valuable diagnostic tool leading to improved management and water use. Integrating a water productivity assessment philosophy with the global reach of CA may be one of the most effective approaches to achieve this.

References

Aandahl AR (1982) Soils of the Great Plains: land use, crops and grasses. University of Nebraska Press, Lincoln

Aase JK, Reitz LL (1989) Annual cropping may be practical and profitable. Montana Farmer-Stockman, Great Falls, MT, p 20

Aase JK, Siddoway FH (1980) Stubble height effects on seasonal microclimate water balance, and plant development of no-till winter wheat. Agric Meteorol 21:1–20

Acosta-Martinez V, Zobeck TM, Allen V (2004) Soil microbial, chemical and physical properties in continuous cotton and integrated crop-livestock systems. Soil Sci Soc Am J 68:1875–1884

Adler PR, Del Grosso SJ, Parton WJ (2007) Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecol Appl 17:675–691

Allen B, Lenssen A, Sainju U, Caesar TC, Lartey R, Evans R (2010) Management strategies to improve yield and nitrogen use of spring wheat and field pea in the semi-arid northern Great Plains USA. In: Gilkes RJ, Prakongkep N (eds) Proceedings of the 19th world congress of soil science; soil solutions for a changing world, Brisbane, Australia, 1–6 August, 2010. IUSS, Crawley, Australia, pp 133–136

Anderson E, Arundale R, Maughan M, Oladeinde A, Wycislo A, Voigt T (2011) Growth and agronomy of *Miscanthus* × *giganteus* for biomass production. Biofuels 2:167–183

Anderson-Teixeira KJ, Davis SC, Masters MD, Delucia EH (2009) Changes in soil organic carbon under biofuel crops. GCB Bioenergy 1:75–96

Angima SD, Kallenbach RL, Riggs WW (2009) Optimizing hay yield under lower nitrogen rates for selected warm-season forages. J Integr Biosci 7:1–6

Baumhardt RL, Anderson RL (2006) Crop choices and rotation principles. In: Peterson GA, Unger PW, Payne WA (eds) Dryland agriculture. Agronomy monograph, vol 23. ASA, CSSA, and SSSA, Madison, pp 113–139

Black AL, Power JF (1965) Effect of chemical and mechanical fallow methods on soil moisture storage wheat yields, and soil erodibility. Soil Sci Soc of Am Proc 29:465–468

Black AL, Brown AD, Halvorson AD, Siddoway FH (1981) Dryland cropping strategies for efficient water-use to control saline seeps in the northern Great Plains, U.S.A. Agric Water Manag 4:295–311

Blevins RL, Frye WW (1993) Conservation tillage: an ecological approach to soil management. Adv Agron 51:33–78

Bowman G, Cramer C, Shirley C (2007) Managing cover crops profitably, 3rd edn. Sustainable Agriculture Research and Education, USDA. Washington, DC. www.sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition. Accessed 29 May 2014

Bransby DI, Sladden SE (1991) A 5-year status report on the screening of herbaceous energy crops in the southeastern United States. In: Klass DL (ed) Energy from biomass and wastes. XV Institute of Gas Technology, Chicago, pp 333–347

Buman RA, Alesii BA, Hatfield JL, Karlen DL (2004) Profit, yield, and soil quality effects of tillage systems in corn-soybean rotations. J Soil Water Conserv 59:260–270

Burgess MH, Miller CA, Jones CA (2012) Pulse crops improve energy intensity and productivity of cereal production in Montana, USA. J Sustain Agric 36:699–718

Campbell CA, Zentner RP, Janzen HH, Bowren KE (1990) Crop rotation studies on the Canadian Prairies. Research Branch, Agriculture Canada, Ottawa

Cherney JH, Cherney DJR, Casler MD (2003) Low intensity harvest management of reed canarygrass. Agron J 95:627–634

Cochran VL, Caesar TC, Kolberg R (2000) Effects of tillage and cropping intensity on soil quality in the semi-arid northern Great Plains. 2000 agronomy abstracts. American Society of Agronomy, Madison, p 314

Cochran V, Danielson J, Kolberg R, Miller P (2006) Dryland cropping in the Canadian Prairies and the U.S. Northern Great Plains. In: Peterson GA (ed) Dryland agriculture. Agronomy monograph, vol 23. ASA, CSSA, SSSA, Madison, pp 293–339

Conservation Technology Information Center (2011) National crop residue management survey. http://www.ctic.purdue.edu/CRM/crm search. Accessed 05 April 2011; data beyond 2008 was available by request

Cutforth HW, McConkey BG (1997) Stubble height effects on microclimate yield and water use efficiency of spring wheat grown in a semiarid climate on the Canadian Prairies. Can J Plant Sci 77:359–366

Cutforth HW, McConkey BG, Ulrich D, Miller PR, Angadi SV (2002) Yield and water use efficiency of pulses seeded directly into standing stubble in the semiarid Canadian Prairie. Can J Plant Sci 82:681–686

Cutforth HW, Angadi SV, McConkey BG (2006) Stubble management and microclimate, yield and water use efficiency of canola grown in the semiarid Canadian Prairie. Can J Plant Sci 86:99–107

Dami I, Bordelon B, Ferree D, Brown M, Ellis M, Williams R, Doohan D (2005) Midwest grape production guide. Bulletin 919. The Ohio State University Extension, Columbus

Davis SC, Parton WJ, Dohleman FG, Smith CM, Del Grosso S, Heaton E, Voigt T, Long SP (2010) A quantitative review comparing the yields of two candidate C4 perennial biomass crops in relation to nitrogen, temperature and water. Biomass Bioenergy 27:21–30

De Bruin JL, Pedersen P (2008) Soybean seed yield response to planting date and seeding rate in the upper midwest. Agron J 100:696–703

DeLaune P, Sij J (2012) Impact of tillage on runoff in long term no-till wheat systems. Soil Tillage Res 124:32–35

Evans RG, Stevens WB, Iversen WM (2010) Development of strip tillage on sprinkler irrigated sugarbeet. Appl Eng Agric 26:59–69

Fae G, Sulc R, Barker D, Dick R, Eastridge M, Lorenz N (2009) Integrating winter annual forages into a no-till corn silage system. Agron J 101:1286–1296

Farmaha BS, Fernández FG, Nafziger ED (2011) No-till and strip-till soybean production with surface and subsurface phosphorus and potassium fertilization. Agron J 103:1862–1869

Farmaha BS, Fernández FG, Nafziger ED (2012) Distribution of soybean roots, soil water, phosphorus and potassium concentrations with broadcast and subsurface-band fertilization. Soil Sci Soc of Am J 76:1079–1089

Fernández FG, Schaefer D (2012) Assessment of soil phosphorus and potassium following real time kinematic-guided broadcast and deep-band placement in strip-till and no-till. Soil Sci Soc Am J 76:1090–1099

Fernández FG, White CE (2012) No-till and strip-till corn production with broadcast and subsurface-band phosphorus and potassium. Agron J 104:996–1005

Franzluebbers AJ (2002) Soil organic matter stratification ratio as an indicator of soil quality. Soil Tillage Res 66:95–106

Frye W, Blevins R, Smith M, Corak S, Varco J (1988) Role of annual legume cover crops in efficient use of water and nitrogen. In: Ellis B, Hargrove W (eds) Cropping strategies for efficient use of water and nitrogen. Special publication, vol 51. American Society of Agronomy. Madison, pp 129–154

Gascho GJ, Hubbard RK, Brenneman TB, Johnson AW, Sumner DR, Harris GH (2001) Effects of broiler litter in an irrigated, double-cropped, conservation-tilled rotation. Agron J 93:1315–1320

Gesch RW, Archer DW (2013) Double-cropping with winter *Camelina* in the northern Corn Belt to produce fuel and food. Ind Crops Prod 44:718–725

Gilliam J, Baker J, Reddy K (1999) Water quality effects of drainage in humid regions. In: Skaggs R, van Schilfgaarde J (eds) Agricultural drainage. Agronomy monograph, vol 38. American Society of Agronomy, Madison, pp 801–830

Greb BW, Smika DE, Woodruff NP, Whitfield CJ (1970) Summer fallow in the central Great Plains. In: Haas JJ, Willis WO, Bond JJ (eds) Summer fallow in the western United States. Conservation Res. Rep. No. 17. USDA-ARS, U.S. Government Printing Office, Washington, pp 51–85

Hall KE, George JR, Riedl RR (1982) Herbage dry matter yields of switchgrass, big bluestem, and indiangrass with N fertilization. Agron J 74:47–51

Hansen NC, Allen BL, Baumhardt RL, Lyon DJ (2012) Research achievements and adoption of no-till, dryland cropping in the semi-arid US Great Plains. Field Crops Res 132:196–203

Harstene L (1991) Hydrologic atlas for Ohio. Average annual precipitation, temperature, streamflow, and water loss for 50-year period, 1931–1980. Ohio Department of Natural Resources. Division of Water, Ground Water Resources Section. Water Inventory Report. No. 28. Available at: http://www.ohiodnr.com/water/pubs/hydatlas/atlasfg3/tabid/4181/Default.aspx. Accessed 21 Feb 2014

Hatfield JL, Sauer TJ, Prueger JH (2001) Managing soils to achieve greater water use efficiency. A review. Agron J 93:271–280

Heatherly L, Elmore R (2004) Managing inputs for peak production. In: Boerma H, Specht J (eds) Soybeans: improvement, production, and uses. Monograph, vol 16. America Society of Agronomy, Madison, pp 451–536

Heaton EA, Clifton-Brown J, Voigt TB, Jones B, Long SP (2004a) *Miscanthus* for renewable energy generation: European union experience and projections for Illinois. Mitig Adapt Strategies Glob Change 9:433–451

Heaton E, Voigt T, Long SP (2004b) A quantitative review comparing the yields of two candidate C4 perennial biomass crops in relation to nitrogen, temperature and water. Biomass Bioenergy 27:21–30

Heggenstaller AH, Moore KJ, Liebman M, Anex RP (2009) Nitrogen influences biomass and nutrient partitioning by perennial, warm-season grasses. Agron J 101:1363–1371

Hohenstein WG, Wright LL (1994) Biomass energy- production in the United States—an overview. Biomass Bioenergy 6:161–173

Holland JM (2004) The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric Ecosyst Environ 103:1–25

Holanda FSR, Mengel DB, Paula DB, Carvaho JB, Bertoni JC (1998) Influence of crop rotations and tillage systems on phosphorus and potassium stratification and root distribution in the soil profile. Commun Soil Sci Plant Anal 29:2383–2394

Horowitz J, Ebel R, Ueda K (2010) No-till farming is a growing practice. Economic Information Bulletin, Number 70. Economic Research Service, USDA, Washington. http://www.ers.usda.gov/publications/eib-economic-information-bulletin/eib70.aspx. Accessed 28 May 2014

Horton R, Bristow KL, Kluitenberg GJ, Sauer TJ (1996) Crop residue effects on surface radiation and energy balance—review. Theoretical Appl Climatol 54:27–37

Jabro JD, Stevens WB, Iversen WM, Evans RG (2011) Bulk density, water content and hydraulic properties of a sandy loam soil following conventional or strip tillage. Appl Eng Agric 27:765–768

Janzen HH (1987) Soil organic matter changes after long-term cropping to various spring wheat rotations. Can J Soil Sci 67:845–856

Johnson AW, Dowler CC, Handoo ZA (2000) Population dynamics of *Meloidogyne incognita*, *M. arenaria*, and other nematodes and crop yields in rotations of cotton, peanut, and wheat under minimum tillage. J Nematol 32:52–61

Jones OR, Häuser VL, Popham TW (1994) No-tillage effects on infiltration, runoff, and water conservation on dryland. Trans ASAE 37:473–479

Kaan DA, O'Brien DM, Burgener PA, Peterson GA, Westfall DG (2002) An economic evaluation of alternative crop rotations compared to wheat–fallow in Northeastern Colorado. TB02–1 Agricultural Experiment Station. Colorado State University, Fort Collins

Katsvairo TW, Rich JR, Dunn RA (2006) Perennial grass rotation: an effective and challenging tactic for nematode management with many other positive effects. Pest Manag Sci 62:793–796

Kleinman P (2012) Managing agricultural phosphorus for environmental protection. In: Sims J, Sharpley A (eds) Phosphorus: agriculture and the environment. Agronomy monograph, vol 46. American Society of Agronomy, Madison, pp 1021–1068

Lamb JFS, Russelle MP, Schmitt MA (2005) Alfalfa and reed canarygrass response to midsummer manure application. Crop Sci 45:2293–2300

Lewandowski I, Clifton-Brown JC, Scurlock JMO, Huisman W (2000) *Miscanthus*: European experience with a novel energy crop. Biomass Bioenergy 19:209–227

Long L (2003) Conservation practices adoption by agricultural landowners. Ph. D. Dissertation. Northern Illinois University, Dekalb

Lyon D, Miller S, Wicks G (1996) The future of herbicides in weed control systems of the Great Plains. J Prod Agric 9:209–215

Lyon DJ, Bruce S, Vyn T (2004) Achievements and future challenges in conservation tillage. In: Proceedings of the 4th international crop science congress, Brisbane, Australia, 26 September–1 October 2004

Meehan TD, Hulbert AH, Gratton C (2010) Bird communities in future bioenergy landscapes of the Upper Midwest. Proc Natl Acad Sci 107:18533–18538

Miller PR, Gan Y, McConkey BG, McDonald CL (2003) Pulse crops for the northern Great Plains. II. Cropping sequence effects on cereal oilseed, and pulse crops. Agron J 95:980–986

Miller PR, Engel RE, Holmes JA (2006) Cropping sequence effect of pea and pea management on spring wheat in the northern Great Plains. Agron J 98:1610–1619

Mooney DF, Roberts RK, English BC, Tyler DD, Larson JA (2009) Yield and breakeven price of ‘Alamo’ switchgrass for biofuels in Tennessee. Agron J 101:1234–1242

Morrison JE (2002) Strip tillage for “no-till” row crop production. Appl Eng Agric 18:277–284

NASS (2012) U.S. Department of Agriculture, National Agricultural Statistics Service. http://www.nass.usda.gov/Statistics_by_State. Accessed 01 May 2012

Nielsen DC, Vigil MF (2005) Legume green fallow effect on soil water content at wheat planting and wheat yield. Agron J 97:684–689

OMAFRA (Ontario Ministry of Agriculture and Food) (2013) Estimated area, yield, production, and farm value of specified field crops, Ontario, 2011–2013. http://www.omafra.gov.on.ca/english/stats/crops/estimate_new.htm. Accessed 21 Feb 2014

Overstreet LF (2009) Strip tillage for sugarbeet production. Intern Sugar J 111:292–304

Pannell DJ, Llewellyn RS, Corbeels M (2014) The farm-level economics of conservation agriculture for resource-poor farmers. Agric Ecosyst Environ 187:52–64

Peterson GA, Westfall DG (2004) Managing precipitation use in sustainable dryland agroecosystems. Ann Appl Biol 144:127–138

Peterson GA, Schlegel AJ, Tanaka DL, Jones OR (1996) Precipitation use efficiency as affected by cropping and tillage systems. J Prod Agric 9:180–186

Phillips RE, Blevins RL, Thomas GW, Frye WW, Phillips SH (1980) No-tillage. Agric Sci 208:1108–1113

Pikul JL, Jr, Aase JK, Cochran VL (1997) Lentil green manure as fallow replacement in the semiarid northern Great Plains. Agron J 89:867–874

Randall G, Vetsch J (2008) Optimum placement of phosphorus for corn/soybean rotations in a strip-tillage system. J Soil Water Conserv 63:152–153

Richards R, Baker D, Crumrine J, Kramer J, Ewing D, Merryfield B (2007) Thirty-year trends in suspended sediment in seven Lake Erie tributaries. J Environ Qual 37:1894–1908

Robertson BA, Doran PJ, Loomis LR, Robertson JR, Schemske DW (2011) Perennial biomass feedstocks enhance avian diversity. GCB Bioenergy 3:235–246

Sainju UM, Lenssen AW, Caesar TC, Evans RG (2009) Dryland crop yields and soil organic matter as influenced by long-term tillage and cropping sequence. Agron J 101:243–251

Sanderson MA, Reed RL, McLaughlin SB, Wullschleger SD, Conger BV, Parrish DJ et al (1996) Switchgrass as a sustainable bioenergy crop. Bioresour Technol 56:83–93

Scanlon BR, Faunt CC, Longuevergne L, Reedy RC, Alley WM, McGuire VL, McMahon PB (2012) Groundwater depletion and sustainability of irrigation in the US high plains and central valley. Proc Natl Acad Sci 109:9320–9325

Scully B, Webster T (2012) Initial assessment of energy beets in the Southeast Coastal Plain. USDA-ARS Research Notes

Sharpley A, Jarvie H, Buda A, May L, Speras B, Kleinman P (2013) Phosphorus legacy: overcoming the effects of past management practices to mitigate future water quality impairment. J Environ Qual 42:1308–1326

Shaver TM, Peterson GA, Ahuja LA, Westfall DG, Sherrod LA, Dunn G (2002) Surface soil properties after twelve years of dryland no-till management. Soil Sci Soc Am J 66:1296–1303

Simmons FW, Nafziger ED (2009) Soil management and tillage. In: Nafziger ED (ed) Illinois agronomy handbook, 24th ed. University of Illinois, Urbana, pp 133–142

Six J, Elliott ET, Paustian K (1999) Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci Soc Am J 63:1350–1358

Slaton NA, DeLong RE, Bacon RK, Kelly J (2011) Canola response to nitrogen and phosphorus fertilization rate in Arkansas. In: Slaton NA, Sabbe WE (eds) Arkansas soil fertility studies. Arkansas Agricultural Experiment Station, Fayetteville, pp 38–41

Stewart BA, Baumhardt RL, Evett SR (2010) Major advances of soil and water conservation in the U.S. Southern Great Plains. Soil Sci Soc Am J 60:103–129

Sullivan DG, Truman CC, Schomberg HH, Endale DM, Franklin DH (2007) Potential impact of conservation tillage on conserving water resources in Georgia. J Soil Water Cons 62:145–152

Sundermeier A, Fallon Jr L, Schmalzried H, Sundermeier L (2009) Conservation tillage: repackaging the message for farmers. J Ext 47:pp 2RIB6

Tanaka DL, Aase JK (1987) Fallow method influences on soil water and precipitation storage efficiency. Soil Tillage Res 9:307–316

Truman CC, Shaw JN, Reeves DW (2005) Tillage effects on rainfall partitioning and sediment yield from an ultisol in central Alabama. J Soil Water Cons 60:89–98

Udawatta RP, Anderson SH, Gantzer CJ, Garrett HE (2008) Influence of prairie restoration on CT-measured soil pore characteristics. J Environ Qual 37:219–228

Unger PW (1990) Conservation tillage systems. Adv Soil Sci 13:27–67

USDA (United States Department of Agriculture) (2009) 2007 Census of Agriculture. United States Summary and State Data, vol 1. Geographic Area Series Part 51 AC-07-A-51. Washington, DC

USDA-NRCS (United States Department of Agriculture-Natural Resource Conservation Service) (1999) Core4 conservation practices training guide. www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_025540.pdf. Accessed 29 May 2014

USEPA (United States Environmental Protection Agency) (1995) The Great Lakes: an environmental atlas and resource book, 3rd edn. Jointly produced by government of Canada, Toronto, ON and USEPA. Great Lakes National Program Office, Chicago, IL

Vigil MF, DC Nielsen (1998) Winter wheat yield depression from legume green fallow. Agron J 90:727–734

Vyn TJ, Raimbault BA (1992) Evaluation of strip tillage systems for corn production in Ontario. Soil Tillage Res 23:163–176

Wall G, Dickinson W, van Vliet L (1982) Agriculture and water quality in the Canadian Great Lakes basin: II. Fluvial sediments. J Environ Qual 11:482–486

Werblow S, Watts C (2013) 2012–2013 Cover crop survey: June 2013 survey analysis. North central sustainable agriculture & education and conservation technology information center. Available at: http://www.northcentralsare.org/Educational-Resources/From-the-Field/2012-Cover-Crops-Survey-Analysis. Accessed 20 Feb 2014

Wienhold BJ, Pikul JL, Liebig MA, Mikha MM, Varvel GE, Doran JW, Andrews SS (2006) Cropping system effects on soil quality in the Great Plains synthesis from a regional project. Renew Agric Food Syst 21:49–59

Wortman S, Francis C, Bernards M, Drijber R, Lindquist J (2012) Optimizing cover crop benefits with diverse mixtures and an alternative termination method. Agron J 104:1425–1435

Zentner RP, Wall DD, Nagy CN, Smith EG, Young DL, Miller PR, Campbell CA, McConkey BG, Brandt SA, Lafond GP, Johnston AM, Derksen DA (2002) Economic crop diversification and soil tillage opportunities in the Canadian Prairies. Agron J 94:216–230

Zentner RP, CA Campbell, Biederbeck VO, Selles F, Lemke R, Jefferson PG, Gan Y (2004) Long-term assessment of management of annual legume green manure crop for fallow replacement in the Brown soil zone. Can J Plant Sci 84:11–22

Chapter 18
Conservation Agriculture in Sub-Saharan Africa

Marc Corbeels, Christian Thierfelder and Leonard Rusinamhodzi

Abstract Specific practices of conservation agriculture (CA) in sub-Saharan Africa are diverse and vary according to local farming conditions. However, despite more than two decades of investment in its development and dissemination, adoption of CA is low. Crop responses to CA are highly variable, and not always positive, which is an important hindrance for adoption, especially for resource-poor farmers who need immediate returns with their investments in CA in order to be able to feed their families. In contrast with commercial farms such as in Brazil, reduced costs with CA on smallholder farms in sub-Saharan Africa are not always observed. Another major challenge with the practice of CA is the use of crop residues for mulching since crop residues are a major source of feed for livestock, especially in semiarid regions, where biomass production is limited and livestock plays a crucial role in farming systems. Studies indicate that the three principles of CA, including mulching, are needed to increase crop yields compared with conventional tillage (CT)-based practices. Among the three principles of CA, mulching is certainly the one that is least observed in past and current cropping practices in Africa. CA has a potential to improve the soil water balance and increase soil fertility, and it is undoubtedly a cropping practice that can result in substantial benefits for certain farmers in Africa. The question is when and how it is the best approach for smallholder farmers in sub-Saharan Africa. In general, CA is more likely to be attractive for farmers with a strategy of intensification than for farmers who struggle to produce food for their family. The latter too often face multiple constraints that limit the possibilities to engage in technological innovations. Some farmers may not be interested in new technologies because they earn their income from off-farm activities. Good markets of input supply and sale of extra produce are a prerequisite condition for adoption of CA as they are for any other new agricultural technology

---

M. Corbeels (✉) · L. Rusinamhodzi
French Agricultural Research Centre for International Development (CIRAD),
Avenue Agropolis, 34398 Montpellier cedex 5, France
e-mail: corbeels@cirad.fr

C. Thierfelder
International Maize and Wheat Improvement Centre (CIMMYT),
Mount Pleasant, P. O. Box MP163, Harare, Zimbabwe

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_18

that aims at intensification. In sub-Saharan Africa, there is certainly a need to better target CA to potential end users and adapt the CA practices to their local circumstances and specific farming contexts.

Keywords Adoption · Conservation agriculture · Crop residues · No-tillage · Smallholder farmers · Sub-Saharan Africa

18.1 Introduction

Over the past two decades, conservation agriculture (CA) has arguably become a hegemonic paradigm in scientific and policy thinking about sustainable agricultural development in Africa. CA involves minimal soil disturbance, retention of crop residues as mulch on the soil surface, and the use of crop rotations and/or associations (FAO 2014). Various research and development projects and numerous policy documents have been dedicated to CA, and specialized teams researching and developing CA technologies have emerged in leading international and national research institutes, such as the Consultative Group on International Agricultural Research (CGIAR) and the Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD). CA has been resolutely advocated by the Food and Agriculture Organization (FAO) and by numerous nongovernmental organizations as a means to overcome continuous poor profitability and soil degradation on smallholder farms in sub-Saharan Africa. However, in more recent years, its promotion for African smallholder farmers has received critical scrutiny and analysis (Giller et al. 2009), resulting in a heated debate around the potential benefits and challenges with the dissemination of CA in Africa.

CA is a wider concept than no-tillage or other likewise terminologies, such as zero tillage, direct seeding, reduced tillage, and conservation tillage, putting the emphasis on the cropping system as a whole, and not uniquely on the tillage component. The original interest in CA was related to its potential to conserve soil and water and to enhance soil fertility by reducing soil erosion, soil organic matter decline, and soil structural breakdown. However, recently, and primarily as a response to the wider socioeconomic and institutional context of smallholder farming, CA has been reframed for the African context as a crop production-enhancing technology that should ensure smallholder food security and reduce rural poverty (Andersson and D'Souza 2014). Worldwide, CA has also increasingly been endorsed as a practice to mitigate negative effects of climate change on crop production, and is thus seen as a way of farming to adapt to climate change (Kassam et al. 2009).

CA is undoubtedly an option that can result in substantial benefits for certain farmers in some locations in Africa. The question is when and how it is the best approach for smallholder farmers in sub-Saharan Africa. In this chapter, we first discuss the adoption of CA by commercial farmers in (sub)tropical Brazil and illustrate the limits of using this success story as a justification for promoting CA to smallholders in sub-Saharan Africa. We highlight the diversity and heterogeneity of farms in sub-Saharan Africa, because understanding these features of African farming is important to comprehend the adoptability and performance of CA. We then demonstrate the low adoption of CA in sub-Saharan Africa and try to understand this against the historical background of the development of CA in Africa; the diversity of technologies and its effects on crop yields, soil quality, weeds, and diseases; and farm income. Lastly, the challenges with dissemination of CA in Africa are discussed and the need to tailor CA technologies to the farming context of smallholders is highlighted.

Most of the reported research on CA in sub-Saharan Africa is on cereal-based cropping systems (Brouder and Gomez-Macpherson 2014). The most important cereal production systems are in West, East, and southern Africa and are the maize mixed, cereal–root crop mixed, and agropastoral millet/sorghum farming systems, and to some extent the highland temperate mixed farming systems (Dixon et al. 2001). The development and promotional efforts with CA technologies relate mainly to these farming systems. Maize mixed, cereal–root crop mixed, and agropastoral millet/sorghum farming systems account for 756 million ha (31 %) of the land area in sub-Saharan Africa, 85 million ha (49 %) of the cultivated area, and cover an agricultural population of more than 160 million. Climate in the region where these three farming systems occur varies from semiarid, to dry subhumid, to moist subhumid. The most typical regions have unimodal rainfall, but some regions experience bimodal rainfall. Population density is moderately high (subhumid areas) to modest (semiarid areas). The main staple crops are maize, sorghum, and pearl millet, and the cereal–root crop mixed farming systems also have yams and cassavas. The main cash sources are migrant remittances; cattle and small ruminants; tobacco, coffee, and cotton; and the sale of food crops such as maize and pulses. Cattle are reared for plowing, breeding, milk, manure, savings, and insurance in times of need. The highland temperate mixed farming systems occupy 44 million ha (2 %) of the land area and account for 6 million ha (4 %) of the cultivated area, but support an agricultural population of more than 30 million. Most of the systems are located at altitudes between 1800 and 3000 m in the highlands of Ethiopia. Small grains such as wheat, barley, and teff are the main staple crops, complemented by peas, lentils, broad beans, rape, and Irish potatoes. Cattle density is high in these regions.

18.2 The Brazilian Experience with CA: An Example for Africa?

The first subtropical experiences with no-tillage practices were initiated in the 1960s/1970s in southern Brazil by commercial farmers on their mechanized farms of about 300–500 ha, as a response to the widespread soil degradation in that region. The subsequent transfer of no-tillage in the early 1980s to the tropical Cerrado region in central Brazil involved an adaptation to the different agroecological conditions (hotter and more humid) of that part of Brazil, as well as to the often larger farm sizes (> 500 ha; Bolliger et al. 2006). The rapid expansion of no-tillage in Brazil was driven by the commercial release of the herbicides atrazine, paraquat, and glyphosate and by the energy savings that resulted from eliminating several tillage operations. Direct seeding operations without tillage into a mulch of crop residues were made possible because of the local development and production of no-till planters. Agrochemicals, including fertilizers and herbicides, are readily available, and they are widely used, resulting in high crop yields and biomass production providing sufficient cover of crop residues. All crop residues remain on the fields and are not used for livestock since crop and livestock productions are segregated on these types of farms.

It was only in the second half of the 1980s, that research efforts on no-tillage technologies in Brazil started focusing on small farms (< 100 ha). These developments also began in southern Brazil. Here too, a key role was played by the agricultural machinery industry that developed specific equipment (including special manual and animal-drawn planters, sprayers, and equipment for residue management) that fitted the requirements and abilities of smallholder farmers who rely on animal traction and/or manual labor. However, success with adoption of CA on small farms in Brazil was much less than with the large-scale commercial farmers (e.g., Bolliger et al. 2006; Scopel et al. 2013). Smallholder farmers often fall back on a range of intermediate or partial CA systems, rather than implementing a complete CA package.

Despite these observations and concerns with CA for smallholders, the Brazilian experience has often been seen as a justification for promoting CA in Africa. The rationale for developing CA systems, i.e., reducing soil degradation and production costs, and its guiding principles and practices were considered valid for Africa and consequently sparked large interest among research organizations and funding agencies (Benites et al. 1998; Ekboir 2002). On many occasions, and often through research and development projects, specialized no-tillage implements (including manual jab planters and direct seeders for animal traction) have been imported from Brazil.

Smallholder farming conditions in sub-Saharan Africa differ substantially from farming situations in Brazil, even from those of smallholder farmers in Brazil. First of all, farms in sub-Saharan Africa are much smaller than those of smallholders in Brazil (on average 2 ha vs. 50 ha). This has strong implications on farmers' investment capacity in new technologies and their attitude to risk with trying something new. Second, crop yields in sub-Saharan Africa are generally much lower than in Brazil because of the nutrient-depleted soils and limited use of agrochemicals (e.g., Tittonell and Giller 2013; Affholder et al. 2013), with little crop residues produced as a consequence. Third, many smallholder farming systems in sub-Saharan Africa are mixed crop–livestock production systems with strong demands on available crop residues for livestock feed that compete with their use as soil cover (Corbeels et al. 2014). Fourth, in contrast to Brazil crop rotations, such as cereal–legume rotation, may be difficult to realize on most farms in sub-Saharan Africa, mainly because of the lack of market opportunities for grain legumes (Giller et al. 2009). Consequently, the technologies required to put the principles of CA into practice are very different between Brazil and Africa.

18.3 Diversity and Heterogeneity of Farms in Sub-Saharan Africa: Implications for Adoption of CA

A foremost reality in sub-Saharan Africa is the small and declining farm sizes with about 80 % of farms below 2 ha (Nagayets 2005). Most of the farms can be considered "resource-poor" smallholders. For example, results drawn from nationally representative farm surveys undertaken between 1995 and 1997 revealed that the proportion of surveyed smallholder farms falling below the poverty line was 55 % in Kenya, 75 % in Ethiopia, and 97 % in Mozambique (Jayne et al. 2003). Although these data are rather general and do not show the diversity of farms (see below), they do raise questions about the potential impact of technological interventions on farm income and agricultural development in sub-Saharan Africa (Harris and Orr 2014). Furthermore, small farm sizes make farmers more risk averse and less willing to experiment. Putting a part of the field(s) aside for new technology testing may represent a significant risk in terms of short- to medium-term household food security (Pannell et al. 2014). Moreover, small farms often face difficulties integrating in markets due to their low competitiveness and their severe budgetary and capacity limitations (Barrett 2008).

Despite smallholder farms in sub-Saharan Africa generally being categorized as resource poor, high variations do exist in income. For example, the average annual per capita household incomes varied from US$ 337 in Kenya to US$ 43 in Mozambique (data from 1996/1997); these mean figures hide large variations across surveyed farms: average per capita incomes of the top quartile are typically 15–25 times higher than those of the bottom income quartile (Jayne et al. 2003). This large variation in capital income among households reflects the diversity in resource endowments (land, labor, capital) of farms in sub-Saharan Africa. Capital income and resource endowment can often be linked to the agroecological production potential of a region. In general, farmers living in high-potential areas have better income as a result of the higher returns to production factors with less risk than those farming in areas with low agroecological potential (Ruben and Pender 2004). Access to markets is another factor that explains diversity of farms and is often linked to resource endowment, since farms with more resources and wealth are usually better positioned for acquiring market access. Yet farms with similar resource endowments and opportunities for market exchange do not always engage in the same activities (Ruben and Pender 2004). Differences in production strategies are influenced by a broad range of other factors, including management skills, education, social hierarchy, and tradition (Tittonell et al. 2010). Recognizing these factors that shape the diversity of farms is the first step for targeting new technologies, such as CA, and understanding their performance and adoptability.

Farms have been categorized considering resource endowment and factors representing orientation of production activities and/or main constraints to agricultural production. For example, for East Africa, Tittonell et al. (2010) identified five farm types: (1) farms that rely mainly on permanent off-farm employment; (2) relatively large, wealthy farms growing cash crops; (3) medium wealthy, food self-sufficient farms;

(4) medium to low wealthy farms relying partly on nonfarm activities; and (5) poor farms with family members employed locally as agricultural workers by wealthier farmers. The poorest farms typically cultivate only small areas, due to lack of land or labor, and own little or no livestock. Such households are rarely self-sufficient in food, and are often delayed in land preparation, planting, and weeding due to their need to earn their food by working for wealthier farmers. Market orientation generally increases from low or medium to wealthy farms. The farm types described above can be associated to the three generic livelihood strategies that were identified by Dorward (2009) as (1) "hanging in," which takes place in situations of poor agroecological potential and market opportunities, and where poor households engage in activities to maintain their current livelihood (subsistence farming); (2) "stepping up," in situations of high agroecological potential and market opportunities where investments in assets are made to expand current production activities (semicommercial farming); and (3) "stepping out," when activities are used to accumulate assets that may allow moving into different activities, not necessarily farming (i.e., migration to cities and/or local engagement in nonfarm activities). It is evident that farmers with a strategy of "stepping up" are more likely to experiment with and eventually adopt proposed technologies of CA than farmers who are "hanging in." The latter too often face multiple constraints that limit the possibilities to engage in technological innovations, while those farmers who are "stepping out" are probably not interested in new technologies for agricultural intensification.

Another aspect of African farms that needs attention when proposing new technologies to farmers is the spatial heterogeneity in soil fertility. Next to the inherent variability of soil types in the landscape, management decisions on the allocation of available resources generate gradients of soil fertility within individual farms (Carter and Murwira 1995). This feature is commonly observed in East and southern Africa, in medium to high densely populated regions with relatively intense land use and where livestock is present and farmers use manure or mineral fertilizers. In these contexts, farmers preferentially allocate manure, mineral fertilizers, and labor to fields close to their homesteads, resulting in strong gradients of soil fertility decline with increasing distance from the homestead as this provides the highest returns (Tittonell et al. 2005; Zingore et al. 2007). In West Africa, a similar soil fertility gradient in concentric rings around the household compound has been described as the ring management system (Prudencio 1993). This heterogeneity in soil fertility should be considered when promoting CA technologies, since it has strong effects on resource-use efficiency, i.e., returns to nutrient inputs, land, and labor (Vanlauwe et al. 2006; Tittonell et al. 2008) and therefore on the performance and adoption of newly introduced technologies.

18.4 History of CA in Sub-Saharan Africa

Traditionally in sub-Saharan Africa, planting in mulch of plant residues with minimum tillage (slash-and-mulch systems) was only practiced under very specific social (cultural ban on fire) and climatic (humid equatorial climate without dry season) conditions, or very occasionally in coexistence with the widespread practice of slash-and-burn (Serpantie 2009). On the other hand, cropping practices corresponding to one single principle of CA were more widespread in Africa. For example, minimum tillage has been around for many decades. Farmers traditionally planted directly into the ashes of burned native bush or fallows and used only a hoe to loosen the soil surface and cover the seeds (Page and Page 1991). In fact, throughout most of sub-Saharan Africa (Ethiopia being an exception), the use of animal power for plowing the land is not traditional, and it was introduced and promoted with colonial agricultural departments and, in the postindependence time, with agricultural development projects (Starkey 2000) in order to increase the cropped area and total crop production on farms. Mulching was also practiced in traditional African cropping systems, other than the slash-and-mulch systems cited above, although in specific circumstances such as with tuber crops to reduce heat stress, or on very small patches of land in, e.g., the Sudano-Sahelian region to restore physically degraded soils (Serpantie 2009). Crop rotations and/or associations were also a common feature of traditional farming in Africa during precolonial times (Page and Page 1991). A common practice, for example, in southern Africa was to broadcast sorghum, maize, cowpeas, and pumpkin seeds directly into the ash of burned bush and to fill later the gaps with transplanted finger millet.

Even today, in many regions of sub-Saharan Africa, farmers are implementing practices that can be considered consistent with at least one of the principles of CA, although often these are done from a rather opportunistic attitude, or even out of necessity because of economic constraints. As such, they are not part of a complete CA package. For instance, in the many regions of Africa, farmers who have no access to animal traction commonly practice minimum tillage using a simple planting stick, because of the lack of proper tillage equipment, but without mulching. Mixed cropping of cereals (e.g., maize with millet) or of cereals with beans or peas is also widespread in many regions of Africa, and presumably reflects both the increasing pressure on land and the need to diversify crops for managing production risks. Among the three principles of CA, mulching is certainly the one that is least observed in current cropping practices in Africa.

In southern Africa, CA has its roots in Zimbabwe. Minimum tillage was first introduced on large-scale commercial farms in Rhodesia (now Zimbabwe) in the late 1960s (Andersson and D'Souza 2014). Research on CA for smallholder farmers by governmental research institutes in Zimbabwe began later, in the 1980s (Twomlow et al. 2008). The first promotional project with smallholders started in the 1990s and was run by the River of Life Church (Oldreive 1993). The project focused on the promotion of either permanent planting basins or shallow planting furrows in conjunction with a package of inputs (seed and fertilizer) for cereal–legume rotations. In Zambia, initial interest in CA started in the early 1980s, when several commercial farmers from the Zambian National Farmers Union (ZNFU) traveled to the USA and Australia to learn about it (Baudron et al. 2007). Like for other commercial farmers, reduced fuel consumption was the principal motivation to adopt no-tillage. In 1995, ZNFU set up the Conservation Farming Unit (CFU) to promote CA to smallholder farmers. CFU promotes a package, called conservation farming, which was based on the experience of the River of Life Church in Zimbabwe with the permanent planting basins (Haggblade and Tembo 2003; Aagaard 2013). The earliest experiences with CA in East Africa were in the highlands of Kenya in the mid-1970s: large commercial farmers began with no-tillage in an effort to conserve moisture and to reduce production costs (Apina et al. 2007). In the 1990s, several development projects on soil and water conservation started testing CA technologies for smallholder farmers in Kenya and Tanzania (Kaumbutho and Kienzle 2007; Shetto and Owenya 2007). The very first research trials on no-tillage in West Africa took place in the late 1960s in Ghana (Ofori 1973). During the 1970s, several research activities on CA were initiated in Nigeria at the International Institute of Tropical Agriculture (IITA; Lal 1974; Greenland 1975). Sasakawa Global 2000 introduced CA to smallholders in Ghana in 1993 in collaboration with the national Crop Research Institute and the Monsanto Company (Ekboir et al. 2002; Ito et al. 2007). The project received strong political support from the government (Findlay and Hutchinson 1999) and worked with input suppliers (of herbicides) and credit agencies to address input problems that were seen as a precondition for successfully implementing CA.

It was at the end of the 1990s that major funding agencies began to show increased interest in CA in sub-Saharan Africa, especially the German Development Corporation (GTZ), the Agence Français du Développement (AFD), the Regional Land Management Unit of the Swedish International Development Agency (RELMA), FAO, and the World Bank. This gave rise to several flagship projects such as Conservation Agriculture and Sustainable Agriculture and Rural Development (CASARD) in Kenya and Tanzania, funded by the German trust fund with technical support by FAO and the governments of Kenya and Tanzania and the project Développement Paysannal et Gestion de Terroir in Cameroon implemented by CIRAD, local research and development partners, and the private cotton companies. The African Conservation Tillage Network (ACT)—originally financed by GTZ—was also founded during that period. Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) began a large effort in 2004 to adapt the CA principles to the circumstances of smallholders in southern Africa (Malawi, Zambia, Tanzania, and Zimbabwe), and from 2006 onwards in Mozambique and other countries of East Africa (Wall et al. 2014). Since 2004, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), together with nongovernmental organizations, has been developing and promoting planting basins and rip-line seeded systems, through various donor-funded relief and recovery programs with the aim of improving crop production among vulnerable smallholder farmers in the semiarid regions of southern Africa.

Today, 11 African countries have identified a focal point for CA (Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia, and Zimbabwe). Most of these countries have established National Conservation Agriculture Task Forces, with Zimbabwe taking the lead in the creation of a CA network as a community of practitioners. These task forces comprise a wide range of stakeholders, including government departments, academic and research institutions, the private sector, and nongovernmental and faith-based organizations. Coordination activities at the regional level in southern Africa are being undertaken by the Regional Conservation Agriculture Working Group.

18.5 Adoption of CA in Sub-Saharan Africa

Overall, the adoption of CA systems in sub-Saharan Africa is low. There is ~1,000,000 ha under CA (Table 18.1); 40 % of this area is in South Africa, where it is mainly practiced on large-scale mechanized farms (Friedrich et al. 2012). Adoption by smallholder farmers is generally small; only 0.3 % of the farmed land area under CA worldwide is on smallholder farms (Derpsch et al. 2010). A number of constraints are explanatory, which are discussed in the following sections. Most of the smallholder farmers in southern Africa currently use planting basins, e.g., in Zambia and Zimbabwe. At present, data on the status of CA in West Africa (apart from Ghana) are lacking. In 2009, the area under CA in northern Cameroon was estimated to be 2500 ha (Horus Entreprise 2009).

However, care must be taken when interpreting these adoption figures. National agricultural statistics generally do not report areas under CA or no-tillage separately, and often areas under no-tillage are seen as CA adoption, which can lead to distorted figures. The published data are rough estimates from a network of informants in different countries of Africa coordinated by FAO, taking the extent of adoption as areas with minimum soil disturbance as less than 25 % of the cropped area and with more than 30 % soil cover (Derpsch et al. 2010). Rotation is apparently not seen as a requirement in this assessment. The figures also neglect the time dimension of adoption, and some areas that are considered as surfaces where CA has been adopted may in fact be areas where (large) promotional projects on CA are operating (Grabowski and Kerr 2014). In general, uptake of CA in sub-Saharan Africa has been mainly driven by nongovernmental organizations and funding agencies (Andersson and D’Souza 2014). These adoption claims have limited value, as the projects often incentivize the uptake of CA technologies by providing input support (fertilizers, seeds, and/or herbicides) to farmers. As a consequence, we conclude that it is currently difficult to give a reliable assessment of the real extent of adoption of CA in sub-Saharan Africa. In reality, farmers in Africa often face problems with adopting all the principles of CA for various reasons. These are discussed in the following sections and include limited access to inputs (including no-till equipment), labor constraints, competing uses for crop residues, and the need for knowledge and capacity building with CA technologies.

Table 18.1 Estimated areas under conservation agriculture in sub-Saharan Africa. (Source: Friedrich et al. 2012)

Country	Area (ha)
Ghana	30,000
Kenya	33,000
Sudan	10,000
Tanzania	25,000
Malawi	16,000
Mozambique	152,000
Zambia	200,000
Zimbabwe	139,300
South Africa	368,000
Lesotho	2000
Namibia	340
Total	975,640

18.6 Diversity of CA Technologies

The three principles of CA are common to CA technologies, but the specific practices or components of them (planting techniques, surface crop residue management, crops in the rotation, fertilization, weeding) are diverse and vary according to local farming conditions (Erenstein et al. 2012).

In practical terms, there are three main operational forms of no-tillage or minimum tillage: manual, animal draft power, and motorized systems (Johansen et al. 2012). Manual systems range from very simple systems such as planting with a pointed stick (Fig. 18.1), also called a dibble stick, or with a hoe to more sophisticated systems using mechanical jab planters (*matraca*, Fig. 18.2). With a pointed stick, farmers make two holes and place seed and fertilizer. The jab planter supplies seed and fertilizer in planting holes created by the implement. With animal traction, rippers (Fig. 18.3) and direct seeders (Fig. 18.4) are the most common. With rip-line seeding, the land is ripped in between the crop rows of the previous season with ripper tines that can be attached to the beam of the moldboard plow (e.g., the Magoye ripper in southern Africa). The implement creates a furrow approximately 10–15 cm wide and 10 cm deep. For sandy soils, opening wings are used on the ripper attachment. The rippers are the cheaper option for farmers with draft power; specialized direct planting seeders are aimed at the commercially oriented farmers with draft power. The implement, originally designed in Brazil, creates a rip-line, supplies seed and fertilizer, and covers the line in one operation. Motorized systems (tractors with specialized direct seeders) are almost exclusively used by commercial farmers in Africa.

In Zambia and Zimbabwe, a particular type of CA, locally called "conservation farming," has been developed and promoted; it is based on planting in small, manually dug basins or shallow planting furrows using a hand hoe (Haggblade and Tembo 2003; Twomlow et al. 2008). Digging the basins or furrows is usually carried out in the dry season in anticipation of the rains, which encourages early planting when the first rains arrive. The permanent basins are most suitable for dry regions (<800 mm annual rainfall) and are a modification of the traditional pit systems once common in southern Africa. It is a variation on the Zaï system from West Africa, even though mulching is commonly not applied with Zaï. The Zaï technique originated in Mali in the Dogon area and was adopted and improved in northern Burkina Faso by farmers after the drought of the 1980s. Farmers apply the Zaï technique to recover crusted land called "Zippelle." Before planting, the pits are filled with organic matter which allows moisture to be trapped and stored more easily (Roose et al. 1993).

A relatively new CA-based technology, based on indigenous practices for dry regions (<500 mm annual rainfall), integrates native evergreen woody shrubs (e.g., *P. reticulatum* and *G. senegalensis*) in a relay intercropping system. The shrub accumulates soil fertility, provides material for mulching, and facilitates water supply to the associated annual crop. Implementing such a management system may, however, be time and labor consuming, and should be seen as a first phase in land restoration (Lahmar et al. 2012).

Fig. 18.1 Planting with a pointed stick in mulch of crop residues

Fig. 18.2 Mechanical jab planters for manual direct seeding and fertilizer application

Fig. 18.3 Use of the Magoye ripper for direct seeding

Fig. 18.4 Seeding through a mulch of crop residues with a direct seeder and fertilizer distributor

Recently, the World Agroforestry Centre (ICRAF) developed—under the name of "Evergreen Agriculture"—systems for intercropping 'fertilizer trees' in cereal cropping systems under CA, mostly planting basins. The options include intercropping maize, millet or sorghum with *Faidherbia albida*, *Gliricidia sepium* or *Tephrosia candida* (Garrity et al. 2010). These systems have been promoted to farmers in Malawi, Zambia, Burkina Faso, and Niger.

In recent years, renewed attention has been given to intercropping as a component of CA systems. For example, intercropping maize and pigeon pea has been highly profitable in central Mozambique, but with increased labor requirements for weeding (Rusinamhodzi et al. 2012). Mucheru-Muna et al. (2009) and Ngwira et al. (2012) also reported higher rates of return with intercropping compared to maize cropping alone in Kenya and Malawi, respectively. The development of a market for pigeon pea (with export to India) is a major driver for intercropping in these regions.

18.7 Effects on Crop Yields

Through a meta-analysis of cereal crop yield data from 61 experiments in sub-Saharan Africa, Sakyi et al. (2014) showed large variability in grain yield responses (from positive to negative) to CA compared with CT-based practices (Fig. 18.5). On average, no- or minimum tillage with mulching showed the maximum positive mean difference in grain yields (378 kg ha^{-1}), followed by no- or minimum tillage with mulching and rotations (142 kg ha^{-1}), while no-tillage without mulching showed negative yield responses compared to the conventional practice (−24 kg ha^{-1}). The results from this meta-analysis suggest that for farmers to expect yield benefits from CA, they should be able to keep their crop residues as mulch on the soil surface. In addition, recent studies in southern Africa (Thierfelder et al. 2013b; Nyamangara et al. 2013; Ngwira et al. 2014) have shown that appropriate fertilization is critical for positive crop responses with CA. In general, increased use of fertilizer is necessary in sub-Saharan Africa—where the average fertilizer application rate by smallholder farmers is less than 10 kg ha^{-1}—for increasing crop productivity and the availability of crop residues for mulching (Vanlauwe et al. 2014).

Other recent reviews of CA experiments in sub-Saharan Africa (Nyamangara et al. 2014b; Wall et al. 2014; Thierfelder et al. 2014) have also shown the variable character of the effects of CA on grain yield, largely dependent on agroecological conditions Under conditions where water stress occurs (e.g., dry spells), positive yield effects are common since mulching increases soil water availability (e.g.,

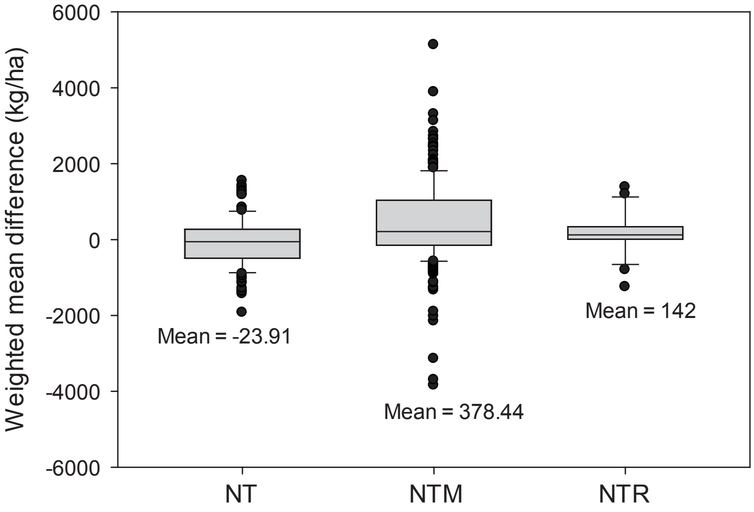


Fig. 18.5 Weighted mean difference in cereal crop grain yield between conservation agriculture and conventional tillage-based practices. The results are from a meta-analysis of 61 experiments in sub-Saharan Africa. The middle lines represent median values with upper and lower 25th percentiles. *NT* no-tillage or minimum tillage, *NTM* no-tillage with mulching, and *NTR* no-tillage with mulching and rotation. (Source: Sakyi et al. 2014)

Thierfelder and Wall 2009; Mkoga et al. 2010; Mupangwa et al. 2012). Negative responses may occur under high rainfall, as mulching may exacerbate waterlogging (Thierfelder and Wall 2012). Increased weed competition and problems with seeding can also cause crop yields to be lower under CA than under CT practices during the initial years of implementation (Mashingaidze et al. 2012). Knowledge on how to use the no-tillage planting technique is critical for good crop establishment. Guto et al. (2012) demonstrated that the effects of minimum tillage and crop residue retention on maize yield varied strongly across soil fertility classes.

While short-term yield effects of CA practices are variable, yield benefits are expected to accumulate over time because CA gradually improves biological, chemical, and physical properties of the soil (e.g., Thierfelder et al. 2013c). Results from a meta-analysis of existing crop yield data from long-term experiments in sub-Saharan Africa do not confirm this hypothesis, and show large variation in the data (Fig. 18.6). Rusinamhodzi et al. (2011) showed through meta-analysis of results from long-term experiments in subhumid and semiarid regions of the world that the highest yield increases in time with CA are encountered when rotations with legumes are practiced. This is corroborated by results from studies in southern Africa: in some cases, maize yields following legumes were almost double that of continuous maize under no-tillage (Thierfelder et al. 2012). Other studies in southern Africa found that in the high rainfall environment of Malawi, substantial maize yield benefits were obtained with the practice of no-tillage with mulching after five seasons (Ngwira et al. 2012), while in on-farm trials in southern Zambia, incremental benefits of CA systems over the conventional practice became significant from the third cropping season onwards (Thierfelder et al. 2013c).

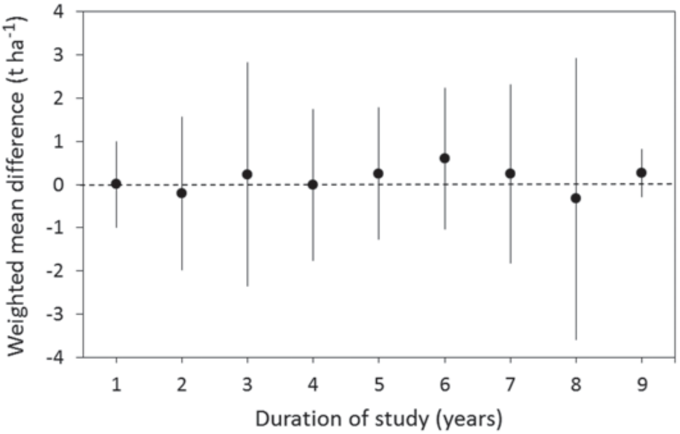


Fig. 18.6 Weighted mean difference in crop grain yield over time between conservation agriculture and conventional tillage-based practices. The results are from a meta-analysis of long-term experiments in sub-Saharan Africa: Vogel (1993), Lal (1997), Nehanda (2000), Moyo (2003), and Thierfelder et al. (2013c). The bars show the 95 % confidence intervals of the means

18.8 Effects on Soil Quality

Various studies have reported beneficial effects of CA on the fertility of (sub)tropical soils in sub-Saharan Africa and elsewhere, including chemical, physical, and biological soil properties (e.g., Lal (1998b) and De Vleeschauwer et al. (1980) in Nigeria; Thierfelder and Wall (2012) and Mupangwa et al. (2013) in Zimbabwe).

18.8.1 Soil Carbon

When no or minimum tillage is applied in combination with crop residue mulching or crop rotations and when this practice is compared to that of CT with removal (burning or grazing) of crop residues, soil carbon increased in some case studies after 3–8 years of practice, but not in other cases (Table 18.1). In general, increased soil carbon under CA can be mainly attributed to increased retention of crop residues compared to conventional practices, as shown in a modeling analysis by Corbeels et al. (2006) for a case study in the Cerrado region of Brazil. Similar conclusions were drawn from a meta-analysis of global data on the effects of CA on soil carbon contents (Luo et al. 2010). No-tillage did not increase the overall soil organic carbon stocks in most cases, except for those with increased biomass production and crop residue retention via double cropping (two crops per year). This also means that soil carbon storage will be limited in drier areas of Africa (< 600 mm of rainfall) where biomass production and amounts of crop residues are low. Besides, conversion from CT to no-tillage significantly alters the vertical distribution of soil carbon in the soil profile, resulting in increased soil carbon in the 0–10 cm soil and decreased soil carbon in the 10–40 cm soil layers. It is also important to note that positive effects on soil carbon are more likely to occur in finer-textured soils than in sandy soils, because of the lack of physical and structural protection of soil organic matter in sandy soils (Chivenge et al. 2007). This may in part explain the lack of significant soil carbon responses to CA at some of the sites with coarse-textured soils in Table 18.2.

18.8.2 Soil Fauna

It is generally believed that the lack of soil disturbance with the supply of organic matter favors the abundance and biodiversity of soil fauna. Few studies exist on the effect of CA on biological activity in soils of sub-Saharan Africa. One detailed study (Brévault et al. 2007) in northern Cameroon found that under 3-year-old no-tillage cotton-based systems, populations of detritivores (especially earthworms, and to a lesser extent also termites and ants) and predators (spiders, carabids, staphylinids, centipedes) were larger and more diverse with crop residue mulching than under conventional systems with tillage and without mulching. A study

Table 18.2 Soil carbon stocks under conventional tillage (*CT*) and conservation agriculture (*CA*) in experiments of different duration in sub-Saharan Africa

Location	Soil texture	Soil depth (cm)	Duration (year)	Soil C (Mg ha^{-1})		Δ*C*/year	Reference
				CT	CA		
Mulching, including rotation or intercropping							
Monze, Zambia	Loamy sand	0–30	5	23.4	32.3	1.78	Thierfelder et al. (2013c)
Henderson, Zimbabwe	Loamy sand	0–30	4	18.4	24.7	1.57	Thierfelder et al. (2012)
Malende, Zambia	Sand	0–30	3	Nonsignificant differences			Thierfelder et al. (2013c)
Lemu, Malawi	Sandy clay loam	0–30	6	Nonsignificant differences			Ngwira et al. (2012)
Zidyana, Malawi	Sandy loam	0–30	6	Nonsignificant differences			Ngwira et al. (2012)
Kayowozi, Zambia	Loamy sand	0–20	3	Nonsignificant differences			Thierfelder et al. (2013c)
Mulching, no rotation or intercropping							
Harare, Zimbabwe	Clay	0–20	8	18.7	26.8	1.01	Nyagumbo (2002); Chivenge et al. (2007)
Domboshawa, Zimbabwe	Loamy sand	0–20	8	13.0	20.7	0.96	Nyagumbo (2002)
Madziwa, Zimbabwe	Sand	0–30	5	7.4	10.0	0.52	Thierfelder et al. (2012)
Chikato, Zimbabwe	Sand	0–20	4	6.9	13.3	1.60	Thierfelder and Wall (2012)
Hereford, Zimbabwe	Sandy clay loam	0–20	3	37.5	43.3	1.93	Thierfelder and Wall (2012)
Domboshawa, Zimbabwe	Sandy clay loam	0–20	2	16.8	16.9	0.05	Nyamadzawo et al. (2008)
Ibadan, Nigeria	Sandy loam	0–10	8	13.4	24.3	1.36	Lal (1998b)
Nyabeda, Kenya	Sandy loam	0–30	5	Nonsignificant differences			Paul et al. (2013)
Abomey-Calavi, Benin	Sandy loam	0–15	1	Nonsignificant differences			Saito et al. (2010)

Δ*C* is the calculated annual difference in soil carbon stock between *CA* and *CT*
CT conventional tillage, *CA* conservation agriculture

in Zimbabwe (Mutema et al. 2013) found a significant correlation between maize residue amounts and macrofauna abundances. This and other studies in southern Africa (Nhamo 2007; Ngwira et al. 2013) reported that termites are particularly attracted by cereal crop residues on the soil surface, mostly on coarse-textured soils. The effect of their biological activity on soil fertility and crop growth is compound and probably depends largely on the type of termite species. They accelerate decomposition of crop residues, thereby releasing nutrients and open up galleries that enhance rainfall infiltration; on the other hand, they can leave the soil bare at an early stage of the cropping season. In some situations, crops (especially cereals) are damaged by termite species, especially toward harvest when residue cover has completely disappeared. Thierfelder and Wall (2010) in Zambia and Ngwira et al. (2013) in Malawi reported significant increases in earthworm populations under no-tillage systems with residue retention. For an Alfisol in southwestern Nigeria, Lal and Akinremi (1983) observed that the rate of earthworm cast production was higher in no-till than in plowed and in mulched than in unmulched treatments. These results confirm the findings from studies in other (sub)tropical parts of the world (e.g., Brown et al. 2002 and Blanchart et al. 2007 for subtropical and tropical Brazil, respectively). Earthworms play an important role in incorporating organic matter, enhancing nutrient cycling, and increasing soil porosity and channels for root development. The above cited studies show clear evidence of enhanced biological activity under CA. However, more research is needed to better understand the functional properties of the diverse soil fauna with respect to nutrient cycling, pest incidences (see below), and plant growth processes under CA systems under (sub)tropical cropping conditions.

18.8.3 Soil Water and Erosion

The original interest in CA stems from the beneficial effect of crop residue mulching on soil water runoff and erosion. Surface residues protect the soil from the impact of raindrops and reduce soil sealing and crust formation. Several studies have demonstrated lower soil water runoff and erosion under no-tillage with mulching in sub-Saharan Africa (e.g., Kamara (1986) in Sierra Leone; Lal (1998a) in Nigeria; Thierfelder and Wall (2009) in Zimbabwe; Araya et al. (2012) in Ethiopia). In a recent review of studies in East and southern Africa, Wall et al. (2014) found that average reduction in runoff with the practices of CA was 51 % with a range from 14 to 95 %. A relationship—based on a set of data from the literature—between reduced water runoff as a result of CA compared to tillage-based systems and the amount of mulching is presented in Fig. 18.7. It shows that the upper boundary line of the surface runoff response to mulching starts to exponentially decline from residue loads of about 3000 kg ha^{-1}. Thirty percent of soil cover has been proposed as a threshold value for effectively controlling soil water runoff and erosion (Allmaras and Dowdy 1985). However, in many African smallholder situations, cover of crop residues falls below 30 % mainly due to other uses for the crop residues combined with low crop biomass production. In cases with low soil cover, untilled soils prone

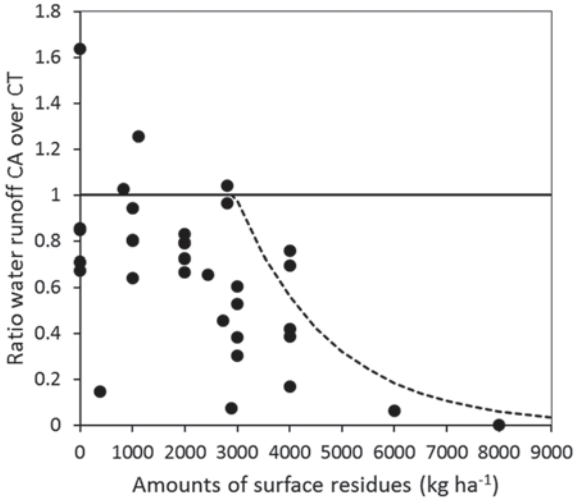


Fig. 18.7 Relationship between surface water runoff under conservation agriculture (*CA*) compared with conventional tillage (*CT*) and mulch amounts. Data from Khatibu et al. (1984), Lal (1998a), Vogel et al. (1994), Woyessa and Bennie (2007), Munodawafa and Zhou (2008), Thierfelder and Wall (2009), and Baudron et al. (2012). The broken line shows the boundary line of minimum reduction in water runoff under CA for mulch amounts >3000 kg ha^{-1}: $y = 5.17 * e^{-0.00056 * x}$

to soil crusting may cause higher surface water runoff and erosion than tilled soils (Okwach and Simiyu 1999; Baudron et al. 2012). Under such circumstances, tillage breaks down the soil crust, resulting in higher rainfall infiltration (Aina et al. 1991). On the other hand, from results of trials in semiarid regions of Ethiopia, Kenya, Tanzania, and Zambia, Rockstrom et al. (2009) suggested that ripping is an efficient strategy to capture and conserve rainfall water compared to tillage, especially if combined with fertilizer application.

Crop residue mulching decreases soil evaporation losses (Scopel et al. 2004). Although no studies from sub-Saharan Africa have been reported on direct measurements of soil evaporation rates under CA systems compared with cropping systems with tillage, several studies have indirectly demonstrated this effect through soil moisture measurements showing increased soil water contents under mulching (e.g., Mkoga et al. 2010; Mupangwa et al. 2012; Thierfelder and Wall 2012). This is an important feature, especially in regions with low and erratic rainfall, resulting in short-term positive crop responses to CA. For example, from the results of a three-year experiment on sandy soils in the semiarid region of Zimbabwe, Vogel (1993) reported that the practice of ripping with mulch gave the highest yields in dry years if there were enough crop residues left on the soil surface. Where this was not the case, moldboard plowing and ripping yielded equal. The same author argued that tied ridging may be the best tillage technique for the subhumid north of Zimbabwe, due mainly to the prevention of waterlogging and increased root depth. Problems with waterlogging may occur under no-tillage with mulching during wet seasons on granitic sandy soils in Zimbabwe (Thierfelder and Wall 2012). On the other hand, Enfors et al. (2011) found in northeastern Tanzania that, although no-tillage with mulching can increase grain yield during good rainy seasons, during poor rainfall seasons, grain harvests may be lower under mulching. This was due to increased vegetative growth early in the season at the expense of grain filling later in the season.

The potential benefit from the practice of CA on the soil water balance has been the grounds for advocating CA as a technology to cope with a changing climate of more erratic rainfall (Kassam et al. 2009). This potential has been theoretically shown in a crop growth modeling analysis for a case study in Zimbabwe (Corbeels et al. 2014). Model predictions suggest 30 % yield reductions in maize production under CT as a result of changing climate (15 % less and more erratic rainfall and higher temperatures of + 1.1 °C on average) in subhumid southern Africa could be compensated by adopting no-tillage with mulching.

18.9 Pest, Disease, and Weed Dynamics Under CA

Published information on the effects of the practice of CA on pests and diseases in sub-Saharan Africa is limited. Some reports from southern Africa mention the increased incidence of white grubs (larvae of *Phyllophaga* spp. and *Heteronychus* spp.) with the practice of no-tillage with mulching under continuous maize cropping, but this seems to disappear when maize is rotated with legumes (Thierfelder et al. 2014). Residue retention and the associated increased humidity at the soil surface favor the survival of pathogens until the following crop is planted. For example, surface crop residues infected with the fungal pathogen *Cercospora-maydis* that is responsible for gray leaf spot disease can represent an early-stage inoculum for the next maize crop, which will give rise to more life cycles of the fungus, resulting in an acute gray leaf spot infection of the crop (Thierfelder et al. 2014). On the other hand, there is evidence that pests and diseases that are carried over through crop residues can be controlled with appropriate rotations, since they break the life cycles of the pests and diseases (Thierfelder et al. 2013a).

The incidence of the parasitic weed striga (*Striga asiatica* (L.) Kuntze) seems to diminish under CA, as observed by Rusinamhodzi et al. (2012) and Thierfelder et al. (2014) on fields in central Mozambique and Malawi, respectively. This observation is probably related to soil fertility effects since striga is often associated with poor soil fertility. In general, it is believed that residue cover helps to control weeds, but experimental results suggest that the amount of residue required for effective weed control would be excessively high (Wall et al. 2014; Ngwira et al. 2014). Under farming conditions with limited soil cover, CA without the use of herbicides leads to higher weed pressure than CT-based systems, as, for example, shown by Nyamangara et al. (2014a) for planting basins in Zimbabwe. A primary reason for tillage is the ability to bury small annual weeds with soil. Mashingaidze et al. (2012) reported that to achieve similar levels of weed control for planting basins and CT, the number of man-hours needs to increase by 50–100 % with the planting basins as compared to the tillage systems. Some reports (e.g., Vogel 1995) mention a change in spectrum of weeds under CA, with mulch initially suppressing annual weeds, but perennial rhizomes persevere, leading to increased late-season weed infestation. Nevertheless, when appropriate weed control strategies are applied, which may involve herbicides for chemical weed control, this constraint can be overcome, and successful examples from Malawi show that indeed the availability and use of herbicides can be a major trigger in the uptake of CA (Thierfelder et al. 2013b).

18.10 Effects on Farm Income

First, a recent review (Pannell et al. 2014) on the economics of CA revealed that the number of published studies in sub-Saharan Africa is small, making it difficult to gain a comprehensive understanding of the factors that make the practice of CA profitable or not for farmers. Second, most of the studies appear to have taken very simple approaches with little information about the assumptions used. Most studies perform simple cost–benefit analyses at field scale, which take into account income through crop yields (and crop residues) and costs related to (no) tillage, seeding and harvest operations, fertilization, and weed control. Most reported analyses consider only the variable costs without considering investment costs such as those for a direct seeder, ripper, or knapsack sprayer. A summary of some results of this type of analysis is given in Table 18.3.

The results from the analysis conducted by Haggblade and Plerhoples (2010) compared the practice of planting basins against conventional hand-hoe tillage in Zambia. The study distinguishes three farmer types: poor farmers without access to inputs; farmers with enough cash to purchase a modest package of inputs (US$ 60 season^{-1}); and farmers purchasing a high level of inputs of fertilizer, hybrid seeds, and herbicides (US$ 150 season^{-1}). All three types benefited substantially from CA compared to CT, increasing income by 85, 100, and 200 %, respectively. Although planting basins required more labor compared to the hand-hoe system, the major advantage of using basins was the disaggregation of peak labor times. For the poorest farmers, about two thirds of the income gain stemmed from increased yield, while the remaining one third came from area expansion made possible due to labor savings during peak labor times with planting basins that are dug before the start of the

Table 18.3 Cost–benefit analyses comparing conventional-based tillage (*CT*) with conservation agriculture (*CA*) practices. (Data from Mazvimavi and Twomlow 2009; Haggblade and Plerhoples 2010; Ngwira et al. 2012, 2013)

	Several districts, Malawi[a]			Several districts, Zimbabwe[b]			800–1000 mm rainfall zone of Zambia[c]		
	CT	CA	+LIC	CT–F	CT+F	CA	CT	CA	CA+H
Revenue (USD ha^{-1})	755	1054	1044	163	177	660	166	244	227
Input costs	218	324	315	31	61	54	0	0	31
Labor (days ha^{-1})	63	40	48	69	77	116	103	144	120
Total variable costs (USD ha^{-1})	373	429	441	92	129	156			
Net return (USD ha^{-1})	382	625	603	71	48	504			
Returns to labor (USD day^{-1})	8.58	18.2	15.0	1.91	1.51	5.22	1.6	1.69	1.63

+LIC: CA system with legume intercropping, –F: without the use of fertilizer, +F: with the use of fertilizer, –H: without the use of herbicides, +H: with the use of herbicides

CT conventional tillage, *CA* conservation agriculture, *LIC* legume intercropping

[a] CT: ridge and furrow systems; CA: no-tillage and use of a dibble stick

[b] CT: moldboard plowing; CA: planting basins

[c] CT: hand-hoe tillage; CA: planting basins

growing season. For the wealthiest group, use of herbicides reduced labor inputs for weed control, allowing the farmer to manage as much as 2.7 ha of cropland, compared with only 1.1 ha under conventional hand-hoe tillage. This study highlights the importance of capital for obtaining maximum benefits from CA. Mazvimavi and Twomlow (2009) conducted a cost–benefit analysis on the use of planting basins for a sample of 1400 farmers in Zimbabwe. The study indicated that farmers increased their income by 39% with planting basins compared with conventional cropping. However, the labor requirements were higher with planting basins as they were compared with animal traction moldboard plowing. Moreover, the use of planting basins is often perceived by farmers to be more labor intensive (Umar et al. 2012). Digging basins during the dry season involves considerable labor (28–34 person days ha^{-1}) in the first year, but since they are exactly dug in the same place, the difficulty and time for digging are reduced in following years. This, however, applies less to sandy soils, since on these soils, basins tend to collapse throughout the winter period. In summary, labor constraints with planting basins are one of the major constraints to their widespread adoption: farmers in Zimbabwe tend to have only 0.5 ha or less of their farms under planting basins. Ngwira et al. (2012) in a study in Malawi found that maize with pigeon pea intercropping plus minimum tillage was more profitable than continuous maize with minimum tillage, which was more profitable than the practice of CT with continuous maize. Manual CA systems practiced in Malawi involve direct seeding using a dibble stick, which requires significantly less labor than preparing the traditional ridges and furrows manually. These labor savings are partially offset by increased input costs, but because of increased crop yields, net returns per hectare increased.

In contrast with commercial farming, reduced costs with CA on smallholder farms in sub-Saharan Africa are not always observed. Reducing tillage can lead to increased costs for weed control, be it through increased labor or the use of herbicides. It is commonly observed that where herbicides are not available or not used, labor savings from land preparation may be offset by labor requirements for manual weeding (Ekboir et al. 2002; Ito et al. 2007; Erenstein et al. 2012; Grabowski and Kerr 2014). On the other hand, labor savings with CA are evident in cases where herbicides are used (e.g., Ekboir et al. (2002) in Ghana; Ngwira et al. (2012) in Malawi). However, herbicide use is not always an option for farmers in sub-Saharan Africa due to limited local availability, cash flow problems, or lack of farmer knowledge and training on the use of herbicides.

In multilocation on-farm trials with maize in central Kenya, Guto et al. (2012) found that minimum tillage with residue retention was a profitable practice on soils of medium fertility, and less profitable than CT practice on the poorer and richer soils. These results were to a large extent explained by the crop yield response to tillage or crop residue management. While yields were not influenced by tillage or residue management in the good fields, yields in the medium fields were higher with no-tillage and crop residue retention; in the poor fields, minimum tillage resulted in yield reductions while crop residue addition did not affect yields.

The economics of mulching with crop residues are highly context-specific, depending on factors such as human population, livestock density, cropping intensity, access to alternative feed sources, land, and markets (Valbuena et al. 2012). Although crop residues are in many regions of sub-Saharan Africa nonprivate products, particularly when the practice of free grazing is the (cultural) rule, their (economic) value can be assumed to be reflected in the costs of fencing the fields and additional labor requirements for collection, transport, and management of the residues (Mazvimavi and Twomlow 2009). In regions where farmers have enclosed fields, their most valuable use may not be for mulching. Farmers may benefit more by using crop residues for animal feed (Akpalu and Ekbom 2010; Jaleta et al. 2012). For example, in a case study in northeastern Zimbabwe, Rusinamhodzi et al. (2014) found little scope for crop residue retention in the field for farmers with cattle as it leads to reduced animal productivity. It was estimated that retention of all crop residues on the fields can reduce total farm income by almost US$ 1000 year^{-1}.

Corbeels et al. (2014) reported a farm-scale analysis comparing the economics of farmers who have adopted or experimented with CA and farmers who had not. Results for a number of case studies are presented in Table 18.4. Typically, farmers who practice CA do this on less than about 30–40 % of their land, presumably since they are still cautious about it and may have land (soils) and crops less suitable for the practice of CA. Earnings from cropping were higher for farmers with CA in the Kenyan and Malawian/Zimbabwean case studies, but lower in the Tanzanian case studies compared with the farmers who did not practice CA on their farms. Fields under CA in all case studies gave higher incomes per hectare than fields that were cultivated with CT. Farmers practicing CA also had higher income per hectare from

Table 18.4 Farm economic data comparing farms with (*CA*) and without (*non-CA*) the practice of conservation agriculture from agro-economic surveys held in three study areas in 2010–2012 (values in Euro). (Source: Corbeels et al. 2014)

Country	Kenya		Tanzania		Malawi/Zimbabwe	
Region	Bungoma		Karatu		(Various)	
Exchange rate (1 €)	105 KES		2000 TSH		215 MWK/1.31 US$	
Year	2011		2011		2012	
Farm category	CA	Non-CA	CA	Non-CA	CA	Non-CA
Sample size (no.)	25	25	25	25	25	13
Average farm size (ha)	1.03	0.93	1.82	1.30	2.13	1.83
Of which CA (%)	31	0	29	0	26	0
Family size (no.)	7	6.8	6.5	5.8	–	–
Average no. of cattle (no.)	3.4	2.9	3.6	2.9	3.04	2.4
Ann. crop income (€/year)	813	615	478	563	423	323
Ann. livest. income (€/year)	165	207	275	237	N/A	N/A
Crop and livest. income (€/year)	978	822	753	800	N/A	N/A
Off-farm income (€/year)	496	514	187	360	353	526
Total farm income (€/year)	1473	1336	940	1160	776	849
Family expenses (€/year)	1149	1013	1099	956	1526	960
Value crop prod (€/ha)	1456	1017	523	551	199	176
CA crop prod (€/ha)	1526	–	598	–	185	–
Non-CA crop prod (€/ha)	1256	1017	419	551	203	176

CA conservation agriculture, *CT* conventional tillage, *EUR* euro, *KES* Kenyan shilling, *TZS* Tanzanian shilling, *MWK* Malawian kwacha their fields under CA than from their other fields, with exception of the Malawi/Zimbabwe case study. In general, the practice of CA resulted in higher crop yields, but these higher yields were often obtained because of higher inputs in terms of fertilizer, herbicides, and labor. For example, in Malawi/Zimbabwe, mean maize yield was 2097 kg ha^{-1} on fields under CA compared with 1038 kg ha^{-1} on the other fields, but farmers applied on average 10 % more fertilizer and spent 45 % more labor time on fields under CA. Overall, the results show that farmers who practice CA do not seem to have systematically higher levels of net income than farmers who do not. This is to a great extent a consequence of the various trade-offs that exist with the use of available resources (land, labor, and cash). We may conclude that in the sub-Sahara African context, the economic benefits from the practice of CA are still difficult to quantify unambiguously, and are confounded by seasonal variability and location and farm specificities.

18.11 Challenges with Adoption of CA

The low adoption figures in sub-Saharan Africa (Table 18.1) are most likely an indication of the challenges with disseminating CA on smallholder farms. They have been summed up and discussed in recent papers on CA in Africa (Wall 2007; Giller et al. 2009; Erenstein et al. 2012; Corbeels et al. 2014; Wall et al. 2014; Thierfelder et al. 2014). The constraints with widespread adoption of CA in Africa were also identified in a more formal way using an expert assessment tool by Ndah et al. (2012, 2014).

A major constraint is that crop production and income benefits from the practice of CA are often not experienced from the first year, but only occur in the longer term (Rusinamhodzi et al. 2011), while associated costs and the farmer's needs to feed his/her family are immediate. Smallholder farmers often attribute a substantially higher value to immediate costs and benefits than those incurred or realized in the future (Pannell et al. 2014). This is particularly true for resource-poor farmers (Grabowski and Kerr 2014). More generally, a literature survey by Harris and Orr (2014) demonstrated the limited impact of improved crop production technologies on income of smallholder farmers in sub-Saharan Africa, i.e., too small to lift them above the poverty line, due to the small farm sizes and the low value of crop products with a lack of commercialization. Direct benefits are in many situations restricted to improved household food security.

The practice of CA incurs strong trade-offs with other activities at the farm level and above. Probably, the strongest trade-offs occur with the use of crop residues. The retention of crop residues on the soil surface as mulch competes with their use as fodder for livestock. Crop residues are also used for bedding in kraals, construction (fencing and thatching), and as a source of fuel. In many situations, especially in the subhumid and semiarid regions, animal feed is often in critically short supply and takes precedence, since livestock plays a crucial role in the livelihoods of smallholder farmers, i.e., as a source of draft power, cash income, and risk buffer (Herrero et al. 2013). Grazing systems that rely on communal use and traditional grazing patterns especially are a threat to mulching. In these systems, individual farmers cannot restrict grazing even on their own land without challenging the traditional rights of others in the community: protecting the crop residues from free grazing through, e.g., fencing of the plots, requires renegotiation of the traditional rules or local bylaws. The promotion of mulching in CA systems has therefore to be done concurrently with the promotion of fodder production. New ways of additional fodder production through intercropping and relay cropping are alternatives that should be explored. Another trade-off with the practice of CA relates to the use of available labor and/or cash on the farm. The increased amount of labor required for weeding with CA may outweigh the labor savings gained by not plowing the soil unless herbicides are used to control weeds, but this requires cash. The reallocation of labor, especially to weeding, often is implying more work for women (Giller et al. 2009).

In many regions in sub-Saharan Africa, the poor functioning and access to markets, exacerbated by the lack of suitable credit opportunities, impede farmers from investing in herbicides, seeds, fertilizers, and no-till equipment. In general, market support for smallholders is needed in order to create economic incentives to invest in new agricultural technologies (Ehui and Pender 2005). These economic constraints to the adoption of CA are likely to vary between countries and regions, as well as market environments as they are determined by the distance to markets, infrastructure, and an overall enabling environment.

Finally, the knowledge-intensive nature of CA technologies presents another major challenge. The number of practices that need to be altered at the same time necessitates a major transformation in crop and soil management (Erenstein 2002). Often, there is a lack of appropriate technical information or support for farmers, but also for extension workers. This, combined with the low education and literacy standards of farmers, constrains the learning and experimenting process with CA technologies. Therefore, adoption is unlikely to be immediate, but will be incremental, with farmers experimenting on small areas and only adopting on a larger scale when they fully get to grips with the new practices.

18.12 The Need for Targeting CA Practices

Given the diversity of farming systems and farmers in sub-Saharan Africa, a major challenge with the development and dissemination of CA is the identification of situations where CA can offer major benefits (Knowler and Bradshaw 2007; Giller et al. 2009; Corbeels et al. 2014). It involves targeting CA technologies to regions and categories of farmers who are likely to adopt practices of CA. This will help development agents to better direct their investments with CA.

Adoption studies may provide ex post insight into the adoptability of particular CA technologies for particular categories of farmers in specific agroecological, socioeconomic, and institutional contexts (Andersson and D’Souza 2014). However, these studies are often biased because of project interferences in the form of input support (fertilizers, seeds, CA implements). Ex ante analyses are required for effective targeting and dissemination of CA. They involve a multiscale analysis of factors that influence the performance and adoption of CA (Corbeels et al. 2014), which can be done based on results from on-station and on-farm agronomic experiments, simulation modeling, farm-level economic studies, and (market) institutional analyses. The socioecological niche approach (Ojiem et al. 2006) provides a practical framework for “ideotyping” the contexts within which CA has most to offer. A series of biophysical, socioeconomical, and institutional factors and their interactions delineate the socioecological niche for a type of CA technology. For each factor, several criteria boundaries must be established and then used to set limits for the niche. Following Sumberg (2005), adoption constraints should be distinguished from prerequisite higher-scale conditions; the former referring to the “goodness-of-fit” between the CA technology and the farmer (type), while the latter focuses on contextual factors, that cannot be influenced by the CA development and dissemination process (Andersson and d’Souza 2014; Corbeels et al. 2014). As illustrated above, CA comprises different practices, each with their specific requirements for labor, equipment, chemical inputs, etc. that are suitable to different types of farmers (and farming environments). For example, direct seeders have a high equipment cost and are only accessible by a small proportion of smallholder farmers in sub-Saharan Africa, although there are cheaper alternatives such as rippers. In general, CA will be most rapidly adopted by smallholder farmers with adequate resources of land, cash, and labor, and not by the most resource-constrained groups. Functional farm typologies based on farmers’ production objectives and resource endowments (including the importance of farm size) will help in better targeting CA technologies. To start with, a clear differentiation has to be made between mechanized and manual CA systems; they will clearly match different categories of farmers (Andersson and Corbeels 2014). Figure 18.8 shows a first typology of situations where CA is likely to be adopted by farmers.

Targeting CA to a group of farmers also involves adaptation of a given technology to their local circumstances and specific contexts. Aspects that need to be considered include farmers’ production objectives and constraints, expected costs

Fig. 18.8 Typology of situations where conservation agriculture is likely to be adopted by smallholder farmers in sub-Saharan Africa. Several of these conditions are interlinked and may interact. (Adapted from Giller et al. 2011)

Likelihood of adoption of conservation agriculture

→

Many livestock	Few livestock
Free grazing	Enclosed fields
Resource-poor farmers	Resource-rich farmers
Subsistence-oriented farmers	(Semi)commercial-oriented farmers
Poor market access	Good market access
Low production potential	High production potential
Low soil fertility	High soil fertility
Land abundance	Land scarcity
Insecure land tenure	Secure land tenure
No erosion	Erosion prone areas
Inadequate extension support	Good extension support

(requirements in terms of inputs, equipment, labor), benefits (especially in the short term), production and financial risk, input supply and marketing, farmers' perceptions, and technical advice (Erenstein 2003; Giller et al. 2009; Mazvimavi and Twomlow 2009). This can be achieved through an innovation systems approach that fosters dynamic interactions among researchers, extension agents, equipment manufacturers, input suppliers, farmers, traders, and processors (e.g., Ekboir 2003). Critically, this depends on learning processes, feedback loops, and iterative interactions that are decidedly nonlinear (Spielman et al. 2008). Only then is a targeted adaptation process likely to create viable CA-based options. The participation of farmers in iterative technology development through action research with a solid involvement of researchers (co-innovation) has fostered the adoption of soil improving technologies (e.g., Misiko and Tittonell 2009).

18.13 Policy Support

Several African countries have incorporated CA in their strategic plans for the development of the agricultural sector. CA is now government policy in Tanzania, Kenya, Malawi, Mozambique, Zimbabwe, Zambia, and Lesotho. West African countries are lagging behind in this respect. In southern and eastern Africa, actions on CA are supported by focal points from national task forces, regional organizations—ACT, the New Partnership for Africa's Development (NEPAD), Southern African Development Community (SADC)—and international research centers (e.g., CIMMYT, ICRISAT, and ICRAF). Under the Common Market for Eastern and Southern Africa's (COMESA) climate change program, CA has been endorsed as an appropriate adaptation and mitigation action for African agriculture. However, the question remains how effective are the policies and programs that are put in place in promoting CA. Besides, the context for private sector support is often uncertain. Strategies for developing and disseminating CA should also take into account market mechanisms, and market support policies should be designed that favor the emergence of CA. The recent food crisis put market regulations and production incentives back on the world agenda, with particular focus on Africa where yield gaps and hence the perspectives of production increases are the largest (Tittonell and Giller 2013; Affholder et al. 2013). Many CA technologies that are inappropriate for subsistence-oriented farms might become opportunities for market-oriented farms, as suggested by studies in emerging countries (e.g., in Brazil and India).

18.14 Conclusions

Several studies compared the performance of CA practices with that of CT-based practices in sub-Saharan Africa. Most of the reported studies come from southern Africa, some from East Africa, and few from West Africa. The studies mostly relate to maize-based cropping systems. Overall, the studies indicate that the three principles of CA are needed to increase crop yields compared with conventional practices. Immediate crop yield benefits from CA are, however, highly variable. They are most likely to be positive when crops are drought stressed, because of the soil moisture conservation effect of mulching. Benefits through increased soil fertility (soil carbon) are expected to increase over time. The published results from long-term experiments point in this way, although, again, experimental results are variable, both in terms of soil carbon and crop yields.

Much less information is available in the literature on the economics of CA. The published studies indicate that the economic attractiveness of CA is highly site-specific and depends on the type of CA technology and the overall farming context. In contrast with commercial farming, reduced costs with CA on smallholder farms in sub-Saharan Africa are not always observed. Moreover, the fact that crop responses to CA are variable, and not always positive, is an important hindrance for adoption by resource-poor farmers, since they need immediate returns with their investments in CA. Farmers with a strategy of intensification are more likely to adopt proposed technologies of CA than farmers who struggle to produce food for their family. The latter too often face multiple constraints that limit the possibilities to engage in technological innovations. Some farmers may not be interested in new technologies for agricultural intensification because they earn their income from off-farm activities.

Adoption figures for CA in sub-Saharan Africa are low despite more than two decades of research and development investments with CA technologies. The small farm sizes in sub-Saharan Africa raise questions about the potential impact of technological interventions on farm income and agricultural development. Small farm sizes make farmers more risk averse: putting a part of the field(s) aside for new technology testing may represent a significant risk in terms of short- to medium-term household food security. Another challenge with the practice of CA is the use of crop residues for mulching since crop residues are a major source of feed for livestock, especially in semiarid regions, where biomass production is limited and livestock plays a crucial role in farming systems.

There is an urgent need to better target investment efforts with dissemination of CA in sub-Saharan Africa. The development and promotion of CA requires the ex ante identification of farmer categories that are potential end users of the technologies and effective adaptation of technologies to the agricultural context and the needs of these types of smallholder farmers. Good markets of input supply and sale of extra produce are a prerequisite condition for the widespread adoption of CA as they are for any other new agricultural technology that aims at intensification. A broad range of stakeholders, including farmers, extension agents, researchers, input suppliers, equipment manufacturers, service providers, traders, and policymakers, need to be involved in the development and diffusion process of CA. An important role for research today is to find out how to effectively foster dynamic interactions and synergies for joint learning and experimenting with CA and how to improve in general the policy and institutional context for agricultural innovation in sub-Saharan Africa.

References

Aagaard PJ (2013) History of the conservation farming unit–Zambia. http://conservationagriculture.org/history-of-the-conservation-farming-unit-zambia. Accessed 10 March 2014

Affholder F, Poeydebat C, Corbeels M, Scopel E, Tittonell P (2013) The yield gap of major food crops in family agriculture in the tropics: assessment and analysis through field surveys and modelling. Field Crop Res 143:106–118

Aina PO, Lal R, Roose EJ (1991) Tillage methods and soil and water conservation in West Africa. Soil Till Res 20:165–186

Akpalu W, Ekbom A (2010) The bioeconomics of conservation agriculture and soil carbon sequestration in developing countries. Environment for Development Discussion Paper Series, EfD DP 10–07, Environment for Development, March 2010

Allmaras RR, Dowdy RH (1985) Conservation systems and their adoption in the United States. Soil Till Res 5:197–222

Andersson JA, D'Souza S (2014) From adoption claims to understanding farmers and contexts: a literature review of conservation agriculture (CA) adoption among smallholder farmers in southern Africa. Agric Ecosyst Environ. 187:116–132

Andersson JA, Corbeels M (2014) Towards a CA targeting tool for project implementers in Africa: identifying the main elements. Book of condensed papers, 1st African Congress on Conservation Agriculture, Lusaka, 18–21 March 2014, http://www.africacacongress.org/sites/default/files/attachments/book_of_condensed_papers.pdf. Accessed 2 Oct 2014, pp 196–200

Apina T, Wamai P, Mwangi PK (2007) Laikipia district. In: Kaumbutho P, Kienzle J (eds) Conservation agriculture as practised in Kenya: two case studies. African Conservation Tillage Network, Centre de Coopération, Internationale de Recherche Agronomique pour le Développement. Food and Agriculture Organization of the United Nations, Nairobi, pp 2–56

Araya T, Cornelis WM, Nyssen J, Govaerts B, Getnet F, Bauer H, Amare K, Raes D, Haile M, Deckers J (2012) Medium-term effects of conservation agriculture based cropping systems for sustainable soil and water management and crop productivity in the Ethiopian highlands. Field Crop Res 132:53–62

Barrett CB (2008) Smallholder market participation: concepts and evidence from eastern and southern Africa. Food Policy 33:299–317

Baudron F, Mwanza HM, Triomphe B, Bwalya M (2007) Conservation agriculture in Zambia: a case study of southern province. Conservation agriculture in Africa Series. African Conservation Tillage Network, Centre de CoopeÌration Internationale de Recherche Agronomique pour le DeÌveloppement. Food and Agriculture Organization of the United Nations, Nairobi, p 28

Baudron F, Tittonell P, Corbeels M, Letourmy P, Giller KE (2012) Comparative performance of conservation agriculture and current smallholder farming practices in semi-arid Zimbabwe. Field Crop Res 132:117–128

Benites J, Chuma E, Fowler R, Kienzle J, Mapolang K, Manu J, Nyagumbo I, Steiner K, van Veenhuizen R (1998) Conservation tillage for sustainable agriculture. Part 1 (Workshop Report). Proceedings from an International Workshop, Harare, 22–27 June 1998

Blanchart E, Bernoux M, Sarda X, Siqueira Neto M, Cerri CC, Piccolo M, Douzet JM, Scopel E, Feller C (2007) Effect of direct seeding mulch-based systems on soil carbon storage and macrofauna in Central Brazil. Agric Conspec Sci 72:81–87

Bolliger A, Magid J, Amado TJC, Neto FS, Ribeiro MDD, Calegari A, Ralisch R, de Neergaard A (2006) Taking stock of the Brazilian "zero-till revolution": a review of landmark research and farmers' practice. Adv Agron 91:47–110

Brévault T, Bikay S, Maldès JM, Naudin K (2007) Impact of a no-till with mulch soil management strategy on soil macrofauna communities in a cotton cropping system. Soil Till Res 97:140–149

Brouder SM, Gomez-Macpherson H (2014) The impact of conservation agriculture on smallholder agricultural yields: a scoping review of the evidence. Agric Ecosyst Environ. 187:11–32

Brown GG, Benito NP, Pasini A, Sautter KD, Guimaraes MF, Torres E (2002) No-tillage greatly increases earthworm populations in Parana state, Brazil. Pedobiologia 47:764–771

Carter S, Murwira H (1995) Spatial variability in soil fertility management and crop response in Mutoko Communal Area, Zimbabwe. Ambio 24:77–84

Chivenge PP, Murwira HK, Giller KE, Mapfumo P, Six J (2007) Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. Soil Till Res 94:328–337

Corbeels M, Scopel E, Cardoso AN, Bernoux M, Douzet JM, Siqueira Neto M (2006) Soil C storage potential of direct seeding mulch-based cropping systems in the Cerrados of Brazil. Glob Change Biol 12:1773–1787

Corbeels M, de Graaff J, Ndah TH, Penot E, Baudron F, Naudin K, Andrieu N, Chirat G, Schuler J, Nyagumbo I, Rusinamhodzi L, Traore K, Mzoba HD, Adolwa IS (2014) Understanding the impact and adoption of conservation agriculture in Africa: a multi-scale analysis. Agric Ecosyst Environ. 187:155–170

Derpsch R, Friedrich T, Kassam A, Hongwen L (2010) Current status of adoption of no-till farming in the world and some of its main benefits. Int J Agric Biol Eng 3:1–25

De Vleeschauwer D, Lal R, Malafa R (1980) Effects of amounts of surface mulch on physical and chemical properties of an Alfisol from Nigeria. J Sci Food Agric 31:730–738

Dixon JA, Gibbon DP, Gulliver A (2001) Farming systems and poverty: Improving farmers' livelihoods in a changing world. Food and Agriculture Organization (FAO) and Word Bank, Rome and Washington, p 41

Dorward A (2009) Integrating contested aspirations, processes and policy: development as hanging in, stepping up and stepping out. Dev Policy Rev 27:131–146

Ehui S, Pender J (2005) Resource degradation, low agricultural productivity, and poverty in sub-Saharan Africa: pathways out of the spiral. Agric Econ 32:225–242

Ekboir J (2002) Developing no-till packages for small-scale farmers. In: Ekboir J (ed) World wheat overview and outlook. CIMMYT, Mexico City, pp 1–38

Ekboir J (2003) Research and technology policies in innovation systems: zero tillage in Brazil. Res Policy 32:573–586

Ekboir J, Boa K, Dankyi AA (2002) Impact of no-till technologies in Ghana. Economics Program Paper. CIMMYT, Mexico City, p 32

Enfors E, Barron J, Makurira H, Rockström J, Tumbo S (2011) Yield and soil system changes from conservation tillage in dryland farming: a case study from north-eastern Tanzania. Agric Water Manage 98:1687–1695

Erenstein O (2002) Crop residue mulching in tropical and semi-tropical countries: an evaluation of residue availability and other technological implications. Soil Till Res 67:115–133

Erenstein O (2003) Smallholder conservation farming in the tropics and subtropics: a guide to the development and dissemination of mulching with crop residues and cover crops. Agric Ecosyst Environ 100:17–37

Erenstein O, Sayre K, Wall P, Hellin J, Dixon J (2012) Conservation agriculture in maize and wheat-based systems in the (sub)tropics: lessons from adaptation initiatives in South Asia, Mexico, and Southern Africa. J Sustain Agric 36:180–206

FAO.org (2014) Conservation agriculture. http://www.fao.org/ag/ca/1a.html. Accessed 10 March 2014

Findlay JBR, Hutchinson NC (1999) Development of conservation tillage in African countries: a partnership approach. In: Breth SA (ed) Partnerships for rural development in sub-Saharan Africa. Centre for Applied Studies in International Negotiations, Geneva, pp 52–63

Friedrich T, Derpsch R, Kassam A (2012) Overview of the global spread of conservation agriculture. Field actions science reports; Special Issue 6. file:///C:/Users/Client/Downloads/factsreports-1941-special-issue-6-document-sans-titre%20.pdf. Accessed 10 March 2014

Garrity DP, Akinnifesi F, Ajayi O, Weldesemayat S, Mowo J, Kalinganire A, Larwanou M, Bayala J (2010) Evergreen agriculture: a robust approach to sustainable food security in Africa. Food Secur 2:197–214

Giller KE, Witter E, Corbeels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crop Res 114:23–34

Giller KE, Corbeels M, Nyamangara J, Triomphe B, Affholder F, Scopel E, Tittonell P (2011) A research agenda to explore the role of conservation agriculture in African smallholder farming systems. Field Crop Res 124:468–472

Grabowski PP, Kerr JM (2014) Resource constraints and partial adoption of conservation agriculture by hand-hoe farmers in Mozambique. Int J Agric Sustain 12:37–53

Greenland DJ (1975) Bringing the green revolution to the shifting cultivator. Science 190:841–844

Guto SN, Pypers P, Vanlauwe B, de Ridder N, Giller KE (2012) Socio-ecological niches for minimum tillage and crop-residue retention in continuous maize cropping systems in smallholder farms of central Kenya. Agron J 104:188–198

Haggblade S, Tembo G (2003) Conservation farming in Zambia. EPTD Discussion Paper No. 108. International Food Policy Research Institute and Michigan State University, Washington and East Lansing, p 113

Haggblade S, Plerhoples C (2010) Productivity impact of conservation farming on smallholder cotton farmers in Zambia. Working Paper No. 47, Food Security Research Project, Lusaka, p 38

Harris D, Orr A (2014) Is rainfed agriculture really a pathway from poverty? Agric Syst. 123:84–96

Herrero M, Grace D, Njuki J, Johnson N, Enahoro D, Silvestri S, Rufino MC (2013) The roles of livestock in developing countries. Animal 7(Suppl 1):3–18

Horus Entreprise (2009) Mission d'appui Ã Sodécoton en vue d'améliorer son système d'appui aux producteurs. Partie 2–aspects relatifs aux SCV (French). Paris, p 32

Ito M, Matsumoto T, Quinones MA (2007) Conservation tillage practice in Sub-Saharan Africa: the experience of Sasakawa global 2000. Crop Prot 26:417–423

Jaleta M, Kassie M, Shiferaw B (2012) Tradeoffs in crop residue utilization in mixed crop-livestock systems and implications for conservation agriculture and sustainable land management. Selected paper prepared for presentation at the International Association of Agricultural Economists (IAAE) Triennial Conference, Foz do Iguacu, 18–24 August 2012. http://ageconsearch.umn.edu/handle/96168. Accessed 10 March 2014

Jayne TS, Yamano T, Weber M, Tschirley D, Benfica R, Chapoto A, Zulu B (2003) Smallholder income and land distribution in Africa: implications for poverty reduction strategies. Food Policy 28:253–275

Johansen C, Haque ME, Bell RW, Thierfelder C, Esdaile RJ (2012) Conservation agriculture for small holder rainfed farming: Opportunities and constraints of new mechanized seeding systems. Field Crop Res 132:18–32

Kamara CS (1986) Mulch-tillage effects on soil loss and soil properties on an Ultisol in the humid tropics. Soil Till Res 8:131–144

Kassam A, Friedrich T, Shaxson F, Pretty J (2009) The spread of conservation agriculture: justification, sustainability and uptake. Int J Agric Sustain 7:292–320

Kaumbutho P, Kienzle J (2007) Conservation agriculture in Kenya. In: Kaumbutho P, Kienzle J (eds) Conservation agriculture as practised in Kenya: two case studies. Conservation Agriculture in Africa Series. African Conservation Tillage Network, Centre de CoopeÌration Internationale de Recherche Agronomique pour le DeÌveloppement. Food and Agriculture Organization of the United Nations, Nairobi, pp 2–56

Khatibu AI, Lal R, Jana RK (1984) Effects of tillage methods and mulching on erosion and physical properties of a sandy clay loam in an equatorial warm humid region. Field Crop Res 8:239–254

Knowler D, Bradshaw B (2007) Farmers' adoption of conservation agriculture: a review and synthesis of recent research. Food Policy 32:25–48

Lahmar R, Bationo BA, Nomaou Dan Lamso N, Guéroc Y, Tittonell P (2012) Tailoring conservation agriculture technologies to West Africa semi-arid zones: Building on traditional local practices for soil restoration. Field Crop Res 132:158–167

Lal R (1974) No-tillage effects on soil properties and maize (*Zea mays* L.) production in Western Nigeria. Plant Soil 40:321–331

Lal R (1997) Long-term tillage and maize monoculture effects on a tropical alfisol in western Nigeria. I. Crop yield and soil physical properties. Soil Till Res 42:145–160

Lal R (1998a) Mulching effects on runoff, soil erosion and crop response on Alfisols in Western Nigeria. J Sustain Agric 11:135–154

Lal R (1998b) Soil quality changes under continuous cropping for seventeen seasons of an Alfisol in western Nigeria. Land Degrad Dev 9:259–274

Lal R, Akinremi OO (1983) Physical properties of earthworm casts and surface soil as influenced by management. Soil Sci 135:114–122

Luo Z, Wang E, Sun OJ (2010) Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric Ecosyst Environ 139:224–231

Mashingaidze N, Madakadze C, Twomlow S, Nyamangara J, Hove L (2012) Crop yield and weed growth under conservation agriculture in semi-arid Zimbabwe. Soil Till Res 124:102–110

Mazvimavi K, Twomlow S (2009) Socioeconomic and institutional factors influencing adoption of conservation agriculture by vulnerable households in Zimbabwe. Agric Syst 101:20–29

Misiko M, Tittonell P (2009) Counting eggs? Smallholder experiments and try-outs as success indicators of adoption of soil fertility technologies. In: Bationo A, Waswa BS, Okeyo JM, Maina F (eds) Innovations as key to the green revolution in Africa: exploring the scientific facts. Springer, Dordrecht, pp 1137–1144

Mkoga ZJ, Tumbo SD, Kihupi N, Semoka J (2010) Extrapolating effects of conservation tillage on yield, soil moisture and dry spell mitigation using simulation modeling. Phys Chem Earth 35:686–698

Moyo A (2003) Assessment of the effect of soil erosion on nutrient loss from granite-derived sandy soils under different tillage systems in Zimbabwe. Dissertation, University of Zimbabwe

Mucheru-Muna M, Pypers P, Mugendi D, Kung'u J, Mugwe J, Merckx R, Vanlauwe B (2009) A staggered maize-legume intercrop arrangement robustly increases crop yields and economic returns in the highlands of Central Kenya. Field Crop Res 115:132–139

Munodawafa A, Zhou N (2008) Improving water utilization in maize production through conservation tillage systems in semi-arid Zimbabwe. Phys Chem Earth 33:757–761

Mupangwa W, Twomlow S, Walker S (2012) Reduced tillage, mulching and rotational effects on maize (*Zea mays* L.), cowpea (*Vigna unguiculata* (Walp) L.) and sorghum (*Sorghum bicolor* (Moench) L.) yields under semi-arid conditions. Field Crop Res 132:139–148

Mupangwa W, Twomlow S, Walker S (2013) Cumulative effects of reduced tillage and mulching on soil properties under semi-arid conditions. J Arid Environ 91:45–52.

Mutema M, Mafongoya PL, Nyagumbo I, Chakukura L (2013) Effects of crop residues and reduced tillage on macrofauna abundance. J Org Syst 8:5–16

Nagayets O (2005) Small farms: current status and key trends. Information brief prepared for the future of small farms research workshop, Wye College, UK, 26–29 June 2005

Ndah HT, Schuler J, Uthes S, Zander P, Triomphe B, Mkomwa S, Corbeels M (2012) Adoption potential for conservation agriculture in Africa: a newly developed assessment approach (QAToCA) applied in Kenya and Tanzania. Land Degrad Dev. http://dx.doi.org/10.1002/ldr.2191

Ndah HT, Schuler J, Uthes S, Zander P, Traore K, Gama M, Nyagumbo I, Triomphe B, Sieber S, Corbeels M (2014) Adoption potential of conservation agriculture practices in Sub-Saharan Africa: results from 5 case studies. Environ Manage. 53:620–635

Nehanda G (2000) The effects of three animal-powered tillage systems on soil-plant-water relations and maize cropping in Zimbabwe. Dissertation, University of Zimbabwe

Ngwira AR, Aune JB, Mkwinda S (2012) On-farm evaluation of yield and economic benefit of short term maize legume intercropping systems under conservation agriculture in Malawi. Field Crop Res 132:149–157

Ngwira AR, Thierfelder C, Lambert DM (2013) Conservation agriculture systems for Malawian smallholder farmers: long-term effects on crop productivity, profitability and soil quality. Renew Agric Food Syst 28:350–363

Ngwira AR, Aune JB, Thierfelder C (2014) On-farm evaluation of the effects of the principles of conservation agriculture on maize yield and weed biomass in Malawi. Exp Agric 50:591–610

Nhamo N (2007) The contribution of different fauna communities to improved soil health: a case of Zimbabwean soils under conservation agriculture. Dissertation, Rheinischen Friedrich-Wilhelms-Universitat, Bonn

Nyagumbo I (2002) Effects of three tillage systems on seasonal water budgets and drainage of two Zimbabwean soils under maize. Dissertation, University of Zimbabwe

Nyamadzawo G, Chikowo R, Nyamugafata P, Nyamangara J, Giller KE (2008) Soil organic carbon dynamics of improved fallow-maize rotation systems under conventional and no-tillage in Central Zimbabwe. Nutr Cycl Agroecosys 81:85–93

Nyamangara J, Masvaya EN, Tirivavi R, Nyengerai K (2013) Effect of hand-hoe based conservation agriculture on soil fertility and maize yield in selected smallholder areas in Zimbabwe. Soil Till Res 126:19–25

Nyamangara J, Mashingaidze N, Masvaya EN, Nyengerai K, Kunzekweguta M, Tirivavi R, Mazvimavi K (2014a) Weed growth and labor demand under hand-hoe based reduced tillage in smallholder farmers' fields in Zimbabwe. Agric Ecosyst Environ. 187:146–154

Nyamangara J, Nyengerai K, Masvaya EN, Tirivavi R, Mashingaidze N, Mupangwa W, Dimes J, Hove L, Twomlow S (2014b) Effect of conservation agriculture on maize yield in the semi-arid areas of Zimbabwe. Exp Agric. 50:159–177

Ofori CS (1973) The effects of ploughing and fertilizer application on yield of cassava (*Manihot esculenta* Grantz). Ghana J Agric Sci 6:21–24

Ojiem J, Ridder N, Vanlauwe B, Giller KE (2006) Socio-ecological niche: a conceptual framework for integration of legumes in smallholder farming systems. Int J Agric Sust 4:79–93

Okwach GE, Simiyu CS (1999) Evaluation of long-term effects of management on land productivity in a semi-arid area of Kenya using simulation models. E Afric Agric For J 65:143–155

Oldreive B (1993) Conservation farming for communal, small-scale, resettlement and co-operative farmers in Zimbabwe. A farm management handbook. Rio Tinto Foundation, Harare, p 77

Page S, Page H (1991) Western hegemony over African agriculture in Southern Rhodesia and its continuing threat to food security in independent Zimbabwe. Agric Human Values 8:3–18

Pannell DJ, Llewellyn RS, Corbeels M (2014) The farm-level economics of conservation agriculture for resource-poor farmers. Agric Ecosyst Environ. 187:52–64

Paul BK, Vanlauwe B, Ayuke F, Gassner A, Hoogmoed M, Hurisso TT, Koala S, Lelei D, Ndabamenye T, Six J, Pulleman MM (2013) Medium-term impact of tillage and residue management on soil aggregate stability, soil carbon and crop productivity. Agric Ecosyst Environ 164:14–22

Prudencio CY (1993) Ring management of soils and crops in the West African semi-arid tropics: the case of the mossi farming system in Burkina Faso. Agric Ecosyst Environ 47:237–264

Rockstrom J, Kaumbutho P, Mwalley J, Nzabi AW, Temesgen M, Mawenya L, Barron J, Mutua J, Damgaard-Larsen S (2009) Conservation farming strategies in East and Southern Africa: yields and rain water productivity from on-farm action research. Soil Till Res 103:23–32

Roose E, Kaboré V, Guenat C (1993) Le zaï: fonctionnement, limites et amélioration d'une pratique traditionnelle africaine de réhabilitation de la végétation et de la productivité des terres dégradées en région soudano-sahélienne (Burkina Faso) (French). Cahiers Orstom, Série Pédologie 28:159–173

Ruben R, Pender J (2004) Rural diversity and heterogeneity in less-favoured areas: the quest for policy targeting. Food Policy 29(4 Spec. Iss.):303–320

Rusinamhodzi L, Corbeels M, van Wijk M, Rufino MC, Nyamangara J, Giller KE (2011) Long-term effects of conservation agriculture practices on maize yields under rain-fed conditions: lessons for southern Africa. Agron Sustain Dev 31:657–673

Rusinamhodzi L, Corbeels M, Nyamangara J, Giller KE (2012) Maize–grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. Field Crop Res 136:12–22

Rusinamhodzi L, van Wijk M, Corbeels M, Rufino MC, Giller KE (2014) Crop residue use and trade-offs on smallholder crop-livestock farms in southern Africa: implications for intensification. (Submitted to) Agric Syst

Saito K, Azoma K, Oikeh SO (2010) Combined effects of Stylosanthes guianensis fallow and tillage management on upland rice yield, weeds and soils in southern Benin. Soil Till Res 107:57–63

Sakyi RK, Corbeels M, Kühne RF, Whitbread A (2014). 2014 Crop yield responses to conservation agriculture practices in sub-Saharan Africa: a meta-analysis. Book of condensed papers, at 1st African Congress on Conservation Agriculture, Lusaka, 18–21 March 2014, http://www.

africacacongress.org/sites/default/files/attachments/book_of_condensed_papers.pdf. Accessed 2 Oct 2014, pp 50–53

Scopel E, da Silva FAM, Corbeels M, Affholder F, Maraux F (2004) Modelling crop residue mulching effects on water use and production of maize under semi-arid and humid tropical conditions. Agronomie 24:1–13

Scopel E, Triomphe B, Affholder F, da Silva FAM, Corbeels M, Xavier JHV, Lahmar R, Recous S, Bernoux M, Blanchart E, De Carvalho Mendes I, De Tourdonnet S (2013) Conservation agriculture cropping systems in temperate and tropical conditions, performances and impacts: a review. Agron Sustain Dev 33:113–130

Serpantie G (2009) L'agriculture de conservation Ã la croisée des chemins. Vertigo, Revue des sciences et de l'environnement (French), vol 9, p 21

Shetto R, Owenya M (2007) Conservation agriculture as practised in Tanzania: three case studies. Conservation Agriculture in Africa Series. African Conservation Tillage Network, Centre de CoopeÌration Internationale de Recherche Agronomique pour le DeÌveloppement. Food and Agriculture Organization of the United Nations, Nairobi, p 146

Spielman DJ, Ekboir J, Davis K, Ochieng CM (2008) An innovation systems perspective on strengthening agricultural education and training in sub-Saharan Africa. Agric Syst 98:1–9

Starkey P (2000) The history of working animals in Africa. In: Blench RM, MacDonald K (eds) The origins and development of African livestock: archaeology, genetics, linguistics and ethnography. University College London Press, London, pp 478–502

Sumberg J (2005) Constraints to the adoption of agricultural innovations. Is it time for a re-think? Outlook Agric 34:7–10

Thierfelder C, Wall PC (2009) Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. Soil Till Res 105:217–227

Thierfelder C, Wall PC (2010) Investigating conservation agriculture (CA) systems in Zambia and Zimbabwe to mitigate future effects of climate change. J Crop Improv 24:113–121

Thierfelder C, Wall PC (2012) Effects of conservation agriculture on soil quality and productivity in contrasting agro-ecological environments of Zimbabwe. Soil Use Manage 28:209–220

Thierfelder C, Cheesman S, Rusinamhodzi L (2012) A comparative analysis of conservation agriculture systems: Benefits and challenges of rotations and intercropping in Zimbabwe. Field Crop Res 137:237–250

Thierfelder C, Cheesman S, Rusinamhodzi L (2013a) Benefits and challenges of crop rotations in maize-based conservation agriculture (CA) cropping systems of southern Africa. J Agric Sustain 11:108–124

Thierfelder C, Mombeyarara T, Mango N, Rusinamhodzi L (2013b) Integration of conservation agriculture in smallholder farming systems of southern Africa. Int J Agric Sustain 11:317–330

Thierfelder C, Mwila M, Rusinamhodzi L (2013c) Conservation agriculture in eastern and southern provinces of Zambia: long-term effects on soil quality and maize productivity. Soil Till Res 126:246–258

Thierfelder C, Rusinamhodzi L, Ngwira AR, Mupangwa W, Nyagumbo I, Kassie GT, Cairns JE (2014) Conservation agriculture in Southern Africa: advances in knowledge. Renew Agric Food Syst. http://dx.doi.org/10.1017/S1742170513000550. Accessed 2 Oct 2014

Tittonell P, Giller KE (2013) When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crop Res 143:76–90

Tittonell P, Vanlauwe B, Leffelaar PA, Shepherd KD, Giller KE (2005) Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agric Ecosyst Environ 110:166–184

Tittonell P, Vanlauwe B, Corbeels M, Giller KE (2008) Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant Soil 313:19–37

Tittonell P, Muriuki A, Shepherd KD, Mugendi D, Kaizzi KC, Okeyo J, Verchot L, Coe R, Vanlauwe B (2010) The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa—a typology of smallholder farms. Agric Syst 103:83–97

Twomlow SJ, Urolov JC, Jenrich M, Oldrieve B (2008) Lessons from the field—Zimbabwe's Conservation Agriculture Task Force. J SAT Agric Res 6:1–11

Umar BB, Aune JB, Johnsen FH, Lungu IO (2012) Are smallholder Zambian farmers economists? A dual-analysis of farmers' expenditure in conservation and conventional agriculture systems. J Sustain Agric 36:908–929

Valbuena D, Erenstein O, Homann-Kee Tui S, Abdoulaye T, Claessens L, Duncan AJ, Gérard B, Rufino MC, Teufel N, van Rooyen A, van Wijk MT (2012) Conservation agriculture in mixed crop-livestock systems: scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. Field Crop Res 132:175–184

Vanlauwe B, Tittonell P, Mukalama J (2006) Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. Nutr Cycl Agroecosyst 76:71–182

Vanlauwe B, Wendt J, Giller KE, Corbeels M, Gérard B, Nolte C (2014) A fourth principle is required to define Conservation Agriculture in sub-Saharan Africa: the appropriate use of fertilizer to enhance crop productivity. Field Crop Res 155:10–13

Vogel H (1993) Tillage effects on maize yield, rooting depth and soil water content on sandy soils in Zimbabwe. Field Crops Res 33:367–384

Vogel H (1995) The need for integrated weed management-systems in smallholder conservation farming in Zimbabwe. Tropenlandwirt 96:35–56

Vogel H, Nyagumbo I, Olsen K (1994) Effect of tied-ridging and mulch ripping on waterconservation in maize production on sandveld soils. Tropenlandwirt 95:33–44

Wall PC (2007) Tailoring conservation agriculture to the needs of small farmers in developing countries: an analysis of issues. J Crop Improv 19:137–155

Wall PC, Thierfelder C, Ngwira A, Govaerts B, Nyagumbo I, Baudron F (2014) Conservation agriculture in Eastern and Southern Africa. In: Jat RA, Graziano de Silva J (eds) Conservation agriculture: global prospects and challenges. CABI, Cambridge

Woyessa YE, Bennie ATP (2007) Tillage-crop residue management and rainfall-runoff relationships for the Alemaya catchment in Eastern Ethiopia. S Afr J Plant Soil 24:8–15

Zingore S, Murwira HK, Delve RJ, Giller KE (2007) Soil type, management history and current resource allocation: three dimensions regulating variability in crop productivity on African smallholder farms. Field Crop Res 101:296–305

Part V

Conservation Agriculture in Agricultural Systems

Chapter 19
Conservation Agriculture and Soil Carbon Sequestration

Ch. Srinivasarao, Rattan Lal, Sumanta Kundu and Pravin B Thakur

Abstract Changes to agricultural practices in response to climate change and widespread soil degradation are being investigated to improve food security, enhance environmental conservation, and achieve sustainability. Since soil organic carbon (SOC) concentration is a strong determinant of soil physicochemical and biological activities, carbon (C) sequestration in agricultural soils requires changes to management practices. Conservation agriculture (CA)—based on minimum soil disturbance, adequate surface cover, and complex crop rotations—has been proposed as an alternative system to conventional agriculture. This chapter reviews potential impacts of CA mainly on C sequestration, collates information on the influence of tillage, integrated nutrient management (INM), fertilizers, residue management and cover crops on SOC stocks, and deliberates on the mitigation of greenhouse gas (GHG) emissions, economics, etc. by CA from existing case studies. Whether conversion to a CA system can increase C sequestration is not yet clear. More research is needed, particularly long-term research, to delineate ecological conditions suitable for adaptation in a CA system. Harshness of arid and semiarid climate exacerbates the risk of soil degradation by depleting SOC stock and increasing risks of erosion and salinization. Widespread adoption of CA can reduce the cost of farm operations including fuel consumption, while conserving soil water, improving soil functions, controlling erosion, and sustaining productivity.

Keywords Conservation tillage · Carbon management · Carbon credit · Organic matter · System productivity · Zero tillage · Sustainability · India

---

Ch. Srinivasarao (✉) · S. Kundu · P. B. Thakur
Central Research Institute for Dryland Agriculture,
Santoshnagar, Saidabad, Hyderabad 500 009, Andhra Pradesh, India
e-mail: cherukumalli2011@gmail.com

R. Lal
Carbon Management and Sequestration Center, SNER/OAR DC,
The Ohio State University, Columbus, OH 43210, USA

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_19

Abbreviations

AICRPDA	All India Coordinated Research Project for Dryland Agriculture
BGA	Blue–Green Algae
BMPs	Best management practices
C	Carbon
CA	Conservation agriculture
CDM	Clean development mechanisms
CER	Certified emission reduction
CIMMYT	International Maize and Wheat Improvement Center
CR	Crop residue
CT	Conventional tillage
FYM	Farm yard manure
GHGs	Greenhouse gases
GWP	Global warming potential
IGP	Indo-Gangetic Plains
INM	Integrated nutrient management
IPNS	Integrated plant nutrient system
K	Potassium
N	Nitrogen
NT	No-till
P	Phosphorus
PDFSR	Project Directorate of Farming Systems Research
RDF	Recommended dose of fertilizer
RDN	Recommended dose of nitrogen
RMPs	Recommended management practices
S	Sulfur
SOC	Soil organic carbon
SOM	Soil organic matter
SSNM	Site-specific nutrient management
UNFCC	United Nations Framework Convention on climate change
VAM	Vesicular Arbuscular Mycorrhyza
Zn	Zinc

19.1 Introduction

Global warming has already increased temperatures and by the end of twenty-first century is likely to exceed 1.5 °C due to anthropogenic emissions of greenhouse gases (GHGs), such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (IPCC 2013). Global anthropogenic emissions by fossil fuel combustion and cement production are estimated at ~ 10 Pg C $year^{-1}$ (Le Quere et al. 2013). The projected climate change may alter terrestrial carbon (C) storage because of changes in temperature, precipitation, and CO_2 concentrations that could affect net primary production (NPP), C inputs to soil, and soil C decomposition rates. It may also accelerate land use change, thus further altering terrestrial C fluxes (Falloon et al. 2007). Despite 50 years of the green revolution, agriculture is faced with numerous challenges to increase food production for the growing human population (Hobbs 2007). The world population has increased by 3.7 billion people, rising from 7.2 billion from mid-2013 to 10.9 billion by the end of this century (United Nations 2013). World agricultural production has grown, on average, between 2 and 4 % per year over the last 50 years, while the cultivated area has increased by only 1 % annually. However, global per capita arable land has declined from ~ 0.44 ha to < 0.25 ha (Foresight 2009), which indicates successful agricultural intensification. More than 40 % of the increased food production has come from irrigated areas, which have doubled in size since the 1960s. Geographically uneven distributed land could not be brought under production because much of it has been characterized for suitability and agronomic constraints. Moreover, suitable land for cropping is skewed in countries that have the most need to increase production (FAO 2013b).

Traditionally, some form of plowing has been done since the beginning of agriculture for land preparation and planting. Continuous monoculture, ecological constraints, lack of good quality seed and crop rotations, and use of extensive farming have led to degradation of soil and other natural resources. Degradation of natural resources threatens food security and livelihood opportunities of farmers, especially those who are poor and underprivileged (Souvenir 2009). On a global scale, the annual loss of 75 billion t of soil translates into US$ 400 billion per year and about US$ 70 per person per year due to land degradation (Pimentel et al. 1997, Eswaran et al. 2001). Soil erosion, nutrient mining, and C loss are among the major causes of soil degradation. Agricultural soils are comparatively more susceptible to erosion because of the removal of vegetation before planting the following crop, coupled with frequent cultivation of the soils. From the compilation of global data, Lal (1994) showed that the yield of rainfed agriculture may decrease by 29 % over 25 years (1995–2020) because of accelerated soil erosion. It is estimated that 30 % of the world's arable land is severely degraded (Kendall and Pimentel 1994) and each year ten million cropland are lost due to accelerated soil erosion (Pimentel and Burgess 2013). Nutrient mining is especially severe in Africa (Smaling 1993, Stoorvogel and Smaling 1990a, b). In 2000, global soil nutrient depletion was estimated at an average rate of 19, 5, and 39 kg ha^{-1} $year^{-1}$ of N, P, and K, respectively.

The loss of C due to soil degradation in the past 1000 years represents 16–20 % of the present-day global soil C stock of 1200–1500 Pg ($1 \text{ Pg} = 10^{15}$ g) to 1 m depth (Haider 1999). In addition, mechanization of agriculture has depleted the soil C pool by 78 ± 12 Tg ($1 \text{ Tg} = 10^{12}$ g) of C since 1750 (Lal 2004) and conversion of forest to agricultural land has depleted soil C stock by ~ 22 % C. Decomposition of biomass and soil C stock has been a principal source of atmospheric CO_2 over the past century (Lal 1997).The loss of SOC by mineralization may range from about 20 % in 20 years in temperate climates to about 50 % in 10 years in the tropics (Woomer et al. 1994). Thus, strategies toward sustainable management of natural resources to reduce the widespread problem of land/soil degradation with adverse impacts on food security and environmental quality need to be identified.

Sequestration of C is the removal of CO_2 from the atmosphere into various long-lived chemically bound forms, either on land or in the ocean (Franzluebbers 2008). Soil is an important sink to capture and store atmospheric CO_2 in the form of organic (through photosynthesis by plants and humification of the biomass) and inorganic C (through formation of pedogenic carbonates (Bhattacharyya et al. 2008). Thus, C sequestration can partly offset emissions of fossil fuel combustion and other anthropogenic activities, while also enhancing soil quality and agronomic productivity. However, lack of an accurate estimation of soil C sequestration and inherent variability of soil properties hinder identification of best management practices (BMPs) Srinivasarao et al. 2009b). Naitam and Bhattacharyya (2004) reported that the quality and quantity of inorganic colloid is the main substrate to sequester C in soils. A constraint of C sequestration in tropical soils because of continuously high temperatures can be alleviated through adoption of BMPs such as appropriate cropping systems in subhumid and humid regions (Srinivasarao et al. 2009b, 2011b, 2012b) through stabilization of soil C stocks. Restoring and maintaining soil fertility in a sustainable manner is also essential to increasing productivity, and SOC is a key determinant of soil quality, through its strong influence on physical, chemical, and biological properties and processes. Therefore, it is necessary to restore soil C stock by using judicious land use and adopting BMPs because agriculture is integral to any solution to adapt and mitigate climate change (Lal et al. 1997; Lal 2008).

Conservation agriculture (CA) is gaining acceptance in many parts of the world as an alternative to conventional agriculture. It improves soils and crop environments and can mitigate and adapt to climate change (Govaerts et al. 2009a; Hobbs 2007; Kassam and Friedrich 2012). Conversion to CA improves water infiltration and reduces erosion, moderates soil temperature, suppresses weeds, improves soil aggregation, reduces soil compaction, increases surface soil organic matter (SOM) content, reduces emissions of GHGs, decreases costs of production, saves time, and maintains some fallow through direct seeding (Giller et al. 2009; Verhulst et al. 2010). In 2009, CA was practiced worldwide on ~ 120 million hectares which corresponded to a 6-million-ha global growth rate per annum (Derpsch et al. 2010; Kassam and Friedrich 2012). It is a complete package of agricultural practices which not only protects natural resources but also sustains yields. Potential rates of C sequestration in soils through adoption of CA systems can be high, especially through restoration of degraded soils (Lal 1997; Socolow and Pacala 2006). Conversion to no-till (NT) sequesters C in the soil (Kern and Johnson 1993; West and Marland 2002; Sa and Lal 2009), and long-term use of NT is an effective technology for maintaining high crop productivity and sequestering more atmospheric CO_2 in soil (Dick and Durkalski 1997). Conversion to CA enhances soil C sequestration by maximizing C inputs and minimizing C outputs (Franzluebbers 2008). Examples of the rates of C sequestration through conversion to NT have been reported by Lal et al. (1997) are 0.12–0.29, 0.09–0.29, 0.12–0.29, and 0.14–0.56 Mg C ha^{-1} $year^{-1}$ in the continent of Asia, Africa, America, and the USA, respectively. Comparison of data from 67 long-term experiments indicated an average rate of C sequestration under NT at 57 ± 14 g C m^{-2} $year^{-1}$ (excluding NT in wheat fallow systems) with peak sequestration rates attained within 5–10 years after conversion (West and Post

2002). Some studies indicated that the increase in SOC concentration primarily occurred in the surface layer (Lal 1997), while others indicated either no effect or negative effects when the entire soil profile was considered (Blanco-Canqui and Lal 2008; Baker et al. 2007). Jat et al. (2012) reported that adoption of NT increased SOC concentration in soils up to 40 cm deep. However, a careful reexamination of the data is needed to assess the impact of the NT system on depth distribution of soil C (Blanco-Canqui and Lal 2008). The magnitude of C sequestration may depend on the amount of biomass-C input rather than on the absence of tillage per se (Franzluebbers 2010a), as well as due to differences in soil composition (texture and native SOM content), soil conditions (temperature and moisture), and sampling depth. All too often, experimental protocols are not rigorous enough to show real differences among tillage systems (Christopher et al. 2009).

In this chapter, sustainable use of soil and other natural resources in relation to agronomic productivity and environment quality is discussed. Soil C pool and its dynamics are the principal determinants of soil quality, productivity, and socio-economic status of farmers. This chapter addresses soil C sequestration potential through CA, and its management in diverse soils and agro-ecosystems with regard to reducing GHG emission, enhancing system productivity, increasing benefits, and alleviating constraints to adoption of CA.

19.2 Carbon and Nitrogen Cycling

The degradation of plant and animal material in soil is a fundamental biological process (Stevenson and Cole 1999). Soil C comprises soil inorganic C (SIC) and SOC. Biomass C enters the soil through photosynthesis and dead plant materials; agricultural practices affect soil C reserve by influencing the rate of biomass decomposition/mineralization and releasing CO_2 into the atmosphere, and exposing SOC at the soil surface to climatic elements, thereby increasing its mineralization (Lal and Kimble 1997). Several exogenous and endogenous factors including micro- and meso-climate, management practices, and inherent soil properties affect this process. Extractive agricultural systems, with none or little external input, may accentuate C efflux. Total N pools in soil comprise organic (urea, amines, proteins, and amides), inorganic (NO_3^- and NH_4^+), and gaseous (e.g., NO_2, NH_3^+) components. Soil C and N cycles are strongly linked and influenced by the work of microorganisms and quality of SOM. In CA, addition of large amount of crop residue (CR) with high C:N ratio lead immobilization of nutrient, particularly N. Decomposition organic matter organisms use C as energy source and consequently affect C and N cycles. N release by mineralization is an important source for plants; generally, NT is recognized for lower N availability because of more immobilization by residues left on surface (Bradford and Peterson 2000). Combined effect of reduced tillage and residue retention has greater SOC and total N (Kushwaha et al. 2000). Qun et al. (2004) reported that root density is more on the surface soil under NT compared to that under CT. CA helps to improve soil aggregation and physical protection of SOM. The adoption of NT improves the soil biological N cycling and N retention; however, microbial biomass carbon (MBC) and particulate organic matter nitrogen (POM-N), along with the ratios of N mineralization/MBC and N mineralization/CO_2–C may be sensitive indicators of management-induced changes in total soil C and N (Purakayastha et al. 2009). The activities regarding nutrient cycling and functions of soil properties under CA are limited up to surface layers; therefore, long-term dataset could draw better information, particularly for soil C and N.

19.3 Soil Organic Matter

Soil organic matter (SOM) and its quality are among the key indicators of soil quality, and are a strong determinant of biological activity. The amount, diversity, and activity of soil fauna and microorganisms are directly related to SOM. The SOM content, and the biological activity that it generates, has a major influence on the physical and chemical properties of soils (Robert 1996b). Aggregation and stability of soil structure increase with increasing SOM content. These, in turn, increase water infiltration rate and available water capacity of the soil, as well as resistance against erosion by water and wind. SOM also improves the dynamics and bioavailability of principal plant nutrient elements (FAO 2014a). CA practices such as NT, use of cover crops, and CRs on the soil surface increase the accumulation of SOM in surface soil (FAO 2014b). SOM comprises organic constituents derived from the remains of plants and animals which are at different stages of decomposition by soil microorganisms. It is a storehouse of many plant nutrients, and improves the physical, chemical, and biological environments of the soil (Sharma 2011). The term SOC refers to the C contained in SOM (Milne and Heimsath 2008); Fig. 19.1 shows the impact of SOM on soil and the environment quality. Improved management practices which keep the soil surface cool and wet will stabilize the SOC pool (Follett 1993; Kern and Johnson 1993). Important among these are mulches and CA systems which also change the soil microclimate. The principal processes of C sequestration in soil include humification, aggregation, and sedimentation while the processes that decrease SOC include erosion, decomposition, volatilization, and leaching (Batjes 1999).

19.3.1 Soil Organic Matter and System Productivity

SOM plays a significant role in improving the physical, chemical, and biological quality of the soil in terms of nutrient cycling, reducing bulk density (BD), buffering pH, improving water retention, and overall increasing system productivity. Adoption of recommended management practices (RMPs) which could increase SOC stock by 1 Mg ha^{-1} $year^{-1}$ can increase food grain production by 32 million Mg $year^{-1}$ in developing countries (Lal 2006). Long-term experiments

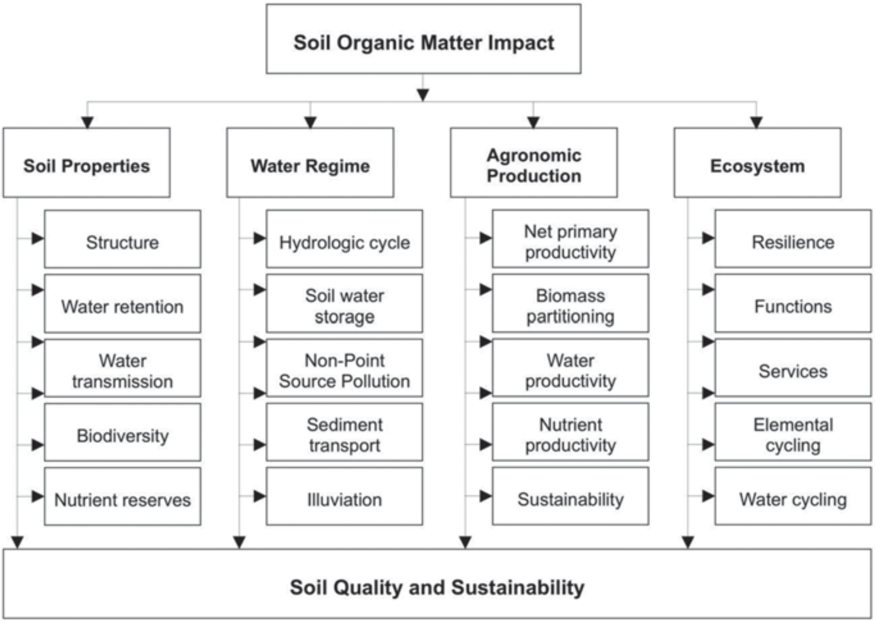


Fig. 19.1 The impact of soil organic matter on soil and environment

conducted in tropical regions of India show that for every Mg ha^{-1} increase in SOC stock in the root zone, grain yield (kg ha^{-1}) increased by 13 for groundnut (*Arachis hypogaea*), 18 for lentil (*Lens culinaris*), 90 for sorghum (*Sorghum bicolor*), 101 for finger millet (*Eleucine coracana*), 145 for soybean (*Glycine max*), 160 for rice (*Oryza sativa*), and 170 for pearl millet (*Pennisetum glaucum*; Srinivasarao et al. 2013a). An increase in SOC stock by 1 Mg ha^{-1} increased grain yield by 27 kg ha^{-1} in wheat (*Triticum aestivum*) in North Dakota, USA (Lal 2006), 40 kg ha^{-1} in wheat in the semiarid pampas of Argentina (Diaz-Zorita et al. 2002), 6 kg ha^{-1} in wheat and 3 kg ha^{-1} in maize (*Zea mays*) in alluvial soils of northern India (Kanchikerimath and Singh 2001), 17 kg ha^{-1} in maize in Thailand (Petchawee and Chaitep 1995), and 10 kg ha^{-1} in maize and 1 kg ha^{-1} in cowpea (*Vigna unguiculata*) in western Nigeria (Lal 1981). Tree-based systems can sequester substantial quantities of C in biomass even over a short period. In eastern Indo-Gangetic Plains (IGP), conversion to NT increased productivity of the rice–maize system by15–20% compared with that of CT (Gupta et al. 2009). Studies involving on-station trials across the IGP generally reported increased wheat yields with NT in the range of 1–12%, with an average gain of 6.4% (Erenstein and Laxmi 2008). Gupta et al. (2010) reported wheat grain yields of 5393, 5056, and 4537 kg ha^{-1} under NT with residue retention, NT without residue, and CT with rotavator and broadcast, respectively. Experiments conducted on irrigated maize-based smallholder CA systems in the Eastern Cape regions of South Africa suggest that grazing vetch (*Vicia dasycarpa*) and oat (*Avena sativa*) winter cover crops can produce in excess of 6 Mg ha^{-1} dry matter annually, providing good cover, weed control, moisture conservation, and maize yield benefits (Murungu et al. 2010a; Musunda 2010).

19.3.2 SOM and Nutrient Cycling

The principal processes involved in nutrient cycles are dissolution–precipitation, sorption–desorption, mineralization–demineralization, and oxidation–reduction (Sanyal and Majumadar 2009). The SOM in topsoil significantly contributes toward nutrient cycling in soil water and the plant system, and it is related to the mineralization–demineralization process (Duxbury et al. 1989). The quality and quantity of organic material (i.e., C:N ratio), climate, and soil minerals impact decomposition of SOM (Jastrow and Miller 1997). As CA systems leave maximum organic matter on surface of the soils, consequently changing the soil environment (physicochemical and biological) that influence the nature of fixation and exchange of nutrients transformation in soils. During the SOM decomposition when high C/N ratio inorganic N is utilized, this process is called mineralization. Kumar and Ghosh (2002) reported that total N significantly correlated with C/N ratio of residues. Additional N is required but it cannot be added at a time; therefore, in NT systems, crop yields will often suffer due to inadequate amounts of available N. This, in turn, limits the biomass entering into soil, leading to low amount of SOM accumulation, reducing N mineralization, and, thus, reducing available N. Therefore, increased rate of fertilizer application is often required (Triplett and Dick 2008). This is true but over time the accumulation of SOM increased through higher input rates and offset reduction in fertilizer and nutrient losses through erosion and leaching under zero tillage (ZT) (Friedrich and Kassam 2012) and acting as an N source, thereby effectively managing N limitations encouraged by residues (Sa 2004). Tillage disrupts soil aggregation and exposes SOM making it easily accessible for microorganism which further increases mineralization of N from physically protected N pools, whereas residue retention with ZT resulted in more stable macroaggregates and protect C and N (Chaudhury et al. 2014). Several long-term CA experiments reported that N availability or content in soil was higher in NT than under CT. A 3-year nutrient transformation study in Indian Himalayan subtemperate region by different tillage methods revealed that N, P, and K content, dehydrogenase, alkaline phosphatase and protease activity were higher in the ZT over CT system in sandy clay loam soil (Mina et al. 2008). Guertal et al. (1991) reported more P on surface soil in NT than tilled soil because of lower retention characteristics.

19.3.3 GHG Mitigation

Agriculture contributes about 30 % of the total emissions of CO_2, N_2O, and CH_4, while also being directly affected by the consequences of a changing climate

(IPCC 2007). Conversion to NT enables adequate retention of CRs and regulates terminal temperature up to 2°C in wheat (Jat et al. 2010). Burning of CRs contributes a significant quantity of GHGs. Burning 1 Mg of straw releases 3 kg of particulate matter, 60 kg CO, 1460 kg CO_2, 199 kg ash and 2 kg SO_2 (Gupta et al. 2006). Gupta et al. (2004) used Intergovernmental Panel on Climate Change (IPCC) methodology to estimate emissions from open burning of CR (assuming that one fourth of available CR is burnt in the field) and reported that the emissions of CH_4, CO, N_2O, and NO_x in 2000 were 110, 2306, 2.3, and 84 Gg, respectively, and had increased by 7.84, 7.85, 4.54, and 7.69 %, respectively, since 1994, from field burning of rice and wheat straw in India. It has been reported that an NT system can effectively reduce GHG emissions by half and groundwater pumping by 3–28 % (Grace et al. 2003). Field experiments conducted by the International Maize and Wheat Improvement Center (CIMMYT) in the rainfed Mexican highlands, to assess CA as a sustainable alternative for conventional maize production practices (conventional tillage, CT), indicated that CT deteriorated soil fertility and reduced agronomic yields. In contrast, CA restored soil fertility and increased yields. Further, SOM increased in CA compared to that in CT, but increases in GHG emissions in CA may offset any gains toward mitigating global warming. Thus, cumulative GHGs emitted were similar in CA and CT, but SOC concentration in the 0–60-cm layer was higher in CA than in the CT system. The net global warming potential (GWP) of CA (considering soil C sequestration, GHG emissions, fuel use, fertilizer, and seed production) was -7729 kg CO_2 ha^{-1} $year^{-1}$ compared with 1327 kg CO_2 ha^{-1} $year^{-1}$ in CT. The contribution of CA to GWP was small compared to that of CT (Dendooven et al. 2012).

19.4 Management Approaches for Positive Carbon Balance

Management approaches for a positive C balance are termed “best practice” agricultural techniques, and include the use of legume cover crops in rotation cycles, judicious use of chemical fertilizers and organic amendments, improvements in soil-water management for irrigation and drainage, and improved varieties with high biomass production (Rosenzweig and Tubiello 2007). Many literatures on CA recognized that there is no clear scientific evidence confirming whether or to what extent NT stimulates C sequestration in agricultural soils globally (Gattinger et al. 2011). Second, complete CA system could not be adopted because variability of resources in region to region limits the practice. But some management practices, as Lal (2004a) reported RMPs for C sequestration in comparison with traditional methods (Table 19.1) in agriculture, not only contribute toward soil conservation and water quality goals but also enhance the amount of SOC and mitigate CO_2 emissions (Follett et al. 2009) as well as maintain a steady state of SOC (Govaerts et al. 2009b).

Table 19.1 Recommended management practices for carbon sequestration

Principle	Practices
Creating positive ecosystem carbon budget	Mulch farming Conservation agriculture Cover cropping Agroforestry
Reducing losses	Erosion control Moderating mineralization by managing soil temperature, plant species, and root:shoot ratio Increasing humification by improving C:N, C:P, and C:S ration Improving soil aggregation
Deep transfer of carbon	Plants with deep root system Bioturbation (e.g., earthworm and termite activity)
Protecting soil carbon	Increasing aggregation Decreasing soil disturbance Enhancing recalcitrance of biomass C

19.4.1 Maximizing Carbon Input

The amount and type of C input every year affects SOC concentration. Thus, strategies need to be developed to increase the C input in the soil, and decrease its loss.

19.4.1.1 Influence of Crops/Cropping Systems

The main sources of C input into soil through plants are roots–shoots, root exudates, and root-borne organic substances released into the rhizosphere during plant growth as well as root hairs and fine roots sloughed by root elongation (Kuzyakov and Domanski 2000). Changes in soil conditions alter the rate of plant biomass decomposition and SOM mineralization; therefore, appropriate soil and crop management is important to C sink in soils. Grant and Lafond (1994) reported that a 4-year rotation of three different crops enhances total C and N surface layer under reduce tillage system. Mina et al. (2008) reported that lentil (*Lens esculenta,* variety VL-4; October–April) and finger millet (*Eleusine coracana,* variety VL-149; June–September), in rotation per year, increased C, N, and enhanced enzymatic activity under zero–zero tillage systems.

In general, the relative contribution of plant roots to SOC stock is larger than that of plant shoots (Johnson et al. 2006; Molina et al. 2001), and this can be achieved by selecting plants/cultivars with deeper, thicker roots through appropriate breeding strategies (Kell 2011). Sisti et al. (2004) found increased roots under ZT compared to plowed soils. Further, they postulate that hairy vetch planted as a winter cover crop in rotations with common oat and wheat in winter and maize or soybean in summer increased soil C stocks by ~10 t ha^{-1} at 1-m soil depth after 13 years of ZT. Katterer and colleagues revisited the long-term experiment which started in 1956 and reported that the humification coefficient for root-derived carbon was about 2.3 times higher than that for aboveground plant residues in spring cereal crop rotation;

this suggests that root-derived C contributes more stable soil C stock than plant residues (Katterer et al. 2011).

19.4.1.2 Tillage

Tillage plays an important role in the management of nutrient storage and release from SOM with CT inducing rapid C and N mineralization from the soil (Chivenge et al. 2007). In general, C emission is more in CT than NT due to a higher use of diesel (Lal 2004b; Bowers 1989). The data in Table 19.2 show average C emission with different tillage operation (Lal 2004b). Mandiringana et al. (2005) reported that SOM depleted below 1 % (< 10 g kg^{-1}) in the range of 0–20 cm in CT, mono-cropping of maize and CR removal in less input smallholder systems in Eastern Cape, South Africa. Tillage led to the loss of particulate organic carbon (POC) which accounted for 80 % of the total C loss (Chan et al. 2002). A high level of SOM in the surface layer is essential for erosion control, water infiltration, and conservation of nutrients (Franzluebbers 2002). Adoption of NT or reduced tillage systems with little disturbance enhances stabilization of SOC (Six et al. 2000). Under dryland conditions, on the sandy soils of West Africa, use of CENTURY and RothC models suggest that conversion to NT can increase SOC stock from 0.1 to 0.2 Mg ha^{-1} year^{-1} (Farage et al. 2007). Varvel and Wilhelm (2011) conducted a long-term experiment under rainfed conditions with six primary tillage systems (chisel, disk, plow, NT, ridge-till and sub till) and three cropping systems (continuous corn, continuous soybean, and soybean–corn). They reported that soil N and SOC were sequestered deeper in the profile and were protected against mineralization or erosion.

19.4.1.3 Improved Plant Nutrient Supply System

Maintenance of SOC is essential to long-term sustainable agriculture (Bhattacharyya et al. 2007). Fertilization can stimulate C assimilation by plants and increase C allocation to underground biomass (Liu et al. 2006). N fertilizer inputs are essential

Table 19.2 Types of tillage and carbon emissions. (Adapted from Lal 2004b)

Tillage type	Tillage tools	Emission (kg Ce ha^{-1})		Relative emission
		Range	Average	
Primary	Moldboard plow Chisel plow Sub-soiler	13.4–20.1 4.5–11.1 8.5–14.1	12.0	3.0
Secondary	Disking: heavy Disking: standard	4.6–11.2 4.0–7.1	6.7	1.7
Tertiary	Cultivation Hoeing	3.0–8.6 1.2–2.9	3.9	1

Primary: Secondary: Tertiary, 3:1.7:1

at the start of CA to maximize cover-crop biomass yields (Murungu et al. 2010a); in contrast that lack of fertilization may reduce the SOM content in surface layer of CA system (Dube et al. 2012). Kundu et al. (2013) assessed the CA effect with balanced fertilization of a maize–horse gram crop sequence and reported that SOC varied from 3.1 to 4.5 g kg^{-1} which was slightly higher than that under a conventional system (2.9–4.2 g kg^{-1}). Further, the grain yield of maize increased with the use of balanced fertilizers and the adoption of CA in season with below-average rainfall. The efficiency of N, P, K, S, and Zn use increased by 11, 16, 14, 13, and 21 %, respectively, under CA system. Kukal et al. (2009) reported that balanced use of fertilizers had more soil C sink capacity probably because of greater C input in rice–wheat system. Long-term adoption of NT with enough N fertilizer use proved to be effective tools to improve SOC stock by 3.4 and 4.5 Mg C ha^{-1} over unfertilized plots (Soler 2012). It is need to exercise with new NPK ratio for fertilizer application in CA systems (Jat et al. 2011), because in NT systems due to lower N mineralization rates and ammonia volatilization increase nutrient stratification and may increase nutrient loss from the soil surface (Dinkins 2008).

19.4.1.4 Integrated Management

Integrated nutrient management (INM) plays a significant role in C sequestration and building up/restoring soil health and productivity in semiarid subtropical soils which are low in SOM and nutrients (Lakaria et al. 2012, Das et al. 2014). In IGP at Haryana, practicing INM in NT could maintain grain yields of wheat with improved quality of grains in NT treatments as higher in protein (1–3 %), grain hardness (3–10 %), and chapatti score from all four (rice–wheat, cotton–wheat, pearl millet–wheat, cluster bean–wheat) crop rotations (Coventry et al. 2011). Applying ~30 Mg ha^{-1} y^{-1} of composted cattle manure to maize production systems increased the water-stable macroaggregate within 4 years, and aggregation was related to the soil C concentration, suggesting that soils with more water-stable aggregate indicates higher soil C concentration under NT system (Jiao et al. 2006). Aulakh et al. (2013) reported that in a 4-year field experiment conducted at Punjab Agricultural University, Ludhiana, India, with different combinations of fertilizer N, P, and FYM, wheat residues were applied for summer-grown soybean and soybean residue applied to winter-grown wheat crop continuously in both CT and CA; significantly increased water-stable aggregates and mean weight diameter as well as the formation of macroaggregates were the highest in both surface (85 %) and subsurface (81 %) soil layers with application of 20 kg N + 60 kg P_2O_5 + 10 Mg FYM + 6 Mg wheat residue ha^{-1} applied to soybean and 120 kg N + 60 kg P_2O_5 + 3 Mg soybean residue ha^{-1} applied to wheat crop in CA, respectively were 83 and 77 % in CT treatments after 2 years. BMP was 100 % in NP + FYM + CR where macroaggregates were > 50 % of total soil mass and also enhanced total organic carbon (TOC) 5.8 g kg^{-1} in surface layer and from 2.7 to 3.6 g kg^{-1} in subsurface layer after 2 years over control (3.8 g kg^{-1}) in CA. They further mentioned that the changes in TOC stocks after 4 years were 52 and 59 %. Likewise, the labile C and N fractions such as water-soluble C, particulate and light-fraction organic matter, potentially mineralizable N, and microbial biomass were also highest under CA with integrated chemical fertilizer and organic treatment. Some the examples are given below from Indian conditions where integrated use of chemical fertilizers and organic manures applied for aiming to increase SOC stock as complete CA system cannot be implemented universally. Swarup (1998) reported that INM enhanced SOC concentration of soils under rice cultivation from < 5 g kg^{-1} in 1973 to about 8 g kg^{-1} in 1994. Lakaria et al. (2012) reported that combined use of organic and inorganic sources for 5 consecutive years significantly increased SOC concentration in a soybean–wheat cropping sequence in a vertisol in central India. Long-term (20 years) INM experiments increased the SOC concentration in the 0–10-cm layer by 0.2 % in a sandy soil at Ludhiana, 0.6 % in clayey soils in Jabalpur, and 0.5 % in an alluvial soil in Bhubaneswar (Nambiar 1994, 1995). Nayak et al. (2012) reported that application of the RDF to a rice–wheat system in IGP (through either chemical fertilizers or INM strategy) increased the concentrations of SOC, POC, and MBC along with total SOC stocks and the rate of C sequestration. The data in Table 19.3 show that some INM treatments (using manure/CR of soybean, sorghum/green leaf manures, *Leucaena,* etc.) increased the rate of SOC sequestration in semiarid regions of India. The SOC sequestration rate (Mg C ha^{-1} year^{-1}) under best management treatments were: (1) 0.57 for 50 % recommended dose of fertilizer (RDF) + 4 Mg ha^{-1} groundnut shell, (2) 0.82 for 10 Mg ha^{-1} farm yard manure (FYM) + 100 % NPK, (3) 1.64 for 10 Mg ha^{-1} FYM + 100 % NPK, (4) 0.89 for 25 kg N ha^{-1} (sorghum residue) + 25 kg N (*Leucaena* clippings), (5) 0.42 for 50 % recommended dose of nitrogen (RDN) (fertilizer) + 50 % RDN (FYM), (6) 1.26 for 6 Mg ha^{-1} FYM + 20 kg N + 13 kg P, and (6) 0.32 for 100 % organic (FYM; Srinivasarao et al. 2012a, b, c, d, e, f).

19.4.2 Minimizing Carbon Loss

Reduction in tillage frequency, optimal utilization of available soil water, and maintaining a permanent residue cover on the soil are among the important strategies to minimize C loss and maximize C sequestration.

19.4.2.1 Reducing Soil Disturbance

The adverse impact of soil disturbance by intensive (conventional) tillage on soil-structure aggregation (Borie et al. 2006), roots (Brunel et al. 2013), concentration of SOC and MBC, and faunal activities (Sainju et al. 2009; Curaqueo et al. 2011) have been documented and can be exacerbated through accelerated erosion by water and wind. However, the magnitude of changes in soil properties can differ among management systems (Elder and Lal 2008). Tillage disturbs soil aggregates and accelerates the decomposition of aggregate-associated SOM (Paustian et al. 2000). Therefore, restoring soil quality is an essential prerequisite to increasing and sustaining

Table 19.3 SOC sequestration rate in different integrated nutrient management in important rainfed production systems

Production system/Location/Duration/No. of years of permanent manurial experiments	Treatments details	Best management practices	Mean annual C input (Mg C ha^{-1} $year^{-1}$)	C sequestration (Mg C ha^{-1})	C sequestration rate (Mg C ha^{-1} $year^{-1}$)	Critical C input for zero change of SOC (Mg C ha^{-1} $year^{-1}$)	Adapted and redrawn from
Groundnut# (Anantapur)* 1985–2004^ (20 years)+	T_1 = Control (no fertilizer), T_2 = 100 % recommended dose of fertilizer (RDF) (20:40:40 N, P_2O_5, K_2O), T_3 = 50 % RDF + 4 Mg groundnut shells (GNS) ha^{-1}, T_4 = 50 % RDF + 4 Mg FYM ha^{-1}, T_5 = 100 % organic (5 Mg FYM ha^{-1})	T_3 = 50 % RDF + 4 Mg groundnut shells (GNS) ha^{-1}	3.45	11.43	0.57	1.12	Srinivasarao et al. 2012a
Finger millet (Bangalore) 1978–2004 (27 years)	T_1 = Control, T_2 = 10 Mg FYM h a^{-1}, T_3 = 10 Mg FYM ha^{-1} + 50 % NPK, T_4 = 10 Mg FYM ha^{-1} + 100 % NPK, T_5 = Recommended NPK (50: 50:25 kg NPK ha^{-1}—fingermillet	T4 = 10 Mg FYM ha^{-1} + 100 % NPK	3.10	15.4	0.57	1.13	Srinivasarao et al. 2012c
(Finger millet-Groundnut) (Bangalore) 1991–2004 (13 years)	T_1 = Control, T_2 = 10 Mg FYM ha^{-1}, T_3 = 10 Mg FYM ha^{-1} + 50 % NPK, T_4 = 10 Mg FYM ha^{-1} + 100 % NPK, T_5 = Recommended NPK (25:50:25 kg NPK ha^{-1} groundnut; 50:50:25 kg NPK ha^{-1}—fingermillet	T_4 = 10 Mg FYM ha^{-1} + 100 % NPK	3.03	9.3	0.72	1.62	Srinivasarao et al. 2012b
Rabi sorghum (Solapur) 1985–2006 (22 years)	T_1 = Control, T_2 = 25 kg N ha^{-1} (Urea), T_3 = 50 kg N ha^{-1} (Urea), T_4 = 25 kg N ha^{-1} through sorghum residue (CR), T_5 = 25 kg N ha^{-1} through FYM, T_6 = 25 kg N ha^{-1} (CR) + 25 kg N ha^{-1} (Urea), T_7 = 25 kg N ha^{-1} (FYM) + 25 kg Nha^{-1} (Urea), T_8 = 25 kg N ha^{-1} (CR) + 25 kg N ha^{-1} (*Leucaena* clippings), T_9 = 25 kg N ha^{-1} (*Leucaena*), T_{10} = 25 kg N ha^{-1} (*Leucaena*) + 25 kg N ha^{-1} (Urea)	T_8 = 25 kg N ha^{-1} (CR) + 25 kg N ha^{-1} (*Leucaena* clippings)	3.40	14.4	0.65	1.10	Srinivasarao et al. 2012d

Table 19.3 (continued)

Production system/Location/Duration/No. of years of permanent manurial experiments	Treatments details	Best management practices	Mean annual C input (Mg C ha^{-1} $year^{-1}$)	C sequestration (Mg C ha^{-1})	C sequestration rate (Mg C ha^{-1} $year^{-1}$)	Critical C input for zero change of SOC (Mg C ha^{-1} $year^{-1}$)	Adapted and redrawn from
Pearlmillet (S.K. Nagar) 1988–2006 (18 years)	T_1 = Control, T_2 = 100 % recommended dose of N through mineral fertilizer (RDNF), T_3 = 50 % RDNF; T_4 = 50 % recommended N (FYM), T_5 = 50 % recommended N (fertilizer) + 50 % recommended N (FYM), T_6 = Farmers method (5 Mg of FYM ha^{-1} once in 3 years)	T_5 = 50 % recommended N (fertilizer) + 50 % recommended N (FYM)	1.86	−4.4	−0.24	3.30	Srinivasarao et al. 2011a
Soybean (Indore) 1992–2007 (15 years)	T_1 = Control, T_2 = 20 kg N + 13 kg P, T_3 = 30 kg N + 20 kg, T_4 = 40 kg N + 26 kg, T_5 = 60 kg N + 35 kg P, T_6 = 6 Mg FYM ha^{-1} + $N_{20}P_{13}$, T_7 = 5 Mg soybean residue ha^{-1} + $N_{20}P_{13}$, T_8 = 6 Mg FYM ha^{-1}, T_9 = 5 Mg soybean residues ha^{-1}	T_6 = 6 Mg FYM ha^{-1} + $N_{20}P_{13}$	6.99	11.9	0.79	3.47	Srinivasarao et al. 2012e
Rice (Varanasi) 1986–2007 (21 years)	T_1 = Control, T_2 = 100 % RDF (inorganic), T_3 = 50 % RDF (inorganic), T_4 = 100 % organic (FYM), T_5 = 50 % organic (FYM), T_6 = 50 % RDF + 50 % (foliar), T_7 = 50 % organic (FYM) + 50 % RDF, T_8 = Farmers practice	T_7 = 50 % organic (FYM) + 50 % RDF	4.14	3.1	0.14	2.47	Srinivasarao et al. 2012f

agronomic productivity. Adoption of NT increases aggregate stability and promotes the formation of recalcitrant SOM fractions within stabilized micro and macroaggregates. Presence of residue cover in NT system reduces rainfall impact, and minimizes soil and plant nutrient loss in comparison with those under CT (Castro et al. 1991). Chaudhury et al. (2014) studied the influence of different combinations of tillage and residue management on C stabilization in different-sized soil aggregates and also on crop yield after 5 years in a continuous rice–wheat cropping system on a sandy loam-reclaimed sodic soil in northern India. Chaudhury and colleagues observed increases in SOC concentration by 33.6 %, wheat yield by 8.3 %, water-stable macroaggregates by 53.8 %, and macroaggregate-associated C by 20.8 % when compared to those under CT.

19.4.2.2 Utilizing Available Soil Water

The soil and water-related information is less recognized, a healthy soil can store water and nutrients, and regulate the flow of water. Soil disturbances, compaction, and degradation can reduce its ability to perform ecosystem functioning. Increased soil erosion, decreased SOM content, and biological activity result in poor infiltration and water-holding capacity. Furthermore, inefficient use of water may reduce agronomic yields. Poor utilization of water is not only due to relief, slope, and rainfall intensity but also to burning of CRs and extensive tillage. Burning of CR reduces SOM, destroys structure, and reduces soil fauna activity. To minimize the impact of drought, soils need to store rainwater for future use. Surface infiltration depends on aggregation and its stability, pore space and its stability, the existence of cracks, and the soil surface condition. Increased SOM contributes indirectly to soil porosity. SOM influences the physical condition of the soil. CR covers the soil surface and protects it against sealing and crusting by raindrop impact, thereby enhancing rainwater infiltration and reducing runoff. The positive impact of CR retention in the CA system for improving soil stability and water balance has been widely documented. The adoption of a CA system—combining permanent raised beds with 30 % of standing CRs and NT seeding—reduced losses of water runoff and erosion, and increased crop growth and yield after 5 years in the highlands of Mexico (Govaerts et al. 2009a). Similarly, long-term adoption of CA in dryland farming in the Great Plains region of the USA enhanced precipitation storage and use efficiency, increased cropping intensity and higher productivity of diverse crop rotations, and improved soil properties. Ward et al. (2012) concluded that the inclusion of cover crops in Mediterranean-type farming systems is unlikely to have a major impact on water balance, but may increase overall sustainability of the farming system. Because NT does not loosen the soil, the first irrigation flows faster over the land than land prepared by plowing. Thus, irrigating 1 ha may take 10–12 hours in plowed land compared with 2.5–5 hours in an NT field. Therefore, NT saves water and minimizes leaching of nutrients. Water is channeled through the furrows in a bed-planting system which saves about 30 % water and fertilizer; higher efficiency is achieved by placing the top-dress fertilizer in the soil rather than broadcasting on the surface as in the traditional system (Hobbs 2007).

19.4.2.3 Maintaining Surface Residue Cover

Surface residue cover is a physical barrier, and alters the mass and energy exchange. Consequently, solar radiation does not reach the soil surface, strikes the residue, decreases the direct radiation flux on the soil surface and reduces soil evaporation (Carr et al. 2003). Aggarwal (1997) reported that incorporation of the residue of cluster bean (*Cyamopsis tetragonoloba L.*) and mung bean, and manure along with fertilizer N, increased SOC concentration and also agronomic yields. Yadav et al. (2000) reported more than 50 % decline in soil loss and increased SOC concentration by applying CRs as mulch. Blanco-Canqui and Lal (2007) assessed the long-term (10 years) impacts of three levels of wheat straw (0, 8, and 16 Mg ha^{-1} on a dry-matter basis) applied annually on SOC under NT system on an Aeric Epiaqualf in central Ohio. Overall, SOC stock from 0 to 50 cm depth was 82.5 Mg ha^{-1} in the unmulched soil, 94.1 Mg ha^{-1} with 8 Mg ha^{-1} mulch, and 104.9 Mg ha^{-1} with 16 Mg ha^{-1} mulch.

19.5 Managing Soil C: Conventional Versus CA

A CA system comprises three key principles (FAO 2013a):

1. *Minimal disturbance* of soil through NT systems—along with sufficient residue biomass—enhances soil and water conservation, controls soil erosion, improves soil aggregation, increases soil biological activity, improves soil biodiversity, enhances water quality, and increases soil C sequestration. In addition, an NT system also enhances water infiltration, improves soil–water-use efficiency and increases resilience against drought stress.
2. *Permanent soil covers*, maintained during crop growth phases and fallow periods, prevent the physical impact on soil from wind and rain, and moderate soil temperature. The residue cover can be improved by including a cover crop in the rotation cycle.
3. *Crop rotations and associations* reduce the need for pesticides and herbicides, control weeds, minimize off-site pollution and enhance biodiversity. The objective is to complement natural soil biodiversity and create a healthy soil which is naturally aerated, retains and supplies plant-available water, enhances nutrient cycling, and denatures and filters pollutants. Crop rotations and associations can be implemented as cropping sequences—relay cropping or mixed cropping.

The adoption of CA could be a better option for enhancing ecosystem services (Fig. 19.2).

Fig. 19.2 Benefits of CA for food security and sustainability in the ecosystem. CA conservation agriculture

19.5.1 Microbial Carbon Decomposition and Immobilization

Concentration of MBC in soil is the function of C input and output. The rate of organic C input from plant biomass is generally considered the dominant factor controlling the amount of microbial biomass in soil (Campbell et al. 1997). Managing C inputs thereby control microorganism's metabolism that moderate the rate of C mineralization and may have helped to store C into the soil. It has been reported that SOM increase under NT system on soil surface as a result microbial biomass also increases than CT (Feng et al. 2003; Sapkota et al. 2012). Studies on microbial biomass in NT shows stratification pattern (Alvarez et al. 1995) and plays an important role in physical stabilization of aggregates (Franzluebbers et al. 1999) and protected C from mineralization than CT (Nyamadzawo et al. 2009). More biomass on soil surface under NT consequently increases soil respiration and finally more CO_2–C. Lavelle et al. (1993) reported the factors affecting MBC decomposition as (1) climatic (soil temperature and water), (2) soils physical properties, (3) chemical constraints relating to soil biotic resources, and (4) interactions between macro and microorganisms. Content of MBC under NT was 60, 140, and 75% greater than under CT treatments in February, May, and October, respectively; this suggests that the changes in microbial community are primarily due to soil conditions (C input, temperature, moisture) and not by modified tillage (NT/CT) practices (Feng et al. 2003). Decomposition is, therefore, an essential biological process because it regulates the nutrient's cycling and soil properties. Deficiency of nutrient at the time of decomposition may limit microbial activity and reduce nutrient release (Lavelle et al. 1993). In general, N is most often the lacking nutrient. The remaining SOM after mineralization constitutes the "passive" SOM pool or biochemically-protected fraction (Parton et al. 1987).

19.5.2 Stratification of Soil Organic Carbon with Depth

Franzluebbers (2010b) reported that stratification of soil organic carbon (SOC) should be viewed as an improvement in soil quality because several key soil functions are enhanced, including soil structure, water infiltration, soil conservation, nutrient cycling, and C sequestration from the atmosphere. In addition, the SOM under conservation management (pastureland and forestland) is typically more stratified with depth than SOM under conventional cropping. Franzluebbers (2002) reported that stratification ratios of most soil properties are greater under NT than CT, with the greatest difference between tillage systems occurring in hot, wet regions with a low SOM environment, and the least difference in cold, dry regions with a high SOM environment. The stratification ratio of SOM pools increases in the soil surface because this vital interface: (1) receives much of the fertilizers and pesticides applied to cropland, (2) receives the intense impact of rainfall, and (3) partitions the flux of gases into and out of soil. Most of the mechanisms that affect productivity and environmental quality begin at the soil surface.

19.5.3 Sampling Issues for SOC Determination

Sampling issues are debated in the literature when SOC sequestration is assessed in agriculture. The quality of SOC data depends on soil sampling methods, season of collection, types of landscape and vegetation (Velayutham et al. 2000), depth distribution (Blanco-Canqui and Lal 2008), and soil analysis methods in the laboratory (Velayutham et al. 2000). Walkey and Black (1934) reported that a correction factor is needed when calculating SOC in soil as it is known to vary across soil type. For quantifying SOC stocks, the BD and depth of soils are important; since BD values convert SOC data by weight into volume. However, this volume-based calculation does not account for differences in soil mass induced by different BD among tillage treatments. Wendt and Hauser (2013) developed a new equivalent mass procedure for calculating SOC stocks in multiple soil layers and showed that it can be implemented without sampling for BD. BD may change with change in land management practice—mechanization with heavy machinery results in soil compaction, which increases BD and decreases porosity. Furthermore, BD can also vary over and between years as a result of differences in soil type (swell–shrink soils), moisture reserve and field operations. BD influences soil C stock over the entire profile, it is particularly crucial at the soil surface where large SOC is stored and huge SOC flux occurs (Yang et al. 2013). Small errors in BD can translate into large absolute errors in SOC stocks, an overestimation of BD by only 0.1 Mg m^{-3} translates into a 2- Mg C ha^{-1} (or ~10% of the total) error in SOC (Jonathan et al. 2010). Studies have implemented the soil mass equivalent technique to assess soil C stocks (Mishra et al. 2010). Gifford and Roderick (2003) reported that without careful consideration of differences in soil BD and soil C concentrations, as they vary within the soil profile, calculations of soil C stocks can over or underestimate C reserves. Indeed, a wide range of BD can be obtained in NT soils in comparison with conservation or CT. In some cases, soils under NT can have higher, similar, or lower BDs than that under CT or CA system.

19.5.4 Soil Aggregation: Boundaries for Decomposition

The degree, stability, and size distribution of aggregates strongly impact the rate of SOM decomposition. Aggregation depends on soil fauna, roots, inorganic binding agents, and environmental variables (Six et al. 2004). The release of polysaccharides and organic acids during SOM decomposition plays a major role in the stabilization of macroaggregates (Cheshire 1979). The residues and soil particulates are bound into macroaggregates in higher proportions in the surface soil than in subsurface soil (Benbi and Senapati 2010). The formation process of microaggregates within macroaggregates starts when POC of macroaggregate-binding (temporary) agents coated with microorganisms is decomposed and later encrusted with clays (Oades 1984). Isotope tracer studies (Angers et al. 1997; Gale et al. 2000) have indicated that microaggregates form within macroaggregates. This process finally releases stable microaggregates which become macroaggregates (Tisdall and Oades 1982). Aggregation stabilization depends largely on the availability of mineral N and the degradability of C substrates entering the soil (Guillou et al. 2012). The increase in aggregation is generally proportional to the SOC conserved and protected in the soil which allows SOM to function as a reservoir of plant nutrients and energy for soil microflora (Mrabet et al. 1999). Residue incorporation or retention causes a significant increment in total water-stable aggregates in surface soil and to a lesser extent in the subsoil (Chaudhury 2014). Chan et al. (2002) also observed that stubble burning significantly reduced the water stability of aggregate infractions > 2 mm and < 50 µm. In Morocco, Mrabet (2002) reported that CA has the potential to increase SOM concentration and enhance soil aggregation. Creation of an aggregated, fertile surface layer is important for reducing soil erosion and achieving sustainable agriculture.

19.5.5 The Influence on SOC Stocks

Numerous studies have reported the effects of tillage and cropping system on SOC stock. The results presented indicate a wide range of diversity in the data obtained and conclusions drawn. For example, West and Post (2002) concluded from a global database of 67 long-term experiments that SOC levels under NT differed significantly from those under CT and reduced tillage, while those under CT and reduced tillage did not significantly differ from one another. On the contrary, Alvarez (2005) reported no difference in SOC concentration between reduced (chisel, disc, and sweep tillage) and NT systems, whereas CT (moldboard plow, disc plow) was associated with less SOC at 161 sites involved in the study (at least whole tillage depth sampled). The change in frequency and intensity of tillage practices can alter BD and SOM concentration in the soil profile. Mann (1986) reported that the reduction in SOC concentration (by volume) in soils, with an initial level between 20 and 50 g kg^{-1}, was 20 % less after cultivation, and was most pronounced during the first 20 years of cultivation. West and Post (2002) concluded that a move from a CT system to NT system (both with residue retention) can sequester on average 48 ± 13 g C m^{-2} $year^{-1}$.

19.6 Carbon Sequestration Opportunities with CA: Experiences from Long-Term Experiments

There are numerous reports on the benefits of NT on soil quality and productivity and the potential long-term sustainability in terms of carbon storage. West and Post (2002) concluded that peak sequestration rates C attained within 5–10 years after conversion and reaching a new equilibrium in 15–20 years, and enhancing rotation complexity can sequester an average 20 ± 12 g C m^{-2} $year^{-1}$. Govaerts et al. (2009b) reviewed 78 studies on C (reduced tillage and crop rotation); in seven cases, soil C stock was lower in NT compared with CT, in 40 cases it was higher, and in 31 cases there was no significant difference. Kumar et al. (2012), in long-term NT experiments at northeast Ohio (47 years) and at northwest Ohio (49 years), reported highly sustainable and higher SOC (20.7 Mg ha^{-1}), water-stable aggregation, lower bulk density, and increased available water capacity than minimum tillage or plow tillage. A long-term 23-year field experiment conducted in Southwest England on NT, chisel, and mold-board plowing confirmed that NT and chisel plowing maintained carbon in the surface soil horizons, but mold-board plowing distributed carbon more uniformly throughout the soil profile, particularly when straw was incorporated (Hazarika et al. 2009). In India, information on long-term CA practices and C sequestration is rare; the most available information is based on reducing tillage and system productivity. The experiments have not fully implemented all three principles of CA; for examples, in northeast India, conservation tillage in terrace upland, valley upland and lowland ensured double cropping, and improved livelihood;

a long-term experiment (2006–2009) on conservation tillage and residue management showed that double NT rice based restored SOC to 70.75 %, increased biological activity to 46.7 %, saved water and produced 49 % higher yields than CT (Ghosh et. al. 2010). A study conducted on permanent beds with residue retention increased crop yield in maize by 11–17 % and in wheat by 12–15 % over conventional practices in western Uttar Pradesh (Naresh et al. 2012). The benefits of a NT system in the IGP include water and fuel savings (Gupta et al. 2002), and these soils have a low SOC concentration (Pal et al. 2009). A 20-year meta-analysis of an NT system in IGP showed that the associated GHGs emitted in NT systems were 3 % less than those under CT rice–wheat systems; and conversion to NT C sequestration potential is estimated to be 44.1 Tg C. Further, implementation of NT in maize–wheat and cotton–wheat systems would sequester an additional 6.6 Tg C. (Grace et al. 2012).

19.6.1 Biomass Input into Soils and Competing Uses of CRs

Sorghum, finger millet, pearl millet, maize, upland rice, groundnut, soybean, cotton (*Gossypium* spp.), food legumes, etc. are predominant crop production systems in rainfed regions of India. There is little, if any, recycling of CRs in most of these crops. Several studies have revealed that C input through various crop components (viz., leaf fall, stubbles, roots, rhizodeposition, etc.) returned back to soil can enhance C sequestration (Srinivasarao et al. 2013b). Data from the long-term manurial experiments on major rainfed production systems in India showed the highest C input through CR in a soybean–safflower (*Carthamus tinctorius*) system (3.4 Mg ha^{-1} $year^{-1}$) in Vertisols followed by an upland rice–lentil system (1.7 Mg ha^{-1} $year^{-1}$) in Inceptisols, a groundnut-based system (1.2 Mg ha^{-1} $year^{-1}$) in Alfisols, a finger millet and winter-sorghum-based system (0.8 Mg ha^{-1} $year^{-1}$) with the lowest in a pearl-millet-based system (0.3 Mg ha^{-1} $year^{-1}$) in Aridisols (Fig. 19.3). Assessment of a component-wise C input (leaf, stubble, root, nodules and rhizodeposition) into soil under different treatments was undertaken for different long-term manurial experiments conducted under the aegis of All India Coordinated Research Project on Dryland Agriculture (AICRPDA). Across all nutrient management treatments, the highest C input through leaf fall was estimated in cluster bean (0.62 Mg ha^{-1} $year^{-1}$) followed by castor (0.51 Mg ha^{-1} $year^{-1}$), soybean (0.38 Mg ha^{-1} $year^{-1}$), and lentil (0.08 Mg ha^{-1} $year^{-1}$; Fig. 19.4a). The highest C input through roots was also in cluster bean (1.4 Mg ha^{-1} $year^{-1}$) followed by castor (1.04 Mg ha^{-1} $year^{-1}$) and lentil (0.04 Mg ha^{-1} $year^{-1}$; Fig. 19.4b). In leguminous crops, the highest C input through nodules was in lentil (0.22 Mg ha^{-1} $year^{-1}$; Fig. 19.4c). The highest C input through stubble and rhizodeposition was in pearl millet (0.14 Mg ha^{-1} $year^{-1}$) and safflower (0.76 Mg ha^{-1} $year^{-1}$), respectively (Fig. 19.4d, e).

CR can be converted into high-value manure of better quality than FYM, and its use, along with chemical fertilizers, can help sustain or even increase agronomic yield. Use of chemical fertilizers has played a significant role in the intensification

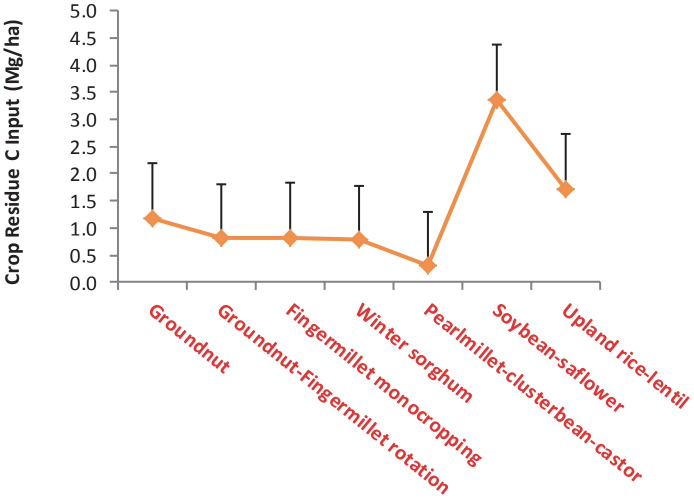


Fig. 19.3 Annual crop residue C input (Mg/ha) in different rainfed crop production systems. (Adapted and redrawn from Srinivasarao et al., 2013b)

of cropping systems, along with increased crop production. However, increased use of inorganic fertilizers alone, often in an unbalanced manner, leads to reduced soil quality and multiple nutrient deficiencies even in regions of high agronomic potential. Efficient management of CR can also play a vital role in refurbishing soil productivity as well as increasing the use efficiency of inorganic fertilizers. Thus, CR management is receiving attention because of its diverse and positive effects on physical, chemical, and biological properties of soil. Indeed, CR is a precious resource, and must not be labeled as waste.

Although benefits of CR incorporation are widely documented, the major problem is their availability in sufficient amounts for effective conservation of soil and water and for increasing SOC stocks. Most CRs (except root biomass) are taken away in regions of rainfed farming. Above all, other farming practices (e.g., excessive tillage, harvesting of residues as animal feed, burning to facilitate preparation of a clean seed bed, open grazing) exacerbate the process of soil degradation and deplete SOC stocks and plant nutrients.

Most CRs are widely used in India as animal feed, and this practice must be taken into account when assessing availability and profitability of livestock production systems. In addition to feed, CRs are used as litter and bedding material (providing FYM or compost), and chopped straw is used as poultry litter. Among industrial uses, rice straw is a raw material for paper production and as packing material. Rice husk is widely used in semi-artisan brick manufacture; chopped straw mixed with mud is used for plastering, both internally and (in hot, dry climates) externally. Relatively strong stems of maize, sorghum, and bulrush or pearl millet are used in traditional buildings, screens, and in constructing traditional grain storage bins. Furthermore, long straw is used as thatch, and residues are widely used as fuel in rural communities, and are often mixed into dung cakes for generating household energy.

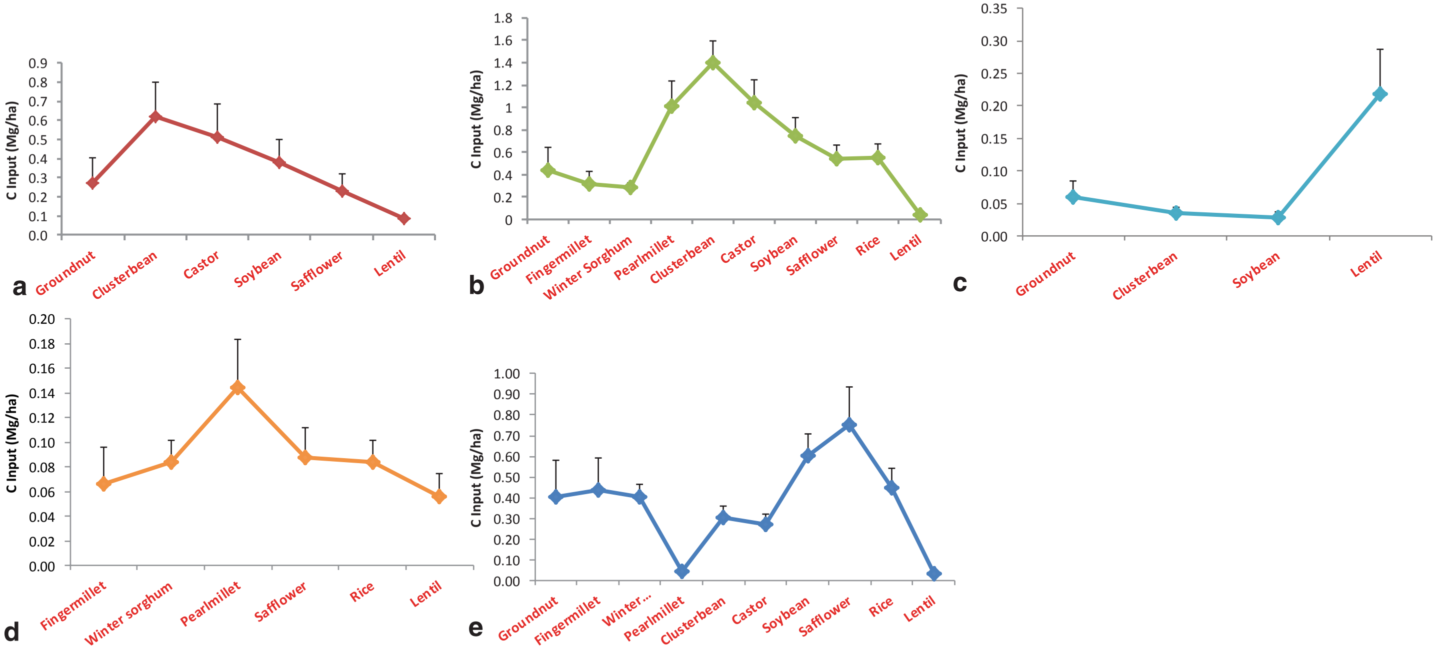


Fig. 19.4 Annual C input (Mg ha^{-1}) through (**a**) leaf fall, (**b**) root, (**c**) nodules, (**d**) stubble and (**e**) rhizodeposition in different rainfed production systems. (Adapted and redrawn from Srinivasarao et al. 2013b)

Despite their multiple and competing uses, CRs are an integral component of sustainable rainfed agriculture. Options available to farmers for the management of CR (including burning) are baling and removal, incorporation in soil with tillage, and retention on the surface as mulch. Burning, while exacerbating the loss of SOM, volatilization of nutrients, and adverse effects on soil biota, also causes air pollution and the associated adverse effects on human and animal health. In India, baling is not practiced by small landholders. Nonetheless, removal of CR by any means is a loss of organic resources essential to maintaining soil quality. However, it is also necessary to feed livestock and sustain mixed farming by integrating crops and livestock. While soil incorporation of CR is beneficial in recycling nutrients, plowing requires energy and time, and leads to temporary immobilization of nutrients (e.g., N). The C:N ratio must be decreased or corrected by applying N at the time of residue incorporation.

19.6.2 Profile SOC Stock and Carbon Sequestration

Sequestration of SOC in agricultural and restored ecosystems depends on soil texture, profile characteristics, and climate (Lal 2004). Adoption of CA is not a one-component technology but the cumulative effect of all three components (FAO 2013a). Based on the historical movement from CA toward NT, researchers in the USA and Canada take it for granted that NT or reduced tillage is always practiced in conjunction with sufficient retention of CRs. However, in arid regions and developing countries, competition for residues is extremely high and farmers struggle to keep sufficient residues on the soil surface. In fact, reducing tillage without applying sufficient residue cover exacerbates the reduced crop yields in rainfed semiarid areas (Govaerts et al. 2005, 2006a, b, 2007; Lichter et al. 2008) as well as in arid irrigated conditions (Limon-Ortega et al. 2006). Thus, crop intensification can result in an added effect on C storage in NT systems. West and Post (2002) reported that although relative increases in SOM concentrations may be small, increases due to adoption of NT are greater, and occur much faster in continuously cropped than in fallow-based rotations. Halvorson et al. (2002) observed that NT had little impact on SOC storage in dry climates if the cropping system had a year of bare, summer fallow, presumably due to enhanced decomposition during fallow that negated any benefit of reduced soil disturbance. Sisti et al. (2004) observed that under a continuous sequence of wheat (winter) and soybean (summer), SOC stock to 1 m depth under NT was not significantly different from that under CT. However, in the rotations with vetch planted as a winter green-manure crop, soil C stocks were approximately 17 Mg ha^{-1} higher under NT than under the CT system. It appears that the contribution of N_2 fixation by the leguminous green manure (vetch) in the cropping system is the principal factor responsible for the observed C accumulation in the soil under NT, and that most accumulated C is derived from crop roots. To accumulate SOM, there must not only be a C input from CRs but also a net external input of N, e.g., including an N-fixing green manure in the crop rotation (Sisti et al. 2004). A CT system can diminish the effect of an N-fixing green manure because the N input can be reduced by soil–mineral N release or the N can be lost by leaching (NO_3^-) or in gaseous forms (via NH_3 volatilization or denitrification) due to SOM mineralization stimulated by disk plowing that immediately precedes this crop (Alves et al. 2002). Hence, intensification of cropping practices, by eliminating fallow, and moving toward continuous cropping is the first step toward increased C sequestration. Reducing tillage intensity, by the adoption of NT, enhances the cropping intensity effect. The mechanisms that govern the balance between increased, similar, or lower SOC after conversion to NT are not clear. Although more research is needed, especially in tropical areas where good quantitative information is lacking, some factors that play a role can be identified (e.g., inadequate residue input, low activity and species diversity of soil fauna, high C:N ratio).

19.7 Carbon-Enhancing Management Options

SOM is the storehouse of many plant nutrients, and it strongly influences the biological activity and productive capacity of soils. Over the years, efforts have been made to improve SOM status in continuously cropped soils by fertilization, manuring, and residue management practices. However, maintaining and increasing SOC concentration is a major challenge in dryland soils due to high temperatures and moisture stress compared to that under temperate climate. A study undertaken at 21 locations across rainfed regions of India covering eight production systems revealed that most soils have low SOC concentrations, low available N, and low-to-high available P, K, and S. Many soils are deficient in available Mg, Zn, and B (Srinivasarao et al. 2006). Therefore, crop and soil management practices must be tailored to ensure long-term cropping systems. Application of plant nutrients (Paustian et al. 1997) and organic amendments and the inclusion/cultivation of legumes favor improved soil fertility and sustainability. Such a trend is directly related to maintaining the quantity of SOM, which is a critical component of soil productivity. However, resource-poor farmers in dryland regions apply meager quantities of nutrients, and thus crops suffer from multi-nutrient deficiencies (Srinivasarao et al. 2003). The best option to improve SOM, increase productivity, and advance sustainability of dryland agriculture seems to be the integration of farm-generated organic manure with inorganic fertilizers. Crop rotation, residue management, and fertilization can maintain the desired level of SOM (Campbell et al. 1992). Ali et al. (2002) stated that by improving physical, chemical, and biological properties of soils, food legume cultivation could arrest the declining trend in productivity of cereal–cereal systems. The availability of CR is a major problem in India and elsewhere in South Asia due to competing alternative uses but in some crop by-products, like groundnut shells, are available for soil application, as they do not have major alternate uses. Although chemical fertilization has positive effect on yields, poor farmers in rainfed regions mostly rely on FYM and other organic manures because of the high cost of chemical fertilizers. Thus, nutrient management and residue incorporation make a substantial contribution to SOC sequestration.

19.7.1 Cover Cropping

Besides reducing soil erosion, cover crops also aid in nutrient cycling, reduce soil temperature fluctuations, provide habitat for beneficial insects, and suppress weed populations. Cover crops have significant effects on SOC level in the surface layer, and winter cover crops increase SOC concentration more than soils under fallow (Calegari and Alexander 1998).

In most semiarid regions in India, a single crop is grown during the rainy or post-rainy season, and the land remains fallow for the remainder of the year. The rainy season crops depend on southwestern monsoon rains (June to September). About 20–30 % of annual rainfall, which occurs during the post-rainy season (October to December), is largely unutilized. Cover crops improve soil by increasing infiltration of the excess surface water, alleviating compaction and improving structure of tilled soil, and adding SOM that encourages beneficial soil microbial life and enhances nutrient cycling. Short-duration drought-hardy legumes like horse gram (*Macrotyloma uniflorum* L.) can be grown with off-season rainfall for fodder/green manuring to improve SOC concentration and partially meet the nutrient requirements of the following rainy season crops.

Horse gram is sown late in the rainy season by resource-poor farmers in marginal, drought-prone regions in India. As sowing and early crop growth coincides with declining rainfall, crop establishment is often poor and yields are low. A reasonable yield of horse gram can be achieved after an early pearl millet crop, giving an extra profit of ₹ 1000–2000 ha^{-1} compared with sole pearl millet grown in a medium-deep Alfisol (red soil) (Reddy and Willey 1985). Although grain production in horse gram is not assured in winter, in a deficit rainfall year, biomass production is assured. It is also possible to use off-season rainfall for on-farm generation of horse gram biomass. Data from a 10-year experiment produced 3.0–4.3 Mg ha^{-1} year^{-1} of fresh biomass, and incorporating of this in soil for a long period can improve SOC and MBC reserves (Venkateswarlu et al. 2007).

19.7.2 CR Harvest

Perpetual removal of CR can adversely impact soil quality (Blanco-Canqui and Lal 2008). Karlen et al. (1994) assessed the impact of corn stover harvest for 5 years in central Iowa, USA, and found strong adverse impacts on soil properties. Table 19.4 shows factors impacting effects of residue removal on SOC. CRs contain about 45 % of C on a weight basis. In addition, residue removal can increase SOM decomposition by about 16 % or 0.54–0.8 Mg C ha^{-1}. In India, 500–550 Tg CR is produced annually (NASS 2012; IARI 2012). CR production is the highest in Uttar Pradesh (60 Tg) followed by Punjab (51 Tg) and Maharashtra (46 Tg) (Table 19.5). Among different crops, the residue produced (Tg) is 352 by cereals, 66 by fiber crops, 29 by oilseeds, 13 by pulses, and 12 by sugarcane (NASS 2012). The availability and competitive uses of CR have been discussed in Sect. 19.6.1. Chaudhury et al. (2014)

Table 19.4 Factors impacting effects of residue removal on soil organic carbon

Parameters	Attributes
Climate	Precipitation amount, distribution Soil and air temperatures Growing season duration Frost-free days
Soil	Solum depth and horizonation Texture, and pH Clay mineralogy Soil biodiversity Parent material
Terrain	Slope gradient Slope shape and aspect Landscape position Drainage characteristics
Land use	Arable, pastoral, silvicultural, mixed Species composition and spatial arrangements Internal and off-farm inputs Mechanization type and intensity
Residue harvesting	Amount Height of harvest Physical condition of residues (size, placement) Distribution

Table 19.5 State-wise remaining surplus and generation of CR in India (IARI 2012)

State	Crop residue generation	Crop residue surplus	Crop residues burnt	Crop residues burnt
	(MNRE 2009)	(MNRE 2009)	(based on IPCC coefficients)	Pathak et al. 2010
Andhra Pradesh	43.89	6.96	6.46	2.73
Arunachal Pradesh	0.40	0.07	0.06	0.04
Assam	11.43	2.34	1.42	0.73
Bihar	25.29	5.08	3.77	3.19
Chhattisgarh	11.25	2.12	1.84	0.83
Goa	0.57	0.14	0.08	0.04
Gujarat	28.73	8.9	9.64	3.81
Haryana	27.83	11.22	6.06	9.06
Himachal Pradesh	2.85	1.03	0.20	0.41
Jammu and Kashmir	1.59	0.28	0.35	0.89
Jharkhand	3.61	0.89	1.11	1.10
Karnataka	33.94	8.98	3.05	5.66
Kerala	9.74	5.07	0.40	0.22
Madhya Pradesh	33.18	10.22	3.74	1.91
Maharashtra	46.45	14.67	7.82	7.41
Manipur	0.90	0.11	0.14	0.07
Meghalaya	0.51	0.09	0.10	0.05
Mizoram	0.06	0.01	0.02	0.01
Nagaland	0.49	0.09	0.11	0.08
Odisha	20.07	3.68	2.61	1.34
Punjab	50.75	24.83	9.84	19.62

Table 19.5 (continued)

State	Crop residue generation	Crop residue surplus	Crop residues burnt	Crop residues burnt
	(MNRE 2009)	(MNRE 2009)	(based on IPCC coefficients)	Pathak et al. 2010
Rajasthan	29.32	8.52	3.84	1.78
Sikkim	0.15	0.02	0.01	0.01
Tamilnadu	19.93	7.05	3.62	4.08
Tripura	0.04	0.02	0.22	0.11
Uttarakhand	2.86	0.63	0.58	0.78
Uttar Pradesh	59.97	13.53	13.34	21.92
West Bengal	35.93	4.29	10.82	4.96
Total	501.76	140.84	91.25	92.81

MNRE Ministry of new and renewable energy resources, *IPCC* intergovernmental panel on climate change

reported that direct-seeded rice and wheat in NT coupled with residue retention is a suitable management practice for enhancing soil C sequestration and sustainable yield increment even in reclaimed sodic soil in the hot semiarid zone of the Indian subcontinent. CR has the potential to increase total SOC content by 33.6 %, equivalent wheat yield by 8.3 %, water-stable macroaggregates by 53.8 % and macroaggregate-associated C by 20.8 % over CT with transplanted rice after 5 years of continuous rice–wheat cropping (Chaudhury et al. 2014). A maize–horse gram sequence under CT and a CA system with retaining above 30-cm maize CR was practiced on Alfisols at Hyderabad (Fig. 19.5).

19.7.3 Fertilizer Application and Manuring

Nutrient management is an important aspect of sustainable crop production in dryland farming and for maintaining of soil quality. The strategy of integrated plant nutrient supply (IPNS) adapts plant nutrition to specific farming systems and the

Fig. 19.5 CA and CT system in maize–horse gram sequence practice in semiarid Alfisol of Hyderabad, India. *CA* conservation agriculture, *CT* conventional tillage

desired "yield target" and considers improving the resource base, diversifying available plant nutrient sources, and addressing socioeconomic factors. Since plant nutrients are transferred in cyclical processes, IPNS strategy also involves monitoring all pathways of flow of plant nutrients in agricultural production systems to maximize profit, sustain the farming profession, and ensure food production. Thus, IPNS encompasses a holistic approach to nutrient management for crop production, and involves the judicious combination of fertilizers, biofertilizers, organic manures (FYM, compost, vermicompost, biogas sludge), green manures, CRs, etc., and growing legumes in the cropping system (Prasad 2008).The IPNS also encompasses balanced fertilization and site-specific nutrient management (SSNM). Considerable research on IPNS has been done in India (Katyal and Rattan 2003; Gupta et al. 2006). Moreover, long-term fertilizer experiments have shown that addition of organic manures as well as NPK (add-on series) results in high yields over long periods as opposed to reduced yields over time when only chemical fertilizer's application (Swarup 2002). Sarkar and Singh (2002) reported that for soybean–wheat cropping system (over 28 years), in the acidic soils of Ranchi, India ($\text{pH} < 5.4$), soybean yield averaged 0.33 Mg ha^{-1} and wheat yield averaged 0.43 Mg ha^{-1} for plots receiving N alone compared with 1.59 Mg ha^{-1} for soybean and wheat 2.65 Mg ha^{-1} for plots receiving NPK. Application of FYM with NPK increased soybean yield to 1.86 Mg ha^{-1} and wheat to 3.19 Mg ha^{-1}. Further, the effects of NPK + FYM were similar to those of NPK + lime, implying that continuous application of FYM can also partially offset acidity in acid soils.

Data from "replacement series" trials under the Project Directorate of Farming Systems Research (PDFSR) revealed that in most cropping systems (e.g., rice–wheat and rice–rice), application of 50 % N through green manure, FYM or CRs, and 50 % through RDF for summer rice, and 100 % RDF for winter crops (rice/wheat) produced the same yield as those obtained with 100 % RDF to both crops, saving 25 % of NPK fertilizers by this strategy. However, conclusions derived from such studies are mostly based on agronomic yields and the results are reported without accounting for NPK added through organic manures and without due consideration of the interaction effects.

Green manure crops have the potential to recycle considerable quantities of organic materials and nutrients. In India, Mandal et al. (2003) reported that green manuring with *Sesbania* adds/recycles large quantities of NPK when compared to other green manures on an equivalent weight basis of FYM. Addition of wheat straw adds the least amount of NPK. Further, use of *Sesbania* or cowpea and mung bean residues produced the same grain yield of rice + wheat, without any N application to rice, as that obtained with 120 kg N ha^{-1} applied to rice in the control plot (Mandal et al. 2003). Further, productivity of rice–wheat cropping increased by 1.2 Mg ha^{-1} with 80 kg N ha^{-1} applied to rice compared with that from 120 kg N ha^{-1} applied to control plots (no green manure, residue, or FYM). Use of FYM and *Leucaena* loppings produced lower yields than that obtained with application of *Sesbania* or cowpea green manure, or by incorporating mung bean residue. Although incorporation of wheat straw is the least effective, it produced more grain yield than the control (Prasad 2009).

Legumes are the most important component of IPNS. They may be grown as a green manure, grain crop, or as a dual-purpose crop (grain as well as green manure) within site-specific cropping systems. Soil-restoring capacity of legumes has been known in India since prehistoric times (Ali et al. 2002) even when their capacity to fix N was not known. Legumes fix 50–500 kg N ha^{-1} depending upon the crop and its growth period (Srinivasarao et al. 2003), and leave residual N varying from 30–70 kg N ha^{-1} for the succeeding crop (Srinivasarao et al. 2003)—a saving of 5.6–39.1 kg N ha^{-1} in wheat following mung bean or black gram. The N saving in wheat decreases as the level of N application increases. In India, legumes fix about 2.4 Tg of N annually (Singh et al. 2006).

Green manures contribute 60–120 kg N ha^{-1} to the succeeding crop (Srinivasarao et al. 2003). In a study on a sodic soil, green manure crops complemented with 75 kg N + 30 kg P_2O_5 + 25 kg K_2O ha^{-1} produced the same grain yield as those receiving 180 kg N + 90 kg P_2O_5 + 75 kg K_2O + 5 kg Zn ha^{-1}, showing that benefits of green manuring are not limited to N only (Swarup 1998). Despite such encouraging results, the area under green manure crops has been declining, mainly because of the nonremunerative nature of these crops. A better alternative is growing a dual-purpose legume such as cowpea or mung bean. When mung bean is grown as a summer cash crop and its residue is incorporated into the soil after the first pod picking (producing about 0.5 Mg ha^{-1} grain), the equivalent of 60–90 kg N ha^{-1} is added to the cropping system (Prasad 2009). Organic manures also supply small amounts of N but, when applied regularly over a long time, can overcome micronutrient deficiencies. Application of organic manures also improves physical, chemical, and biological properties of soil.

Biofertilizer (*Rhizobium, Azotobacter, Azosprillum,* blue–green algae (BGA), azolla, phosphate-solubilizing organisms, vesicular arbuscular mycorrhyza; VAM) can be an important component of IPNS, especially in dryland agriculture, where only low levels of fertilizers are applied. Organisms accelerating the decomposition of CRs are also important for enhancing soil fertility (Rao and Patra 2009).

19.8 Farmers Managing Soil Carbon

19.8.1 The Economic Potential of CA for Carbon Sequestration

The economic potential of C sequestration is important with improved management practices that store C or reduce C loss within soil profile over time. We know that the C and N cycle strongly connect; however, the cost of N for C storage is often overlooked when assessing the benefits of C credit (Lam et al. 2013). It has been reported that for 1 Mg C sequestered in humus, 833 kg N, 200 kg P, and 143 kg S are required (Himes 1997). A modeling study suggested that increased irrigation and fertilizer application would increase the C efficiency ratio even as net emissions rise in the rice–wheat system of India (Bhatia et al. 2010). But increasing fertilizer use increased both yields and CH_4 emissions. Practices such as mid-season drainage are viable in some situations to reduce CH_4 emissions (Babu et al. 2006). Generally, in India, the economic potential of CA has been assessed in terms of saving irrigation and fuel and increased crop productivity. Recently, Grace et al. (2012) reported 20 years of economic potential of C sequestration under NT-adopted IGP states. A total of 3 Tg C at US$ 25 Mg^{-1} C and 7.3 Tg C at US$ 50 Mg^{-1} C could be sequestered over 20 years through the implementation of NT cropping practices in soils under rice–wheat systems. The states of Uttar Pradesh, Bihar, and Punjab all offer similar returns in C credits of between US$ 25 Mg^{-1} C and US$ 100 Mg^{-1} C. Maximum levels of sequestration (100 % NT) could be attained in Bihar and Punjab with C prices approaching US$ 200 Mg^{-1} C and at this price 34.7 Tg C could be sequestered over 20 years in rice–wheat systems. Of which, Uttar Pradesh contributed 13.9 Tg C. In maize–wheat systems under NT, a C price of US$ 50 Mg^{-1} C would realize 252,000 Mg C—approximately 14 % of the sequestration potential, increasing to 811,000 Mg C (or 35 % of potential) at a C price of US$ 100 Mg^{-1} C. For cotton–wheat, US$ 50 Mg^{-1} C would return 173,000 Mg C over 20 years—6 % of the simulated C sequestration potential, increasing to 18 % at US$ 100 Mg^{-1} C. The clean development mechanism (CDM) of the Kyoto Protocol (IPCC 2007) has offered to reduce the C emission. Carbon markets offer additional income as certified emission reduction (CER) and may provide added incentive for the adoption of C sequestration technology to farmers. In Himachal Pradesh, India, the farmers in 177 gram panchayats of ten districts will receive ₹ 2000–2500 ha^{-1} annually. If the growth of biomass is good, the state can avail itself of the benefit of another 100,000 tCERs in the second phase (2017–2026) for which another agreement will be signed, an official said (The Hindu 2011). India is trying to build a case to include agriculture in an estimated global market of US$ 200 billion for C credit from the CDM (The Hindu 2011). The effective development of C markets requires functional techniques to assess baselines and changes in the soil C pool at a field and landscape level over a short period. Trading of C credits may be facilitated by effective community organization to minimize transaction costs.

19.8.2 Farmers Managing Soil C: Beyond Direct Incentives

Competitive demands on resources at the farm level, such as CRs, can constitute serious bottlenecks to CA implementation, particularly in semiarid rainfed agriculture, as opposed to cropping systems in wetter conditions or under irrigation (Erenstein 2002). Although exposure to market forces can be advantageous in the sense that farmers can reap the benefits of cost savings, access to fodder markets can create disincentives for the retention on-farm of CRs. This is often the case in densely populated regions with heavy demand on biomass and strong demand for livestock products, such as in India. Such market opportunities for straw and stover accentuate the value of CRs with competing uses for livestock fodder, household energy, and construction purposes (alternatives to leaving on the field to protect the soil surface). Moreover, most smallholders practice mixed crop–livestock systems and traditionally use CRs for maintaining their livestock. In these cases, farmers are reluctant to leave residues on the surface despite demonstrable yield advantages. More research is needed to establish minimum residue retention levels (thresholds) with positive impacts on SOC storage (Govaerts 2009b).

19.8.3 Constraints and Pathways for Adoption

There are numerous constraints to adoption of CA by small landholders in India and elsewhere in developing countries. Lal (1997) suggested establishing long-term NT studies in different soils and climates to assess C sequestration and soil quality. The success of CA in rainfed areas depends on two critical elements, viz. residue retention on the soil surface and weed control. Since residues are generally used as fodder in drylands, there is a need to determine the minimum amount of residue that can be retained without affecting the crop–livestock system and vice versa. Initially, emphasis may be given to crops whose residues are not used as fodder. More research is also needed on weed management under NT within a cropping system perspective. Identification of alternative sources of fodder for livestock is essential to spare CRs for adoption of CA systems. Identification of critical thresholds of tillage is needed for diverse rainfall, soil, and cropping systems, such that the main objectives of rainwater conservation are not compromised. Knowledge about these unknown factors will balance the need for conserving soil and capturing rainwater in the soil solum. Farm implements are needed for seed and fertilizer placement simultaneously to ensure optimum plant stand and early seedling vigor in rainfed crops under minimum tillage. Control of termites is required in order to enhance the value of residue left on the surface during long intervals between two crops (Venkateswarlu et al. 2010). Sometimes, CR is difficult to handle during sowing and other farm operations. Increased herbicides are needed to control weeds which may involve additional expenditure. There are also challenges to update farm machinery to cater to CA practices (Patle 2013).

19.8.4 The Consequences of Rotating Tillage Practices for Carbon Sequestration

Tillage costs money in the form of fuel for tractors, wear and tear on equipment, and the time of the operator. If animals are used as the power source, the costs of feeding and caring for the animals over a full year are also high. Emissions of GHGs from the burning of diesel fuel add to global warming. Further, SOM is oxidized when exposed to the air by tillage with antecedent decline in its amount, unless biomass-C is returned to the soil as residues, compost or other means. Tillage disrupts the bio-pores created by roots and biotic activity. Lesser known is the effect this has on belowground soil biology. The bare surface exposed after tillage is prone to breakdown of soil aggregates as the energy from raindrops dissipates. This results in

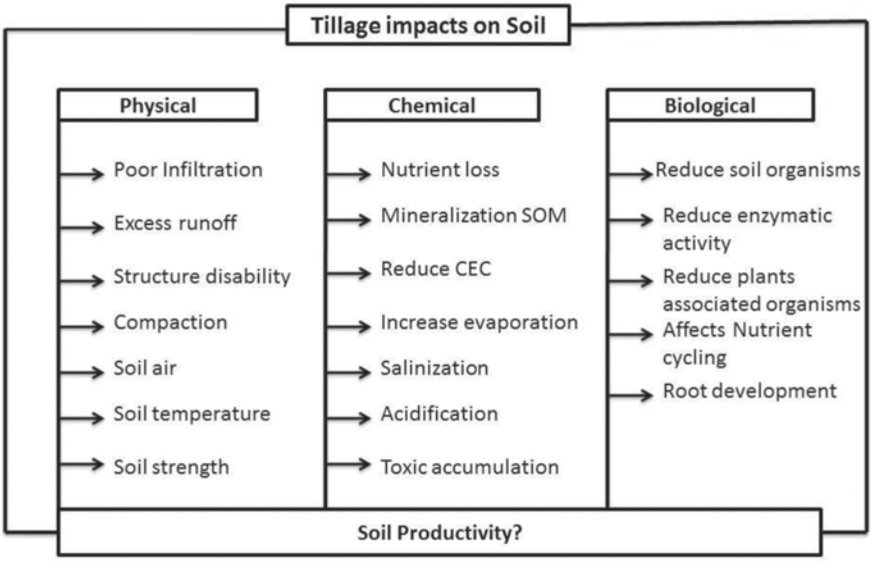


Fig. 19.6 The impacts of tillage practices on soil environment

clogging of soil pores, reduced infiltration of water and runoff, and acceleration of soil erosion. When the soil surface dries, it crusts and inhibits seedling emergence, and the bare surface after tillage is prone to wind erosion. The tractor wheels and vehicular traffic compact the subsoil. Schematic in Fig. 19.6 is a representation of the negative effects stemming from inappropriate tillage practices.

19.9 Future Outlook

Some research and development frontiers to promote adoption of CA in the semi-arid tropics of India and elsewhere in developing countries include the following:

1. Lack of knowledge and information are the main constraints to NT adoption in most countries. Information has to be relevant, factual, locally appropriate, credible, and useful in order to generate impact among farmers. The first step before converting to an NT system should be that farmers, researchers, technicians, and extension specialists improve their knowledge about all aspects of the system, and establish channels of communication among one another.
2. The superiority of the NT system over CT has generally been proven under diverse conditions worldwide. It is necessary now to develop and adapt the system locally and make sure that the technology works under the special environmental and socioeconomic conditions of each specific site. It is also important to learn which soils are not suited to or have some specific constraints to applying the system and how to alleviate these constraints.

3. It is also pertinent to identify other constraints to adoption of NT under local conditions (i.e., machines, herbicides, adequate crop rotations, adequate green manure cover crops, knowledge) and also be aware of socioeconomic factors and human dimensions affecting its adoption. The mindset "it does not work" is not helpful to promote adoption of NT. Knowing that NT is the only truly sustainable production system in improving productivity of soils in the tropics and subtropics, technological options need to be identified to address the problems and alleviate constraints.
4. Rather than agronomic yield, it is also important to assess profitability. Erosion control; improvement of chemical, physical, and biological soil conditions; lower machinery costs; reduced labor and tractor hours; timelines; higher economic returns; and other benefits of the system are important to study the growth of an NT system.
5. It is important that CA and NT systems are recognized within any renegotiated CDM undertaken by the United Nations framework convention on climate change (UNFCC) or any other mechanism at regional and global levels.
6. A closer interaction is needed between government agencies, farmers, private sector, technology generators and disseminators, and nongovernment organizations in policy reform, as well as for the design and application of stewardship incentives toward a broad acceptance of NT farming and CA.
7. Strong ties are needed with the private sector to recognize the importance of ecosystem services provided by CA, particularly for its role in soil C sequestration, to adopt and mitigate climate change.
8. A science-based synthesis must be developed on how C sequestration might provide ecosystem services through adoption of CA. Such a synthesis should include standardized measurement methodologies to determine the potential of soil C sequestration for site-specific crop management systems and eco-regions.
9. Standardized protocols are needed to apply science-based information to CA projects that provide ecological goods and services using internationally accepted guidance, such as ISO 14064 for GHG emission reductions.
10. Government endorsement must be sought for adoption of CA in the development of national and international policies for provision of numerous ecosystem services.
11. Adoption of CA technologies can be appropriately promoted through payments for ecosystem services (e.g., soil–carbon sequestration and water-quality benefits).

19.10 Conclusions

Arable lands are prone to severe soil degradation. Thus, crops require ever-increasing input to maintain yields, even in high-yielding areas where soils are moderately degraded. Therefore, agriculture should not only be high yielding but also sustainable. CA has the capacity for short-term maximization of crop production as well as the potential for long-term sustainability (i.e., C storage) at microsite (i.e., soil aggregation studies) and farm level (i.e., yields analysis, profitability). Concerning the potential of CA as a strategy for C sequestration, there are several knowledge gaps. For example, research information is lacking on the influence of tillage and crop rotations on soil C sink capacity. Available data have been obtained at the plot level, and more holistic research is needed at the farm level, including agro-ecosystem constraints along with soil and ecosystem C budgets at national and regional levels. Most available research data are from regions where CA has been implemented for a long time. Thus, there is a strong need to develop an international network of benchmark pilot studies on CA in diverse agro-ecological regions and farming systems. Long-term operations of such a network are needed to understand the mechanisms of C sink capacity by CA.

While C sequestration may be questionable in some eco-regions and cropping systems, CA is an important technology to restore soil processes, control soil erosion, and reduce tillage-related production costs. These are sufficient reasons to promote the systematic conversion of the traditional system to CA. While detailed knowledge of functional relationships is needed to determine the real potential of CA as a carbon offset technology, it is pertinent to adopt agricultural practices that preserve and restore soil functions such as food security, climate change adoption and mitigation, and water resources improvement.

Soil C sink capacity depends on several factors including climate, soil type, crops and vegetation cover, and management practices. Harshness of arid and semiarid climate exacerbates the risk of soil degradation by depleting SOC, increasing the risk of erosion, and salinization. Recycling organic resources containing polyphenols and lignin may affect the long-term decomposition dynamics and contribute to the buildup of SOC. Hence, it is important to explore a wide range of adaptation strategies which could reduce the vulnerability of agriculture to climate change. A wide adoption of CA will reduce the cost of labor, fuel, and machinery, while conserving water, reducing erosion, and sequestering C.

References

Aggarwal RK, Kumar P, Power JF (1997) Use of crop residue and manure to conserve water and enhance nutrient availability and pearl millet yields in an arid tropical region. Soil Tillage Res 41:43–51

Ali M, Ganeshamurthy AN, Srinivasarao Ch (2002) Role of pulses in soil health and sustainable crop production. Indian J Pulse Res 15(2):1–14

Alvarez R, Diaz RA, Barberob N, Santanatogliaa OJ, Blotta L (1995) Soil organic carbon, microbial biomass and CO2-C production from three tillage systems. Soil Tillage Res 33:17–28

Alvarez R. (2005) A review of nitrogen fertilizer, conservation tillage effects on soil organic carbon storage. Soil Use Manage 21:38–52

Alves BJR, Zotarelli L, Boddey RM, Urquiaga S (2002) Soybean benefit to a subsequent wheat cropping system under zero tillage. In Nuclear techniques in integrated plant nutrient, water and soil management. IAEA, Vienna, pp 87–93

Angers DA, Recous S, Aita C (1997) Fate of carbon, nitrogen in water-stable aggregates during decomposition of 13 C 15 N-labelled wheat straw in situ. Eur J Soil Sci 48:295–300

Aulakh MS, Garg AK, Kumar S (2013) Impact of integrated nutrient, crop residue and tillage management on soil aggregates and organic matter fractions in semiarid subtropical soil under soybean-wheat rotation. Am J Plant Sci 4:2148–2164

Babu Y, Li C, Frolking S, Naya D, Adhya T (2006) Field validation of DNDC model for ethane and nitrous oxide emissions from rice-based production systems of India. Nutr Cycl Agroecosys 74:157–174

Baker JM, Ochsner TE, Venterea RT, Griffis TJ (2007) Tillage and soil carbon sequestration-what do we really know? Agric Ecosyst Environ 118:1–5

Batjes NH (1999) Management option for reducing CO2 concentration in the atmosphere by increasing carbon sequestration in the soil. Dutch national research programme on global air pollution, climate change & technical paper 30. International soil reference information centre, Wageningen. Report 410-200-031

Benbi D, Senapati N (2010) Soil aggregation and carbon and nitrogen stabilization in relation to residue and manure application in rice-wheat systems in northwest India. Nutr Cycl Agroecosyst 87(2):233–247

Bhatia A, Pathak H, Aggarwal PK, Jain N (2010) Trade-off between productivity enhancement and global warming potential of rice and wheat in India. Nutr Cycl Agroecosyst 86:413–424

Bhattacharyya R, Chandra S, Singh RD, Kundu S, Srivastva AK, Gupta HS (2007) Long-term farmyard manure application effects on properties of a silty clay loam soil under irrigated wheat-soybean rotation. Soil Tillage Res 94:386–396

Bhattacharyya T, Pal DK, Chandran P, Ray SK, Mandal C, Telpande B (2008) Soil carbon storage as a tool to prioritize areas for carbon sequestration. Curr Sci India 95(4):482–494

Blanco-Canqui CH, Lal R (2007) Impact of long-term wheat straw management on soil hydraulic properties under no-tillage. Soil Sci Soc Am J 71:1166–1173

Blanco-Canqui CH, Lal R (2008) No-tillage and soil profile carbon sequestration: an on farm assessment. Soil Sci Soc Am J 72:693–701

Borie F, Rubio R, Rouanet JL, Morales A, Borie G, Rojas C (2006) Effects of tillage systems on soil characteristics, glomalin and mycorrhizalpropagules in a Chilean Ultisol. Soil Tillage Res 88:253–261

Bowers CG (1989) Tillage draft, energy measurements for twelve south eastern soil series. Trans ASAE 32(1):492–502

Bradford JM, Peterson GA (2000) Conservation tillage. In: Sumner ME (ed) Handbook of soil science. CRC, Boca Raton, pp 247–269

Brunel N, Seguel O, Acevedo E (2013) Conservation tillage and water availability for wheat in the dryland of central Chile. J Plant Nutr Soil Sci 13(3):622–637

Calegari A, Alexander I (1998) The effects of tillage and cover crops on some chemical properties of an Oxisol and summer crops yields in south western Parana, Brazil. Adv Geo Ecol 31:1239–1246

Campbell CA, Bowren KE, Schnitzer M, Zentner RP, Townley SL (1992) Effect of crop rotations and fertilization on soil biochemical properties in a thick Black Chernozem. Can J Soil Sci 71:377–387

Campbell CA, Janzen HH, Juma NG (1997) Case studies of soil quality in the Canadian prairies: long-term field experiments. In: Gregorich EG, Carte MR (eds) Soil quality for crop production and ecosystems health. The Netherlands Elsevier, Amsterdam, pp 351–397

Carr PM, Horsley RD, Poland WW (2003) Tillage and seedling rate effects on wheat cultivars: i grain production. Crop Sci 43:202–209

Castro F, Henklain JC, Vieira MJ, Casao R Jr (1991) Tillage methods, soil physical conditions. Soil Sci Soc Am J 59:1436–1443

Chan KY, Heenam DP, Oates A (2002) Soil carbon fractions, relationship to soil quality under different tillage, stubble management. Soil Tillage Res 63:133–139

Cheshire MV (1979) Nature and origin of carbohydrates in soil. Academic, London, p 216

Chivenge PP, Murwira HK, Giller KE, Mapfumo P, Six J (2007) Long-term impact of reduced tillage, residue management on soil carbon stabilization: implications for conservation agriculture on contrasting soil. Soil Tillage Res 94:328–337

Chaudhury SG, Srivastava S, Singh R, Chaudhari SK, Sharma DK, Singh SK, Sarkar D (2014) Tillage, residue management effects on soil aggregation, organic carbon dynamics, yield attribute in rice-wheat cropping system under reclaimed sodic soil. Soil Tillage Res 136:76–83

Christopher SF, Lal R, Mishra U (2009) Regional study of no-till effects on carbon sequestration in the mid-western United States. Soil Sci Soc Am J 73:207–216

Coventry DR, Poswal RS, Yadav A, Gupta RK, Gill SC, Chhokar RS, Kumar V, Sharma RK, Kumar A, Mehta A, Kleemann SGL, Cummins JA (2011) Effect of tillage and nutrient management on wheat productivity and quality in Haryana, India. Field Crop Res 23:234–240

Curaqueo G, Barea JM, Acevedo E, Rubio R, Cornejo P, Borie F (2011) Effects of different tillage system on arbuscular mycorrhizal fungal propagules and physical properties in a Mediterranean agroecosystem in central Chile. Soil Tillage Res 113:11–18

Das B, Chakraborty D, Singh VK, Aggarwal P, Singh R, Dwivedi BS, Mishra RP (2014) Effect of integrated nutrient management practice on soil aggregate properties, its stability, aggregate-associated carbon content in an intensive rice-wheat system. Soil Tillage Res 136:9–18

Dendooven L, Gutierrez-Oliva VF, Patino-Zuniga L, Ramirez-Villanueva DA, Verhulst N, Luna-Guido M, Marsch R, Montes-Molina J, Gutiérrez-Miceli FA, Vásquez-Murrieta S, Govaerts B (2012) Greenhouse gas emission under conservation agriculture compared to traditional cultivation of maize in the central highlands of Mexico. Sci Total Environ 431:237–244

Derpsch R, Friedrich T, Kassam A, Hongwen Li (2010) Current status of adoption of no-till farming in the world and some of its main benefits. Int J Agric Biol Eng 3(1):1–25

Diaz-zorita M, Gustavo AD, Grove JH (2002) A review of no-till system, soil management for sustainable crop production in the sub-humid, semi-arid Pampas of Argentina. Soil Tillage Res 65:1–18

Dick WA, Durkalski JT (1997) No-tillage production agriculture and carbon sequestration in a TypicFragiudalf soil of north eastern Ohio: In: Lal R, Kimble J, Follett R (eds) Management of carbon sequestration in soil: advances in soil science. CRC, Boca Raton, pp 59–71

Dinkins P, Jones C, McVay K (2008) Nutrient availability can differ somewhat among no-till, minimum till and till systems. This guide explains how nutrients should be managed in no-till and minimum till systems to optimize crop yield and quality. http://msuextension.org/publications/AgandNaturalResources/EB0182.pdf

Dube E, Chiduza C, Muchaonyerwa P (2012) Conservation agriculture effects on soil organic matter on a Haplic Cambisol after four years of maize–oat and maize-grazing vetch rotations in South Africa. Soil Tillage Res 123:21–28

Duxbury JM, Smith MS, Doran JW (1989) Soil organic matter as a source, sink of plant nutrients. In: Coleman JM et al (eds) Dynamic of soil organic matter in tropical ecosystems. University of Hawaii Press, Honolulu, pp 33–67

Elder JW, Lal R (2008) Tillage effects on physical properties of agricultural organic soils of north central Ohio. Soil Tillage Res 98:208–210

Erenstein O (2002) Crop residue mulching in tropical and semi-tropical countries: an evaluation of residue availability and other technological implications. Soil Tillage Res 67:115–133

Erenstein O, Laxmi V (2008) Zero tillage impacts in India's rice-wheat systems: a review. Soil Tillage Res 100:1–14

Eswaran H, Lal R, Reich PF (2001) Land degradation: an overview. In: Bridges EM et al (eds) Response to land degradation. Proceedings 2nd international conference on land degradation and desertification, KhonKaen, Thailand. Oxford, New Delhi

Falloon P, Jones CD, Cerri CE, Al-Adamat RP, Bhattacharyya T, Easter M, Paustian K, Killian K, Coleman K, Milne E (2007) Climate change and its impact on soil and vegetation carbon storage in Kenya, Jordan, India and Brazil. Agric Ecosys Environ 122:114–124

FAO (2013a) Basic principles of conservation agriculture. www.fao.org/ag/ca/1a.html. Accessed Dec 2013

FAO (2013b) FAO statistical yearbook 2013. World Food and Agriculture Organization of the United Nations, Rome

FAO (2014a). Soil carbon sequestration for improved management. World soil report 96. Based on the work of Michel Robert Institut national de recherché agronomique Paris, France. ftp://ftp.fao.org/agl/agll/docs/wsrr96e.pdf. Accessed Dec 2013

FAO (2014b) The importance of soil organic matter key to drought-resistant soil, sustained food, production by Alexandra Bot and Jose Benites.FAO soil bulletin 80 (2001). www.fao.org/docrep/009/a0100e/a0100e0a.htm#TopOfPage. Accessed Dec 2013

Farage PK, Ardo J, Olsson L, Rienzi EA, Ball AS, Pretty JN (2007) The potential for soil carbon sequestration in three tropical dryland farming systems of Africa, Latin America: a modelling approach. Soil Tillage Res 94:457–472

Feng Y, Motta AC, Reeves DW, Burmester CH, Santena EV, Osbornec JA (2003) Soil microbial communities under conventional-till and no-till continuous cotton systems. Soil Bio Biochem 35:1693–1703

Follett RF (1993) Global climatic change U.S. agriculture carbon dioxide. J Prod Agric 6:181–238

Follett RF, Varvel GE, Kimble J, Vogel KP (2009) No-till corn after brome grass: effect on soil C and soil aggregates. Agron J 101:261–268

Foresight (2009) Global food and farming future. http://www.foresight.gov.uk/OurWork/Activeprojects/foodandfarmingfuture/foodandfarmingprojectHome.asp

Franzluebbers AJ (2002) Soil organic matter stratification ratio as an indicator of soil quality. Soil Tillage Res 66:95–106

Franzluebbers AJ (2008) Soil organic carbon sequestration with conservation agriculture in the south eastern USA: potential and limitations. http://www.fao.org/ag/ca/Carbon%20Offset%20Consultation/carbonmeeting/3fullpapersbyconsultationspeakers/paperfranzluebbers.pdf

Franzluebbers AJ (2010a) Achieving soil organic carbon sequestration with conservation agricultural systems in the south eastern United States. Soil Sci Soc Am J 74:347–357

Franzluebbers AJ (2010b) Depth distribution of soil organic carbon as a signature of soil quality.19th world congress of soil science, soil solutions for a changing world 1–6 Aug 2010. Brisbane (Published on DVD)

Franzluebbers AJ, Haney RL, Hons FM, Zuberer DA (1999) Assessing biological soil quality with chloroform fumigation-incubation: why subtract a control? Can J Soil Sci 79:521–528

Friedrich T, Kassam A (2012) No-till farming and the environment: do no-till systems require more chemicals? Outlooks Pest Manag 153–157. doi:10.1564/23aug02

Gale WJ, Cambardella CA, Bailey TB (2000) Root-derived carbon the formation stabilization of aggregates. Soil Sci Soc Am J 64:201–207

Gattinger A, Jawtusch J, Muller A, Mader P (2011) No-till agriculture- a climate smart farming. In: Piepenbrink N, Schroeder A (eds) Climate change and agriculture, Report no. 2. MISEREOR, Anchen pp 1–24

Ghosh PK, Das A, Saha R, Kharkrang E, Tripati AK, Munda GC, Nagchan SV (2010) Conservation agriculture towards achieving food security in North East India. Curr Sci India 99(7):915–921

Gifford RM, Roderick ML (2003) Soil carbon stocks, bulk density: spatial or cumulative mass coordinates as a basis of expression? Glob Change Biol 9:1507–1514

Giller KE, Witter E, Corbeels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: the heretics view. Field Crop Res 114:23–34

Govaerts B, Sayre KD, Decker J (2005) Stable high yield with zero tillage and permanent bed planting? Soil Tillage Res 94:33–42

Govaerts B, Mezzalama M, Sayre KD, Crossa J, Nicol JM, Deckers J (2006a) Long-term consequences of tillage, residue management, and crop rotation on maize/wheat root rot and nematode populations in subtropical highlands. Appl Soil Ecol 32:305–315

Govaerts B, Sayre KD, Deckers J (2006b) A minimum data set for soil quality assessment of wheat and maize cropping in the highlands of Mexico. Soil Tillage Res 87:163–174

Govaerts B, Fuentes M, Mezzalama M, Nicol JM, Deckers J, Etchevers JD, Figueroa SB, Sayre KD (2007) Infiltration soil moisture root rot and nematode populations after 12 years of different tillage, residue and crop rotation managements. Soil Tillage Res 94:209–219

Govaerts B, Sayre KD, Goudeseune B, De Corte P, Lichter K, Dendooven L, Deckers J (2009a) Conservation agriculture as a sustainable option for the central Mexican highlands. Soil Tillage Res 103:222–230

Govaerts B, Verhulst N, Navarrete C, Sayre A, Dixon KD, Dendooven JL (2009b) Conservation agriculture and soil carbon sequestration: between myth and farmer reality. Crit Rev Plant Sci 28:97–122

Grace PR, Jain MC, Harrington LW (2003) Environmental concerns in rice-wheat system. In: Proceedings of the international workshop on developing action programme for farm level impact in rice-wheat system of the Indo-Gangetic plains held during 25–27 Sept 2000, New Delhi, India. Rice–wheat consortium paper series 14, pp 99–111

Grace PR, Antle J, Aggarwal PK, Ogle S, Paustian K, Basso B (2012) Soil carbon sequestration and associated economic cost for farming systems of the Indo-Gangetic plain: a meta-analysis. Agric Ecosyst Environ 146:137–146

Grant CA, Lafond GPL (1994) The effects of tillage systems and crop rotations on soil chemical properties of a black Chernozemic soil. Can J Soil Sci 74(3):301–306

Guertal EA, Eckert DJ, Traina SJ, Logan TJ (1991) Differential phosphorus retention in soil profiles under no-till crop production. Soil Sci Soc Am J 55:410–413

Guillou CL, Angers DA, Maron PA, Leterme P, Aubry SM (2012) Linking microbial community to soil water-stable aggregation during crop residue decomposition. Soil Biol Biochem 50:126–133

Gupta PK. Sahai S (2006) Residue open burning in rice-wheat cropping system in India: an agenda for conservation of environment & agricultural resources. Proceedings of the symposium, CASA-ICAR, Pusa, New Delhi, 2006

Gupta RK, Naresh RK, Hobbs PR, Ladha JK (2002) Adopting conservation agriculture in the rice-wheat system of the Indo-Gangetic Plains: new opportunities for saving water. In: Bouman, BAM et al (eds) Water wise rice production: Proceedings of the international workshop on water wise rice production, April 8–11, 2002, Los Banos, Philippines. International Rice Research Institute, Los Banos, pp 207–222

Gupta RK, Singh Y, Singh V, Singh B (2006) Integrated nutrient management for improving soil, crop productivity in rice-wheat crop rotation in north western India. Indian Fmg 56(4):10–14

Gupta PK, Sahai S, Singh N, Dixit CK, Singh DP, Sharma C, Tiwari MK, Gupta RK, Garg SC (2004) Residue burning in rice-wheat cropping system: causes, implications. Curr Sci India 87(12):1713–1717

Gupta RK, Malik RK, Jat ML, Saharawat YS (2009) Conservation agriculture-current status, prospects in South Asia. In: 4th world congress on conservation agriculture, New Delhi, 4–7 Feb, p 82

Gupta RK, Gopal R, Jat ML, Jat RK, Sidhu HS, Minhas PS, Malik RK (2010) Wheat productivity in Indo-Gangetic plains of India during 2010: terminal heat effects, mitigation strategies. PACA Newsletter, pp 1–3

Haider K (1999) Von der totenorgnischensubtanzzum humus. PflanzenernahrBodenk 162:363–371

Halvorson AD, Gary AP, Curtis AR (2002) Tillage system and crop rotation effects on dryland crop yields and soil carbon in the Central Great Plains. Agron J 94:1429–1436

Hazarika S, Parkinson R, Bol R, Dixon L, Russell P, Donovan S, Allen D (2009) Effect of tillage system and straw management on organic matter dynamics. Agron Sustain Dev 29:525–533

Himes FL (1997) Nitrogen, sulfur and phosphorus and the sequestering of carbon. In: Lal R, Kimble JM, Follett RF, Stewart BA (eds) Soil processes and the carbon cycle: advances in soil science. CRC: Boca Raton pp 315–319

Hobbs PR (2007) Conservation agriculture: what is it and why is it important for future sustainable food production? J Agr Sci Cambridge 145:127–137

IARI (2012) Crop residues management with conservation agriculture: potential, constraints, policy needs. Indian Agricultural Research Institute, New Delhi, p 32

IPCC (2007) Climate change; fourth assessment report of the intergovernmental panel on climate change, Cambridge University Press, Cambridge

IPCC (2013) Climate change 2013: the physical science basis. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, p 1535

Jastrow JD, Miller RM (1997) Soil aggregate stabilization, carbon sequestration: feedbacks through organomineral associations. In: Lal R et al (eds) Soil processes, the carbon cycle, advances in soil science. CRC, Boca Raton, p 207

Jat ML, Singh RG, Sahrawat YS, Gathala MK, Kumar V, Sidhu HS, Gupta RK (2010) Innovation through conservation agriculture: progress, prospects of participatory approach in the Indo-Gangetic plains of South Asia. In: Joshi PK et al (eds) Conservation agriculture—innovation for improving efficiency, equity, environment. National Academy of Agriculture Science (NASS), Pusa

Jat ML, Saharawat YS, Gupta R (2011) Conservation agriculture in cereal systems of south Asia: nutrient management perspectives. Karnataka J Agric Sci 24(1):100–105

Jat RA, Wani SP, Sahrawat KL (2012) Conservation agriculture in the semi-arid tropics: prospects and problems. In: Donald Sparks (ed) Advances in agronomy, vol 117. Academic, New York, pp 191–272

Jiao Y, Whalen JK, Hendershot WH (2006) No-tillage and manure applications increase aggregation and improve nutrient retention in a sandy-loam soil. Geoderma 134:24–33

Johnson JMF, Alimaras RR, Reicosky DC (2006) Estimating source of carbon from crop residues, roots, rhizodiposits using the national grain-yields database. Agron J 98:622–636

Jonathan S, Ryan F, Jeffrey B (2010) Soil carbon sequestration potential: a review for Australian agriculture. A report prepared for department of climate change, energy efficiency. CSIRO, p 81

Kanchikerimath M, Singh D (2001) Soil organic matter, biological properties after 26 years of maize–wheat–cowpea cropping as affected by manure, fertilization in a Cambisol in semiarid region of India. Agric Ecosyst Environ 86:155

Karlen DL, Wollenhaupt NC, Erbach DC, Berry EC, Swan JB, Eash NS, Jordahl JL (1994) Crop residue effects on soil quality following 10 years of no-till corn. Soil Tillage Res 31:149–167

Kassam A, Friedrich T (2012) An ecologically sustainable approach to agricultural production intensification: global perspectives and developments. Field actions science reports, special issue 6, http://factsreports.revues.org/138

Katterer T, Bolinder MA, Ren O, Kirchmann H, Menichetti L (2011) Roots contribute more to refractory soil organic matter than above ground crop residue, as revealed by a long-term field experiment. Agric Ecosyst Environ 141:184–192

Katyal JC, Rattan RK (2003) Integrated plant nutrition systems to meet the challenges of nutrient mining threatening sustainable agriculture. FAI Ann Sem Papers 511-1/1/-8

Kell DB (2011) Breeding crop plants with deep roots: their roll in sustainable C, nutrient, water sequestration. Ann Bot London. doi:10.1093/aob/mcr175. www.aob.oxfordjournals.org

Kendall HW, Pimentel D (1994) Constraints on the expansion of the global food supply. Ambio 23:198–205

Kern JS, Johnson MG (1993) Conservation tillage impacts on national and atmospheric C levels. Soil Sci Soc Am J 57:200–210

Kukal SS, Rasool R, Benbi DK (2009) Soil organic carbon sequestration in relation to organic, inorganic fertilization in rice–wheat, maize–wheat systems. Soil Tillage Res 102:87–92

Kumar K, Ghosh KM (2002) Management practices of antecedent leguminous and non-leguminous crop residues in relation to winter wheat yields, nitrogen uptake, soil nitrogen mineralization and simple nitrogen balance. Eur J Agron 16:295–308

Kumar S, Kadono A, Lal R, Dick W (2012) Long-term no-till impacts on organic carbon and properties of two contrasting soils and corn yields in Ohio. Soil Sci Soc Am J 76:1798–1809

Kundu S, Srinivasarao Ch, Mallick RB, Satyanarayana T, Naik RP, Johnston A, Venkateswarlu B (2013) Conservation agriculture in maize (*Zea mays L.*) horsegram (*Macrotyloma uniflorum L.*) system in rainfed Alfisols for C sequestration, climate change mitigation. J Agrometeorol 15:144–149

Kushwaha CP, Tripathi SK, Singh KP (2000) Variations in soil microbial biomass and N availability due to residue and tillage management in a dryland rice agroecosystem. Soil Tillage Res 56:153–166

Kuzyakov Y, Domanski G (2000) C input by plants into the soil. Rev J Plant Nutr Soil Sci 163:421–431

Lakaria BL, Sing M, Reddy KS, Biswas AK, Jha P, Caudhary AB (2012) Carbon addition, storage under integrated nutrient management in soybean-wheat cropping sequence in a Vertisol in central India. Natl Acad Sci Lett 35:131–137

Lal R (1981) Soil erosion problem on Alfisol in Western Nigeria, VI. Effect of erosion on experimental plots. Geoderma 25:215–230

Lal R (ed) (1994) Soil erosion research methods, Soil and water conservation society, 2nd edn. CRC, Ankeny, p 1A

Lal R (1997) Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO2 enrichment. Soil Tillage Res 43:81–107

Lal R (2004) Soil Carbon sequestration impacts on global climate change and food security. Science 34:1623–1627

Lal R (2004a) Soil carbon sequestration to mitigate climate change. Geoderma 123:1–22

Lal R (2004b) Carbon emission from farm operations. Environ Int 30:981–90

Lal R (2006) Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural soil. Land Degrad Dev 17:197–209. doi:10.1002/ldr.696

Lal R (2008) Carbon sequestration. Phil Trans R Soc. doi:10.1098/rstb.2007.2185

Lal R, Kimble JM (1997) Conservation tillage for carbon sequestration. Nutr Cycl Agroecosyst 49:243–253

Lal R, Kimble J, Follett R (1997) Land use and soil carbon pools in terrestrial ecosystems: In: Lal R, Kimble J, Follett R (eds) Management of carbon sequestration in soil: advances in soil science. CRC, Boca Raton

Lam SK, Chen D, Mosier AR, Roush R (2013) The potential for carbon sequestration in Australian agricultural soils is technically and economically limited. Sci Rep 3:2179. doi:10.1038/srep02179

Lavelle P, Blanchart E, Martin A, Martin S, Spain A, Toutain F, Barois I, Schaefer R (1993) A hierarchical model for decomposition in terrestrial ecosystems: application to soils of the humid tropics. Biotropica 25:130–150

Le Quere C, Peters GP, Andres RJ, Andrew RM, Boden T, Ciais P, Friedlingstein P, Houghton RA, Marland G, Moriarty R, Sitch S, Tans P, Arneth A, Arvanitis A, Bakker DCE, Bopp L, Canade JG, Chini LP, Doney SC, Harper A, Harris I, House JI, Jain AK, Jones SD, Kato E, Keeling RF, Goldewijk KK, Kortzinger A, Koven C, Lefevre N, Omar A, Ono T, Park GH, Pfeil B, Poulter B, Raupach MR, Regnier P, Rödenbeck C, Saito S, Schwinger J, Segschneider J, Stocker BD, Tilbrook B, Heuven VS, Viovy N, Wanninkhof R, Wiltshire A, Zaehle S, Yue C (2013) Global carbon budget. Earth Syst Sci Data Discuss 6(2):689–760. doi:10.5194/essdd-6-689-2013

Lichter K, Govaerts B, Six J, Sayre KD, Deckers J, Dendooven L (2008) Aggregation and C and N contents of soil organic matter fractions in the permanent raised-bed planting system in the Highlands of Central Mexico. Plant Soil 305:237–252

Limon-Ortega OA, Govaerts B, Deckers J, Sayre KD (2006) Soil aggregate microbial biomass in permanent bed wheat-maize planting system after 12 years. Field Crop Res 97(2–3):302–309

Liu D, Wang Z, Zhang B, Song K, Li X, Li J, Li F, Duan H (2006) Spatial distribution of soil organic carbon and analysis of related factors in croplands of the black soil region, Northeast China. Agric. Ecosyst Environ 113:73–81

Mandal UK, Singh G, Victor US, Sharma KL (2003) Green manuring: its effect on soil properties and crop growth under rice–wheat cropping system. Eur J Agron 19:225–237

Mandiringana OT, Mnkeni PNS, Mkile Z, Van AW, Van RE, Verplancke H (2005) Mineralogy, fertility status of selected soils of the Eastern Cape Province. S Afr Commun Soil Sci Plan Anal 36:2431–2446

Mann L K (1986) Changes in soil carbon storage after cultivation. Soil Sci 142:279–288

Milne E, Heimsath A (2008) Soil organic carbon. In: Cutler J, Level C (eds) Encyclopaedia of earth: environmental information coalition, national council for science, the environment. Washington D. C. www.eoearth.org/article/Soil_organic_carbon

Mina BL, Saha S, Kumar N, Srivastva AK, Gupta HS (2008) Changes in soil nutrient content and enzymatic activity under conventional and zero-tillage practices in an Indian sandy clay loam soil. Nutr Cycl Agroecosyst 82:273–281

Mishra U, Ussiri DAN, Lal R (2010) Tillage effects on soil organic carbon storage, dynamics in Corn Belt of Ohio USA. Soil Tillage Res 107:88–96

MNRE (Ministry of New and Renewable Energy Resources) (2009) Govt. of India, New Delhi. www.mnre.gov.in/biomassrsources

Molina JAE, Clapp CE, Linden DR, Allmaras RR, Layse MF, Dowdy RH, Cheng HH (2001) Modelling incorporation of corn (*Zea mays* L.) C from roots, rhizodiposition into soil organic matter. Soil Biol Biochem 33:83–92

Mrabet R, Bouzza A, El-Brahli A, Bouksirat H (1999) Long-term effects of tillage and crop rotation on wheat performances and soil quality in semiarid Morocco. In: Proceedings of the GCTE focus 3 conference 1999, food and forestry: global change and global challenges, University of Reading, UK, 20–23 Sept 1999

Mrabet R (2002) Stratification of soil aggregation, organic matter under conservation tillage systems in Africa. Soil Tillage Res 66:119–128

Murungu FS, Chiduza C, Muchaonyerwa P, Mnkeni PNS (2010a) Mulch effects on soil moisture, nitrogen, weed growth, irrigated maize productivity in a warm-temperate climate of South Africa. Soil Tillage Res 112(1):58–65

Musunda B (2010) Evaluation of cover crop species for biomass production, weed suppression, maize yields under irrigation in the Eastern Cape Province, South Africa. MSc thesis, University of Fort Hare, South Africa

Naitam R, Bhattacharyya T (2004) Quasi-equilibrium of organic carbon in shrink-swell soils of the sub-humid tropics in India under forest, horticulture, and agricultural systems. Aust J Soil Res 42:181–188

Nambiar KKM (1995) Agricultural sustainability: economics, environmental, statistical considerations. In: Barnett V et al (eds) Major cropping systems of India, Wiley, UK, pp 130–170

Nambiar KKM (1994) Soil fertility, crop productivity under long-term fertilizer use in India. ICAR, New Delhi

Naresh RK, Singh SP, Chauhan P (2012) Influence of conservation agriculture, permanent raised bed planting and residue management on soil quality and productivity in maize-wheat system in western Uttar Pradesh. Int J Life Sci Pharm Rev 1(4):27–34

NASS (2012) Management of crop residues in the context of conservation agriculture. National Academy of Agricultural Sciences, New Delhi; Policy paper no. 58, p 12

Nayak AK, Gangwar B, Shukla AK, Mazumdar SP, Kumar A, Raja R, Kumar A, Kumar V, Rai PK, Nayak UM (2012) Long-term effect of different integrated nutrient management on soil organic carbon, its fractions, sustainability of rice-wheat system in Indo-Gangetic plains of India. Field Crop Res 127:129–139

Nyamadzawo G, Nyamangara J, Nyamugafata P, Muzulu A (2009) Soil microbial biomass and mineralization of aggregate protected carbon in fallow-maize system under conventional and no-tillage in central Zimbabawe. Soil Tillage Res 102:151–157

Oades J M (1984) Soil organic matter, structural stability: mechanisms, implications for management. Plant Soil 76:319–337

Pal DK, Bhattacharyya T, Srivastava P, Chandran P, Ray SK (2009) Soils of the Indo-Gangetic Plains: their historical perspective and management. Curr Sci India 96:1193–1202

Parton WJ, Schimel DS, Cole CV (1987) Analysis of factors controlling soil organic matter levels in great-plains grasslands. Soil Sci Soc Am J 51:1173–1179

Pathak H, Bhatia A, Jain N, Aggarwal PK (2010) Greenhouse gas emission and mitigation in Indian agriculture—a review. In: Singh B (ed) ING bulletins on regional assessment of reactive nitrogen, vol 19. SCON-ING, New Delhi, p 34

Patle GT, Bandyopadhyay KK, Singh DK (2013) Impact of conservation agriculture and resource conservation technologies on carbon sequestration-a review. Indian J Agr Sci 83(1):3–13

Paustian K, Collins HP, Paul EA (1997) Management controls on soil C. In: Paul EA (ed) Soil organic matter in temperate ecosystems: long-term experiments in North America. CRC, Boca Raton pp 15–49

Paustian K, Six J, Elliott ET, Hunt HW (2000) Management options for reducing CO2 emissions from agricultural soils. Biogeochemistry 48(1):147–163

Petchawee S, Chaitep W (1995) Organic matter management in upland systems in Thailand. Australian Centre for International Agricultural Research, Canberra, pp 21–26

Pimentel D Wilson C, McCullum C, Huang R, Dwen P, Flack J, Tran Q, Saltman T, Cliff B (1997) Economic and environmental benefits of biodiversity. BioSci 47(11):747–757

Pimentel D, Burgess M (2013) Soil erosion threatens food production. Agriculture 3:443–463. doi:10.3390/agriculture3030443

Prasad R (2008) Integrated plant nutrient supply system (IPNS) for sustainable agriculture. Indian J Fert 4(12):71–90

Prasad R (2009) Efficient fertilizer use: the key to food security, better environment-review/synthesis. J Trop Agr 47(1–2):1–17

Purakayastha TJ, Smith JL, Huggins DR (2009) Microbial biomass and N cycling under native prairie, conservation reserve and no-tillage in Palouse soils. Geoderma 152(3–4):283–289

Qin RJ, Stamp P, Richner W (2004) Impact of tillage on root systems of winter wheat. Agr J 96:1523–1530

Rao DLN, Patra AK (2009) Soil microbial diversity and sustainable agriculture. J Indian Soc Soil Sci 57(4):513–530

Reddy MS, Willey RW (1985) Evaluations of alternate cropping systems for Alfisols of the Indian semi-arid tropics. Exp Agr 21:271–280

Robert M (1996b) Le sol: interface dansl' environnement, ressource pour le développement. Dunod/Masson, Paris p 240

Rosenzweig C, Tubiello FN (2007) Adaptation, mitigation strategies in agriculture: an analysis of potential synergies. Mitig Adapt Strat Glob Change 12:855–873

Sa J (2004) The evolution of a continuous zero-till system. Passo Fundo, Parana

Sa JCM, Lal R (2009) Stratification ratio of soil organic matter pools as an indicator of carbon sequestration in a tillage chronosequence on a Brazilian Oxisol. Soil Tillage Res 103:46–56

Sainju UM, Caesar-TonThat TC, Jabro JD (2009) Carbon and nitrogen fractions in dryland soil aggregates affected by long-term tillage and cropping sequence. Soil Sci Soc Am J 73:1488–1495

Sanyal SK, Majumadar K (2009) Nutrient dynamic in soil. J Indian Soc Soil Sci 57(4):477–493

Sapkota TB, Mazzoncini M, Barberi P, Antichi D, Silvestri N (2012) Fifteen years of no-till increase soil organic matter, microbial biomass and arthropod diversity in cover crop-based arable cropping systems. Agron Sustain Dev 32:853–863

Sarkar AK, Singh RP (2002) Importance of long-term fertilizer use for sustainable agriculture in Jharkhand. Fert. News 47(11):107–111

Sharma KL (2011) Conservation agriculture for soil carbon build up, mitigation of climate change. In: Srinivasarao Ch, Venkateswarlu B, Srinivas K, Kundu S, Singh A K (eds) Soil carbon sequestration for climate change mitigation, food security. Central Research Institute for Dryland Agriculture, Hyderabad (24 Nov to 3 Dec), p 322

Singh B, Singh Y, Singh M, Sodhi GPS, Ladha JK, Balasubramanian V (2006) Plant need based real time nitrogen management in rice grown by small farmers in Asia. In: 18th world congress of soil science, Philadelphia 9–15 July 2006

Sisti CPJ, Santos HP, Kohhann R, Alves BJR, Urquiaga S (2004) Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. Soil Tillage Res 76:39–58

Six J, Paustian K, Elliott ET, Combrink C (2000) Soil structure and soil organic matter: I. distribution of aggregate size classes and aggregate-associated carbon. Soil Sci Soc Am J 64:681–689

Six J, Bossuyt H, Degryze S, Denef K (2004) A history of research on the link between (micro) aggregates, soil biota, soil organic matter dynamics—a review. Soil Tillage Res 79:7–31

Smaling EMA (1993) The soil nutrient balance: an indicator of sustainable agriculture in sub-Saharan Africa. Int Fertil Soc Proc 340:18

Socolow RH, Pacala SW (2006) A plan to keep carbon in check. Sci Am 2006:52–57

Soler JM (2012) Soil organic carbon dynamics and carbon sequestration in a semiarid Mediterranean agro-ecosystem: effects of conservation tillage and nitrogen fertilization. Doctoral Thesis, Universitat de Lleida pp 1–159

Souvenir (2009) 4th world congress on conservation agriculture. National Academy of Agricultural Sciences, New Delhi, India, 4–7 Feb. http://www.fao.org/ag/ca/doc/wwcca-souvenir.pdf

Srinivasarao Ch, Prasad JVNS, Vittal KPR, Venkateswarlu B, Sharma KL (2003) Role of optimum nutrition in drought management. Fert News 48(12):105–112

Srinivasarao Ch, Vittal KPR, Chary GR, Gajbhiye PN, Venkateswarlu B (2006) Characterization of available major nutrients in dominant soils of rainfed crop production systems of India. Indian J Dryland Agric Res Dev 21(2):105–113

Srinivasarao Ch, Vittal KPR, Venkateswarlu B, Wani SP, Sahrawat KL, Marimuthu S, Kundu S (2009b) Carbon stocks in different soils under diverse rainfed production systems in tropical India. Commun Soil Sci Plant Anal 40(15):2338–2356

Srinivasarao Ch, Venkateswarlu B, Lal R, Singh AK, Kundu S, Vittal KPR, Patel JJ, Patel MM (2011a) Long-term manuring and fertilizer effects on depletion of soil organic carbon stocks under pearl millet-cluster bean-castor rotation in western India. Land Degrad Dev 25:173–183. doi:10.1002/ldr.1158

Srinivasarao Ch, Venkateswarlu B, Srinivas K, Kundu S, Singh AK (2011b) Soil Carbon sequestration for climate change mitigation and food security. In: Srinivasaro Ch, Venkateswarlu B, Srinivas K, Kundu S, Singh AK (eds) Soil carbon sequestration for climate change mitigation and food security. Central Research Institute for Dryland Agriculture, Hyderabad, p 372

Srinivasarao Ch, Venkateswarlu B, Lal R, Singh AK, Kundu S, Vittal KPR, Balaguruvaiah G, Shankar V, Babu M, Chary GR, Prasadbabu MBB, Reddy YT (2012a) Soil carbon sequestration, agronomic productivity of an Alfisol for a groundnut based system in a semi-arid environment in South India. Eur J Agron 43:40–48. http://dx.doi.org/10.1016/j.eja.2012.05.001

Srinivasarao Ch, Venkateswarlu B, Singh AK, Vittal KPR, Kundu S, Gajanan GN, Ramachandrappa BK (2012b) Yield sustainability and carbon sequestration potential of groundnut-fingermillet rotation in Alfisols under semi arid tropical India. Int J Agric Sus 10(3):1–15

Srinivasarao Ch, Venkateswarlu B, Singh AK, Vittal KPR, Kundu S, Gajanan GN, Ramachandrappa B, Chary GR (2012c) Critical carbon inputs to maintain soil organic carbon stocks under long-term finger millet (*Eleusine coracana L. Gaertn*) cropping on Alfisols in semi-arid tropical India. J Plant Nutr Soil Sci 175(5):681–688

Srinivasarao Ch, Deshpande AN, Venkateswarlu B, Lal R, Singh AK, Kundu S, Vittal KPR, Mishra PK, Prasad JVNS, Mandal UK, Sharma KL (2012d) Grain yield, carbon sequestration potential of post monsoon sorghum cultivation in vertisols in the semi-arid tropics of central India. Geoderma 175-176:90–97

Srinivasarao Ch, Venkateswarlu B, Lal R, Singh AK, Kundu S, Vittal KPR, Sharma SK, Sharma RA, Jain MP, Chary GR (2012e) Sustaining agronomic productivity, quality of a Vertisolic Soil (Vertisol) under soybean-safflower cropping system in semi-arid central India. Can J Soil Sci 92(5):771–785. http://dx.doi.org/10.4141/cjss2011-098

Srinivasarao Ch, Venkateswarlu B, Lal R, Singh AK, Vittal KPR, Kundu S, Singh SR, Singh SP (2012f) Long-term effects of soil fertility management on C sequestration in a rice-lentil cropping system of the Indo-Gangetic plains. Soil Sci Soc Am J 76(1):168–178

Srinivasarao Ch, Venkateswarlu B, Lal R, Singh AK, Kundu S (2013a) Sustainable management of soils of dryland ecosystems of India for enhancing agronomic productivity, sequestering carbon. In: Donald LS (ed) Advances in agronomy, vol. 121. Academic, Burlington, pp 253–329, ISBN:978-0-12-407685-3

Srinivasarao Ch, Lal R, Kundu S, Prasadbabu MBB, Venkateswarlu B, Singh AK (2013b) Soil carbon sequestration in rainfed production systems in the semiarid tropics of India. Sci Total Environ 487:587–603. http://dx.doi.org/10.1016/j. scitotenv.2013.10.006

Stevenson FJ, Cole MA (1999) Cycles of soil: carbon, nitrogen, phosphorus, sulphur, micronutrients. Wiley, New York

Stoorvogel JJ, Smaling EMA (1990a) Assessment of soil nutrient depletion in sub-Saharan Africa: 1983–2000. Win and Staring Centre, Wageningen, pp 1–4

Stoorvogel JJ, Smaling EMA (1990b) Research on soil fertility decline in tropical environments: integration of spatial scales. Nutr Cycl Agroecosyst 50:151–158

Swarup A (1998) Emerging soil fertility management issues for sustainable crop productivity in irrigated systems. In: Swarup A et al (eds) Long-term soil fertility management through integrated plant nutrient supply. Indian Institute of Soil Science, Bhopal, pp 54–68

Swarup A (2002) Lessons from long term fertilizer experiments in improving fertilizer use efficiency and crop yields. Fert News 47(12):59–73

The Hindu (2011) Himachal to earn carbon credits with more forests: sect. Environmental issues. The Hindu, 20 June 2011

The Hindu (2011). India may seek carbon credit from agriculture: sect. Other state. The Hindu, 9 April 2011

Tisdall JM, Oades JM (1982) Organic matter water-stable aggregates in soils. J Soil Sci 62:141–163

Triplett GB Jr, Dick WA (2008) No-tillage crop production: a revolution in agriculture! Agron J 100:153–165. doi:10.2134/agronj2007.0005c

United Nations, Department of Economic and Social Affairs, Population Division (2013) World population prospects: the 2012 revision, vol I: Comprehensive tables ST/ESA/SER.A/336. http://esa.un.org/unpd/wpp/Documentation/pdf/WPP2012_Volume-I_Comprehensive-Tables.pdf

Varvel GE, Wilhelm WW (2011) No-tillage increases soil profile carbon, nitrogen under long-term rainfed cropping systems. Soil Tillage Res 114:28–36

Velayutham M, Pal DK, Bhattacharyya T (2000) Organic carbon stock in soils of India. In: Lal R et al (eds) Global climate change, tropical ecosystems. Advances in soil science. Lewis, Boca Raton, pp 71–96

Venkateswarlu B, Srinivasarao Ch, Ramesh G, Venkateswarlu S, Katyal JC (2007) Effects of long-term legume cover crop incorporation on soil organic carbon, microbial biomass, nutrient build-up and grain yield of sorghum/sunflower under rainfed conditions. Soil Use Manage 23:100–107

Venkateswarlu B, Sharma KL, Prasad JVNS (2010) Conservation agriculture - constraints, issues and opportunities in rainfed areas.In: Joshi PK et al (eds) Conservation agriculture- innovations for improving efficiency, equity and environment. National Academy of Agricultural Sciences (NASS), Pusa, pp 119–128

Verhulst N, Govaerts B, Verachtert E, Castellanos-Navarrete A, Mezzalama M, Wall P, Deckers J, Sayre KD (2010) Conservation agriculture, improving soil quality for sustainable production systems? In: Lal R, Stewart BA (eds) Advances in soil science: food security and soil quality. CRC, Boca Raton, pp 137–208

Walkley A, Black IA (1934) An examination of the Degtjareff method for determining organic carbon in soils: effect of variations in digestion conditions and of inorganic soil constituents. Soil Sci 63:251–263

Ward PR, Flower KC, Cordingley N, Weeks C, Micin SF (2012) Soil water balance with cover crops and conservation agriculture in Mediterranean climate. Field Crop Res 132:33–39

Wendt JW, Hauser S (2013) An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. Eur J Soil Sci 64:58–65

West TO, Marland GA (2002) Synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agric Ecosys Environ 91:217–232

West TO, Post WM (2002) Soil organic carbon sequestration rates by tillage and crop rotaion: a global data analysis. Soil Sci Soc Am J 66:1930–1946

Woomer PL, Martin A, Albrecht A, Reseck DVS, Scharpenseel HW (1994) The importance and management of soil organic matter in the tropics. In: Woomer PL, Swift MJ (eds) The biological management of tropical soil fertility. Wiley, Chichester

Yadav RL, Dwivedi BS, Pandey PS (2000) Rice-wheat cropping system: assessment of sustainability under green manuring and chemical fertilizer inputs. Field Crop Res 65:15–30

Yang X, Drury CF, Wander MMA (2013) Wide view of no-tillage practices and soil organic carbon sequestration. Acta Agric Scand 63(6):523–530. doi:10.1080/090 64710.2013.816363

Chapter 20
Application of Microbiology in Conservation Agriculture

J. Habig, A. I. Hassen and A. Swart

Abstract An intricate relationship exists not only between plants and soil microorganisms but also between soil microbial populations within a microbial community. According to their root exudate composition, different plant species attract different soil microbial communities to their rhizosphere. In turn, root exudates are controlled by the plant, depending on its physiology, genetics, and environmental factors. Microbial communities that can utilize specific carbon sources most effectively and efficiently will be most prevalent in a particular rhizosphere. Soil microbes play crucial roles in the cycling of nutrients in an ecosystem. Through this process, they alter their surrounding environment, but, as a result, the surrounding soil environment also alters soil microbial community function and diversity. Soil is not only a matrix to support crop production, nor an unlimited resource that we can exploit to our short-term benefit without replenishing what we have taken. Since soil organic matter is responsible for the energy supply in an ecosystem, conservation agriculture is winning the race in an effort to enrich the soil by retaining crop residue, crop diversification, and minimum soil disturbance. Consequently, soil microbial activity and diversity increase, thereby restoring balance to the ecosystem, leading to increased and sustainable crop production.

Keywords Plant–microbe interactions · Rhizosphere · Conservation agriculture · Soil microbial diversity · Soil microbial activity · Soil health indicators

List of Abbreviations

AFM	Antifungal metabolites
BNF	Biological nitrogen fixation

J. Habig (✉)
Soil Microbiology Unit, Plant Protection Research Institute, Agricultural Research Council, Pretoria, Gauteng, South Africa
e-mail: habigj@arc.agric.za

A. I. Hassen
Biological Nitrogen Fixation Unit, Plant Protection Research Institute, Agricultural Research Council, Pretoria, Gauteng, South Africa

A. Swart
Nematology Unit, Plant Protection Research Institute, Agricultural Research Council, Pretoria, Gauteng, South Africa

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_20

Bt	*Bacillus thuringiensis*
CA	Conservation agriculture
CEC	Cation exchange capacity
CF	Chloroform fumigation
CFE	Chloroform fumigation extraction
CFI	Chloroform fumigation incubation
CLPP	Community-level physiological profiling
C:N ratios	Carbon to nitrogen ratio
C:N:P ratios	Carbon to nitrogen to phosphorous ratio
CO_2	Carbon dioxide
Cp values	Colonizer–persister values
DAPG	2, 4-diacetylphloroglucinol
DNA	Deoxyribonucleic acid
EI	Enrichment index
H'	Shannon–Wiener index
IAA	Indole-acetic acid
ISR	Induced systemic resistance
MDS	Minimum data set
MI	Maturity index
N	Nitrogen
N-fertilizers	Nitrogen fertilizers
N_2	Atmospheric nitrogen
NCR	Nematode channel ratio
PCA	Principal component analysis
PCR	Polymerase chain reaction
PGPB	Plant growth-promoting bacteria
PGPR	Plant growth-promoting rhizobacteria
PPI	Plant parasitic index
PLFA	Phospholipid fatty acids
RNA	Ribonucleic acid
rDNA	Ribosomal DNA
rRNA	Ribosomal RNA
SI	Structure index
SIP	Substrate-induced respiration
SOM	Soil organic matter
SQI	Soil quality index

20.1 Introduction

> Microbiology is the basis of sustainable agriculture. (Tikhonovich and Provorov 2011)

Microorganisms are too small to be observed with the naked eye. With diameters ranging from 1 to 100 μm (i.e., 1 μm = one thousandth of a millimeter), microorganisms can occupy the smallest of spaces inside and between soil particles and other environments. Although microbial activities, such as fast metabolism and growth rate, exponential population growth, and genetic flexibility, might occur at a microscopic level, their impact reaches macroscopic levels (Konopka 2009). In-depth investigations into the intricate relationship between microorganisms (e.g., biological nitrogen fixation (BNF), mycorrhiza, rhizobacterial suppression of diseases), plants, and animals of agricultural importance form the basis of agricultural microbiology. Knowledge obtained from microbial ecology and general microbiology could be transferred through agricultural microbiology to agricultural biotechnologies (Tikhonovich and Provorov 2011).

Konopka (2009) described the field of microbial ecology in ten overarching principles: (1) the primary role of microbes in the biosphere is as catalysts of biogeochemical cycles; (2) although generally unseen to the naked eye, microbes comprise nearly half of all biomass on earth; (3) the effects of microbial catalysis depend upon the population size of microbes and their physiological activity (as determined by extant physical and chemical conditions); (4) the results of microbial catalysis can have profound effects on the physical and chemical characteristics of the macroenvironment; (5) the microbial world exhibits much greater metabolic versatility than is found among macroorganisms; (6) the types and numbers of different microbes present in a habitat are a function of the diversity and number of nutrient resources available; (7) microbial populations and communities often exhibit much larger dynamics in biomass, composition, and activity than do plant and animal populations; (8) the amount of one essential limiting resource is most likely to determine the amount of microbial biomass in an ecosystem; (9) growth of microbes on the limiting nutrient will depress its concentration to a value that limits microbial growth rate; and (10) competition among microbes for low concentrations of limiting substrate and temporal variability in nutrient availability is a strong selective force in natural habitats.

20.1.1 Soil Environment

Soil is a sensitive, living and irreplaceable natural resource linked to everything around us. With increasing demand to grow more food on a resource that only produces 10 cm of fertile soil in 2000 years, it is clear that the responsibility lies with us to look after our soils. Historically, soil was mainly considered as a medium to support crop growth, but it is now realized that they also play vital roles in ecosystem functioning, water and nutrient cycling, and food production (Wagenet and Hutson 1997; Wander et al. 2002). Microorganisms are found in extremely high numbers in soil habitats with bacteria reaching numbers of 10^6–10^9 per gram of soil. Other soil microorganisms include viruses, fungi, nematodes, algae, and protozoa. Indigenous soil microbiotas depend strongly on microhabitats, microenvironments, and abiotic factors found in soil, with unique soils favoring bacterial communities with specific types of metabolisms and adaptive features for optimal survival and nutrient cycling in that specific ecosystem.

Topsoil depth is probably one of the most important soil physical attributes in soil management, biomass production, and control of degradation. It provides a measure of nutrient and water availability, as well as root development for crop production. Soil texture and compaction are characterized by soil porosity and pore size, which determine plant root penetration and the distribution and storage of nutrients, water, and gases, thus affecting site productivity. Soil aggregation measurement serves as an indicator of soil structure, crop emergence, resistance to soil destruction, and infiltration. It measures, therefore, the soil's inclination to erosion, i.e., water runoff and leaching. The soil's potential to retain water, termed water-holding capacity, determines the potential for water transport through the soil. Bulk density (the weight of soil per volume unit) provides a measure of soil structure and penetration resistance (soil strength), which determines the environment for plant root growth and the level of biological activity.

Biological activity of soil microorganisms responsible for decomposition of soil organic matter (SOM) is "any material produced originally by living organisms (plant or animal) that is turned to the soil and goes through the decomposition process" (Bot and Benites 2005). Decomposition is also greatly affected by chemical factors such as cation exchange capacity (CEC), the presence and amount of contaminants, and the level of acidity or alkalinity of the soil. SOM and pH have been recognized as vital attributes in characterizing the quality of soil. Soil pH influences the strength of bond that different soil textures form with nutrients and water, determining its availability for plant growth and biological activity. Soil functions such as nutrient cycling, water retention, aggregation, and soil structural stability are greatly influenced by organic matter (OM) content. Living organisms, readily decomposable materials, and stable humus make up the three components of SOM. Living organisms are responsible for the decomposition of SOM into nutrients available to be taken up by the plant. Remaining residues are further broken down until complex products, resistant to decomposition, remain. These products are known as humus and play an important role in aggregate stability, which, in turn, influences CEC, and the soil's nutrient and water-holding capacity. Although the effective decomposition of SOM strongly relates to soil biological activity, it is limited by restricted access to water, gases, and nutrients. Balesdent et al. (2000) have shown the SOM concentration to be highest in the surface layer of untilled soils, with surface OM additions increasing SOM-level inconsistency in soil profiles. Since falling leaves contribute significantly to SOM inputs, seasonal changes have less noticeable effects on decomposition in soils subjected to conventional tillage (CT) compared to no-till (Balesdent et al. 2000). Nutrient availability, serving as an indication of nutrient limitation, impacts not only the soil's capacity to support plant growth but also soil microbial activity and diversity.

20.1.2 Biological Component

Although the status of soils has always been measured in terms of soil physical and chemical properties over the past decades, researchers are continuously realizing the increasing significance of extending the definition of healthy soil, to include soil microbial populations. The composition and activity of soil microbial populations is responsible for all the major processes in the soil, such as breakdown of contaminants and nutrient recycling, which contributes to soil fertility and quality (Anderson 2003). Specific microbial functions such as respiration, degradation, or mineralization of organic carbon, nitrogen, phosphorous, and sulfur have been studied as biological indicators of healthy soils (Bastida et al. 2008; Dick 2000). Since elements are required to be in different chemical forms to fulfill various functions in the soil ecosystem, all elements need to be continuously cycled through the ecosystem by means of numerous natural biological cycling processes. Microorganisms are crucial in the cycling of nutrients through chemical or biochemical reactions in order to unlock essential elements that are taken up by other organisms and locked in an unusable form by others (Heritage et al. 1999).

In an agricultural production system where mineral fertilizers can provide most nutrient inputs, the effects of decomposition and mineralization almost seem irrelevant, but knowledge about the dynamics between soil microbial communities and the ecosystem might become more significant as conservation agriculture (CA) develops into a system that is less dependent on mineral fertilizers, biocides, and fossil fuels (Philippot et al. 2013).

20.1.3 Carbon Cycle

Plants and certain microorganisms are primary producers that convert carbon dioxide (CO_2), water, and solar energy into organic compounds through photosynthesis. These organic compounds are available as nutrients to different organisms with the ability to break down through various metabolic processes. While certain microbes, chemoorganotrophs, can convert organic carbon compounds to release CO_2, others, chemolithotrophs, convert inorganic carbon into OM in the dark. Under anaerobic conditions with limited or no oxygen, certain bacteria can convert organic compounds to methane and CO_2 through fermentation (Heritage et al. 1999).

20.1.4 Nitrogen Cycle

Nitrogen is found mainly in nucleic acids (deoxyribonucleic acid (DNA) and ribonucleic acid (RNA)), proteins, amines (functional groups of amino acids), and amino acids (the building blocks of proteins). DNA is the basis of genetic inheritance and RNA is responsible for protein synthesis from DNA, whereas amines and amino acids are released from proteins during decomposition by fungi in low pH environments, and bacteria in neutral and higher pH environments. In agriculture and natural ecosystems, BNF through nitrogen-fixing bacteria, which includes symbiotic rhizobia and free-living diazotrophic bacteria, plays a crucial role in fixing nitrogen into a readily available form, such as ammonia, for crop plants. Inorganic nitrogen, such as nitrates, are converted to nitrites by certain bacteria, and then again to ammonia by nitrate-reducing bacteria. Ammonia is predominantly fixed as amino acids into OM, and must be released for continued cycling of nitrogen. Nitrifying bacteria can produce nitrite ions from ammonia oxidation, and to further convert nitrites to nitrates. Compost heaps and soils rich in organic material generally contain bacteria that can reduce available nitrates to nitrogen gas which is returned to the atmosphere and then fixed mainly by rhizobia which form a symbiotic association with roots of leguminous plants (Heritage et al. 1999). High amounts of phosphorous, sulfur, molybdenum, and boron are required by legumes to facilitate the formation of root nodules in order to fix nitrogen; insufficient amounts will lead to the suppression of nitrogen fixation. Fixed nitrogen is released to the soil environment through decomposition of aboveground parts, roots, and legume nodules (West and Mallarino 1996).

20.1.5 Phosphorous Cycle

Phosphorous is found in SOM, minerals, and rocks, and is also required by legumes for effective nitrogen fixation. Phosphorous is taken up by plants as inorganic phosphates at all times, and transformed into more complex forms through biochemical processes as components of nucleic acids (i.e., DNA and RNA), lipids (i.e., phospholipids—playing a crucial role in cell membranes), energy storage compounds, and organic phosphates. Since inorganic phosphates are normally present as insoluble salts, phosphates regularly represent a limiting element in natural ecosystems and crop production, but could be converted into soluble phosphates through soil microbial activity. Since phosphorous is a component of decomposing material, the highest concentration is obtained in surface soils. Acidic soils usually contain high concentrations of iron and aluminum that tends to form tight bonds with phosphorous, but the application of lime could solve this dilemma.

20.1.6 Sulfur Cycle

Sulfur is predominantly found in natural igneous rocks, as well as a component of SOM. As with nitrogen, it forms an important but lesser component of certain amino acids, proteins, and vitamins. Elemental sulfur is oxidized to sulfates by a variety of soil microorganisms. Sulfates are then integrated into organic compounds by reduction to hydrogen sulfide. Nicklin et al. (1999) differentiated two types of sulfate reduction: assimilatory reduction with sulfate reduction for amino acid and protein synthesis and dissimilatory reduction for the conversion to sulfides.

Where fertile soils are depleted and rendered useless through inadequate agricultural practices, urbanization, and other negative anthropogenic activities in only a few years, soil microorganisms replace whatever they take from the soil.

20.2 Microbe–Plant Interaction

20.2.1 Rhizosphere

The rhizosphere is described as the very thin zone of soil surrounding living roots, characterized by the most microbially diverse and active region, stimulated by leakage of organic substances from plant roots (Grayston et al. 1997). It includes the region of soil bound by plant roots which extends a few millimeters from the root surface (Bhattacharyya and Jha 2012). Compared to bulk soil, the rhizosphere zone is rich in nutrients due to the accumulation of several plant root exudates, such as amino acids and sugars, and a rich source of energy and nutrients for bacteria (Beneduzi et al. 2012). As a result, the number of soil microorganisms, especially bacteria, around plant roots in the rhizosphere is generally 10–100 times that of bulk soil (Weller and Thomashow 1994). Rhizosphere organisms could have extreme consequences on nutrition, health, and growth of plants (Berendsen et al. 2012). Increased microbial diversity and activity compel microorganisms to compete, collaborate, or parasitize for food. Changes in activity and diversity greatly depend on the vegetation type and species present (Tate 2000). Recent studies have shown that plants, either individually or as a community, can manipulate the composition of belowground microbial communities (Schweitzer et al. 2008) through rhizodeposits, i.e., exudates, nutrients, mucilage, etc. released by the plant root into the rhizosphere. Root exudate compounds may encourage beneficial symbiosis, inhibition of competing plant species, and adjust soil microbial community activity and diversity. Root exudate composition is greatly influenced by planted crops, as well as the maturity stage of seedlings, based on different nutritional requirements through different growth stages. This leads to successional changes in soil microbial communities as the plant matures (Atlas and Bartha 1993). Successional changes coincide with alteration of root exudate composition during plant development. The difference in root exudate composition between crops, and even cultivars, thus attracts microbial populations that are especially well adapted to utilize the specific compounds (Johansson et al. 2004). This implies that microorganisms are not distributed evenly through the rhizosphere due to root type differences and root growth. It is therefore understandable that direct and indirect interactions between plants and their associated soil microbial communities are inevitable.

20.2.2 Symbiotic Interactions

Mycorrhiza (Greek: *mycos* = "fungi," *rhiza* = "root") are probably one of the most well-known mutualistic interrelationships in ecosystems that exists between the roots of more than 80 % of higher plants and ferns, in association with soilborne fungi. This association involves the formation of integrated morphological units, maintaining a healthy physiological interaction through the integration of fungal mycelia and plant roots (Atlas and Bartha 1993). Two basic mycorrhizal associations exist: endomycorrhizae, invading living root cells with mycelial clusters, and ectomycorrhizae, where fungal hyphae invade intercellular spaces in the root, but do not invade living cells (Hartley 1965). Due to this association, plant root surface is enhanced, leading to increased uptake of water and nutrients (especially phosphorous and nitrogen) from nutrient-deficient soil, resistance to plant pathogens, and increased tolerance to toxins and environmental parameters. In return, mycorrhizal fungi evade competition with other soil microorganisms for food, by receiving organic compounds from the host plant. Another example of a mutualistic microbe–plant interaction is BNF (see *Nitrogen Cycle* and *Biological Nitrogen Fixation*).

However, not all plant–microbe interactions are mutualistic. Some interactions can be negative, causing plant diseases that are of economic or ecological importance. Plant diseases can be caused by nematodes, fungi, bacteria, or viruses that are responsible for growth impairment or plant death, diminishing the plant's ability to survive and occupy its ecological place and function. Plant diseases usually follow a four-phase development pattern: (1) initial contact by pathogen with plant; (2) finding an entry point and entering plant through wounds (e.g., those made by nematodes) or natural openings in roots, leaves, or stems; (3) growth of pathogen inside plant; and (4) development of disease symptoms (Atlas and Bartha 1993).

Multispecies interactions in the rhizosphere could be beneficial to the plant by suppressing soilborne pathogens, thus giving rise to disease-suppressive soils (Haas and Defago 2005). Pathogens in these soils are suppressed by groups of soil and rhizosphere microorganisms through competition, parasitism, and the production of chemical compounds with antimicrobial properties. This association between different species, where one is negatively influenced while the other is not affected, is called amensalism. Soil microbial populations can also influence plant community diversity by reducing the competitiveness of dominant plant species and/or enhancing the competitiveness of subordinate plant species (Wardle et al. 2004). Other microbial populations can induce systemic resistance response, rendering the plant effective against pathogens and insect pests.

Since soil microbial species rarely exist in isolation, interactions between species within soil microbial populations could be either positive or negative. Positive interactions, such as cooperation, occur mainly at low population densities in order to maximize growth rate and species diversification when utilizing insoluble substrates. In these cases, specific enzymes are produced by specific species within the population to make these substrates available to the rest of the population. Cooperation within a population could also increase the protection of the population in a hostile environment, as well as the exchange of genetic material to increase resistance to toxic substances threatening the population. Alternatively, negative interactions, such as competition for the same substrates and ecological niches, occur at high soil microbial population densities as a control measure. Other species within the population might produce toxic compounds or proteins to inhibit growth of other species (Atlas and Bartha 1993).

Interpopulation interactions could be recognized as a lack of interaction between two microbial populations (neutralism), positive (mutualism, synergism, and commensalism), negative (amensalism and competition), or positive for one population

Table 20.1 Categories of interactions between soil microbial populations. (Atlas and Bartha 1993)

Interaction category	Result of interaction	
	Population 1	Population 2
Neutralism	ne	ne
Commensalism	ne	+
Synergism	.	+
Mutualism	+	+
Amensalism	ne/+	−
Predation	+	−
Parasitism	+	−
Competition	−	−

ne no effect

but detrimental to another (predation and parasitism). One or more of these interactions might be observed in complex soil microbial communities (Table 20.1). Positive interactions might occur to enhance the survival abilities of some communities, while negative interactions might occur as a means to limit population densities.

Detailed studies of these natural interactions have led to wide agricultural applications, especially with regard to biocontrol. *Bacillus thuringiensis* (Bt) is probably the best-known example of a bacterium used as an "insecticide" or biopesticide. Bt, a spore-forming bacterium that naturally occurs in soil, produces crystal proteins with insecticidal properties during its sporulation phase. These proteins are only effective once ingested by leaf-chewing insects feeding on crops that have been sprayed with, or genetically modified to contain, the Bt protein (Lei et al. 2011). Bacteria are not the only organisms to be used in this manner. The hyphae of pathogenic fungi are used as biopesticides to penetrate the cuticle of insects, eventually causing death by growing vegetatively inside the insect's body (de Faria and Wraight 2007).

Total annihilation of crop pests and plant pathogens through pesticides or resistance-induced mechanisms not only enforces selection pressure in resistance in pathogen populations but the plant is also left defenseless in the case of pesticide resistance (Newton et al. 2010). Studying and understanding the intrinsic ecological balances that exists in a system—even between pathogens and beneficial microorganisms—will lead to novel approaches in agriculture to improve sustainability and increase crop production (Andrews et al. 2012). In this way, increased crop production and sustainable agriculture have also benefitted from comprehensive studies of positive microbe–plant interactions.

20.2.3 Plant Growth-Promoting Rhizobacteria (PGPR)

The application of chemical inputs, which includes fertilizers, pesticides, and herbicides, has long been practiced worldwide in modern intensive agriculture. However, due to concerns for human health and environmental protection, viable and cost-effective alternatives to these chemicals have been sought in recent years (Franks et al. 2006). For instance, it has been recognized and studied that several naturally occurring rhizosphere bacteria and fungi are antagonistic towards a variety of crop pathogens and may be used as effective substitutes for chemical control agents (Morrissey et al. 2004). Similarly, there are several beneficial microorganisms residing in the rhizosphere that can directly facilitate plant growth and increase crop yield (Masciarelli et al. 2013).

In the mid-1970s, prior to the introduction of the term rhizobacteria by Kloepper and Schroth (1978) based on their experiment on radishes, the late Döberiener and her collaborators rediscovered the genus *Azospirillum* and described it as plant growth-promoting bacteria (PGPB; Döbereiner and Day 1976). Two main characteristics which defined the genus *Azospirillum* as a PGPB were the fixing of atmospheric nitrogen and the production of phytohormones (Bashan and de-Bashan 2010). Three years after the term rhizobacteria was introduced, the same scientists coined the term PGPR (Kloepper and Schroth 1981) to describe soil bacteria that colonize the rhizosphere of plants and stimulate plant growth using various mechanisms (Perez-Montano et al. 2014). Currently, the term PGPR refers to bacterial strains capable of fulfilling at least two of the three criteria, viz. aggressive root colonization, plant growth stimulation, and biocontrol (Weller et al. 2002; Vessey 2003).

Mode of Action of PGPR PGPR was originally used to describe unique rhizosphere bacteria with biocontrol activities, which may not encompass all of the beneficial bacteria in the rhizosphere. Hence, based on their role in the rhizosphere, PGPR generally fall into two major groups: biocontrol PGPR and plantgrowth-promoting PGPR (Bashan and Holguin 1998). The group that promotes plant growth includes both free-living bacteria (e.g., *Azospirillum, Pseudomonas, Bacillus* spp.) and those that form specific symbiotic associations with leguminous plants (e.g., *Rhizobia*; Glick 2012). The remaining biocontrol–PGPR group constitute all rhizosphere bacteria that colonize plant roots and suppress or decrease plant diseases and are commonly antagonistic to soilborne phytopathogens (Jetiyanun and Kloepper 2002; Bashan and de-Bashan 2002). The most widely studied biocontrol PGPR with proven antagonistic activity against phytopathogens include members of the bacterial genera, including *Bacillus*, *Pseudomonas*, *Serratia*, and *Streptomyces* (Perez-Montano et al. 2014).

Most of the free-living plant growth-promoting PGPR have direct mechanisms by which they improve plant growth and crop yield, including fixing atmospheric nitrogen and supplying it to plants, synthesizing siderophores which sequester iron from the soil and providing it to plants, synthesizing phytohormones such as indole-acetic acid (IAA) which enhances or regulates various stages of plant growth, and solubilizing essential minerals such as phosphorous and making it more readily available to plants (Glick et al. 2007; Bhattacharyya and Jha 2012; Bashan and de-Bashan 2010). Although not as effective as the symbiotic BNF by rhizobia, many nonlegume plants benefit from nonsymbiotic nitrogen fixation by being associated with free-living diazotrophic nitrogen-fixing bacteria. PGPR commonly known for asymbiotic nitrogen fixation include *Azospirillum*, *Herbasprillum*, and *Beijerinkia*.

The ability to produce IAA is a key property of many PGPR that stimulate plants directly. *Azospirillum* spp. are well-recognized producers of IAA, which alters the metabolism and morphology of plants, resulting in better absorption of water and minerals, and consequently larger and healthier plants (Bashan and de-Bashan 2010). Some strains of *Pseudomonas putida* and several species of *Bacillus* which produce IAA have been identified and studied for their role in the development of plant roots (Patten and Glick 2002; Goswami et al. 2014). In general, bacterial IAA increases root surface area and length, providing the plant with greater access to soil nutrients (Glick 2012). Bacterial strains belonging to the genera *Azospirillum*, *Bacillus*, *Pseudomonas*, *Burkholderia*, and *Serratia* have efficient phosphate solubilization abilities (Perez-Montano et al. 2014). PGPR solubilize phosphate and make it available to plants by reducing the pH of their surroundings due to the release of organic acids or protons (Gyanshewar et al. 2002).

Biocontrol PGPR on the other hand has a variety of indirect modes of action to suppress plant diseases and enhance growth (Fig. 20.1). The most common indirect mechanisms include the production of antibiotics such as 2, 4-diacetylphloroglucinol (DAPG), phenazine, and pyoluterin; secretion of lytic enzymes like chitinases and protease; competition for nutrients; siderophore secretion; and induction of systemic resistance in host plants (Pliego et al. 2010; Beneduzi et al. 2012). A major PGPR trait which prevents the proliferation of phytopathogenic fungi is the production of a wide range of different antibiotics, many of which have been studied in detail (Whipps 2001; Raajmakers et al. 2002; Compant et al. 2005). The most widely studied antifungal metabolites (AFM) include the antibiotics DAPG and pyoluterin, both of which are secreted by strains of *Pseudomonas fluorescens* (Kidarsa et al. 2011). A typical example for biocontrol by PGPR is the suppression of fusarium wilt by *P. fluorescens* strain WCS374 that resulted in a 40 % yield increase in radish (Bakker et al. 2007).

Siderophores, low molecular weight proteins secreted by several strains of biocontrol PGPR, have a high affinity to iron and can prevent some phytopathogens from proliferating. The bacterial siderophores allow control of several phytopathogens through deprivation of iron nutrition (Perez-Montano et al. 2014). Among the many studied siderophores, those produced by *P. fluorescens* have a high affinity to ferric ion, rendering it unavailable to other organisms and suppressing soilborne fungal pathogens (Beneduzi et al. 2012). Production of antibiotics and secretion of siderophores are not the only mechanisms of action for disease suppression by biocontrol PGPR. Rhizobacteria-mediating induced systemic resistance (ISR) has been detected against several fungal pathogens. *Pseudomonas* and *Bacillus* spp. are the most widely studied PGPR that trigger ISR in plants (Kloepper et al. 2004).

20.2.4 Biological Nitrogen Fixation

Nitrogen (N) is often one of the most limiting nutrients for plant growth, resulting in N-fertilizers ranking first among external inputs to maximize output in agriculture. Chemical nitrogen fertilizers, however, are not only unaffordable or unavailable

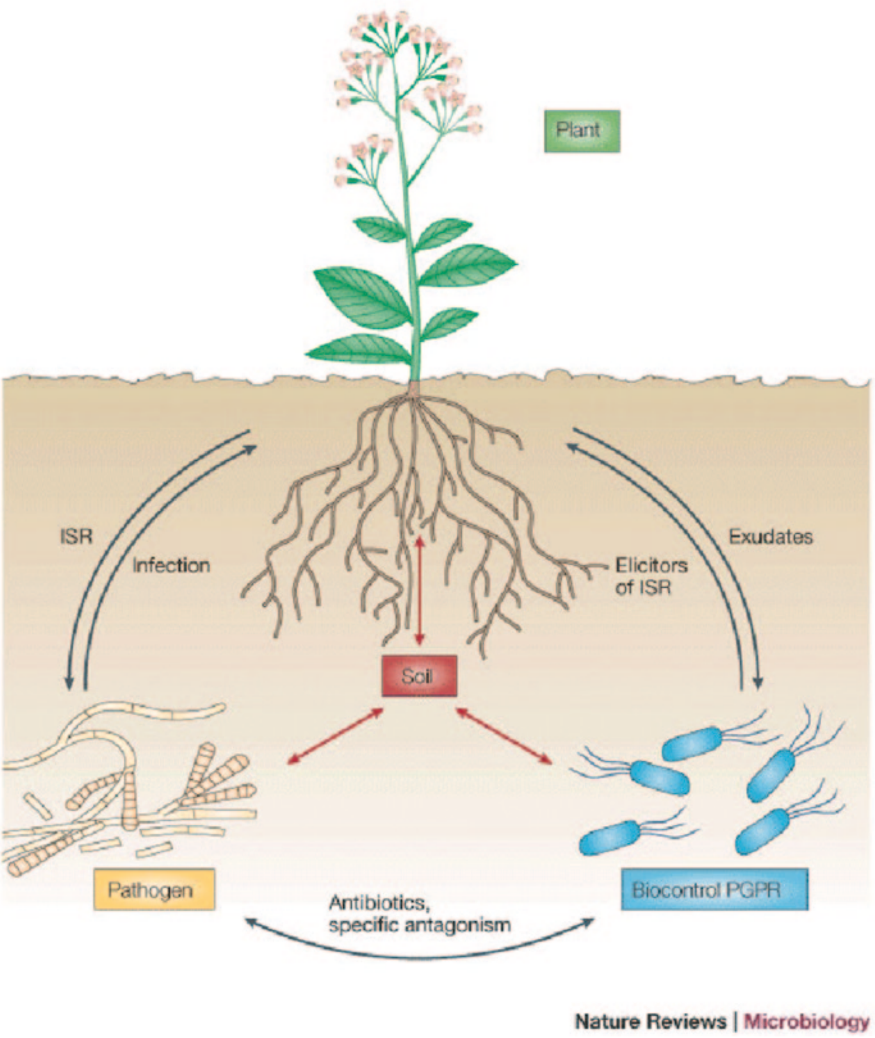


Fig. 20.1 Interaction between plant roots and biocontrol PGPR in the rhizosphere. The plant roots secrete root exudates which are used by the rhizobacteria for metabolic processes. The root-colonizing rhizobacteria, in return, produce antibiotics and elicitors of induced systemic resistance (*ISR*), thereby suppressing infection by plant pathogens. *PGPR* plant growth-promoting rhizobacteria. (Picture adapted from Haas and Defago 2005)

in many countries but also have other drawbacks. They have the lowest input efficiency among plant nutrients, and the continuous use of N-fertilizers leads to a decline in crop yield (Bohlool et al. 1992). Additional drawbacks of N-fertilizers include environmental pollution and speeding up the depletion of nonrenewable energy resources. BNF, on the other hand, converts atmospheric nitrogen (N_2) into a plant-usable form through nitrogenase activity in the rhizosphere and root nodule bacteria, i.e., rhizobia.

Rhizobia are the most widely studied PGPR. The term rhizobia is derived from the Greek words *riza* = roots, *bios* = life. More importantly, the sustainability of many food crops, forage, and green manure legumes mainly depends on their ability to establish a symbiotic association with nitrogen-fixing rhizobia (Menna et al. 2006). A peculiar characteristic that distinguishes rhizobia from other nitrogen-fixing bacteria is their unique ability to elicit the development of a specialized nodule to form a symbiotic association with their legume host (Lindstrom et al. 2006). The process of BNF is initiated when rhizobia, growing in the rhizosphere of the legume host, recognize compounds such as flavonoids secreted by the roots. These flavonoids then activate the expression of rhizobial *nod* genes which produce the nodulation (Nod) factors (certain lipochitin oligosaccharides). Nod factors are perceived by a receptor in the legume host and initiate a sequence of events. Root hairs start curling around the invading rhizobia, the rhizobia enter into the plant through infection threads, which leads to the induction of cell division in the root cortex, marking the formation of the actual nodule (Eckardt 2006). This association converts N_2 to a renewable source of N for agriculture with estimated values falling in the range of 200–300 kg of N ha^{-1} $year^{-1}$ (Zahran 1999). In contrast to inputs of inorganic N-fertilizers, N input through the process of BNF not only maintains the soil's N reserve but can also serve as the best substitute for N-fertilizer to increase crop yields more efficiently (Peoples and Craswell 1992).

20.2.5 Terrestrial Nematodes

Most nematodes (Phylum: Nematoda) are wormlike or vermiform, microscopic in size, inhabiting almost every niche available from polar regions to deserts and deep ocean sediments to hot sulfuric volcanic springs. They use a wide range of resources, and according to Mulder et al. (2005), nematodes are the most important secondary consumers of the mesofauna (i.e., intermediate-sized soil animals between 0.1 and 2.0 mm long) in the soil food web. Table 20.2 shows a breakdown of known nematode species by lifestyle (Hugot et al. 2001).

For the agriculturalist, terrestrial (soil-inhabiting) nematodes are of particular interest. They are small, generally between 0.3 and 5.0 mm long and can be abundant (in millions), but also diverse (commonly more than 30 groups of related nematodes) in all soils (Yeates 1979). As nematodes feed on a wide variety of soil organisms and depend on the continuity of soil water films for movement, their activities

Table 20.2 A breakdown of nematode species (worldwide) by lifestyle reveals the following distribution of species. (Hugot et al. 2001)

Lifestyle	Number of species
Free-living (marine, freshwater, terrestrial)	10,681
Plant parasites (herbivores)	4,105
Invertebrate parasites	3,501
Vertebrate parasites	8,359
Total	26,646

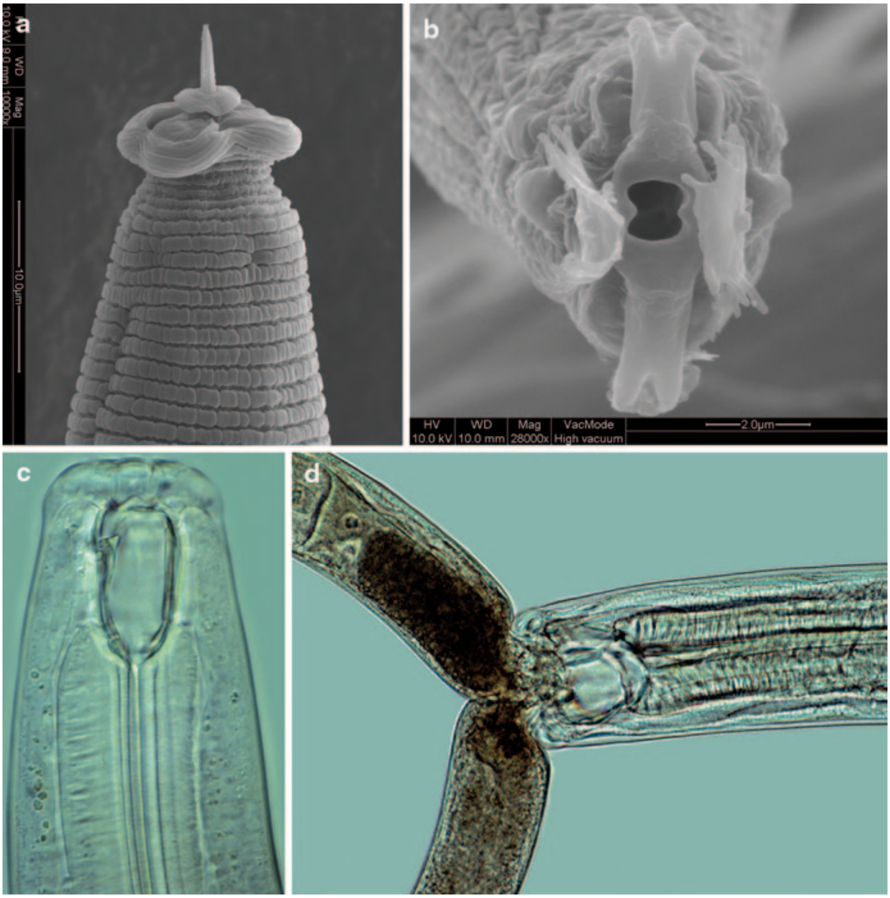


Fig. 20.2 **a** *Dolichodorus* spp. is a plant parasitic nematode. Note stomatostylet projecting from mouth opening for penetration of plant roots. (Photo: Tiedt L, Laboratory for Microscopy, North-West University, South Africa) **b** Photo of *en face* view of *Diploscaper* spp., a typical bacterivore in soil, showing the stomatal opening and lips transformed to probolae and hooks. (Photo: Tiedt L, Laboratory for Microscopy, North-West University, South Africa) **c** Light micrograph of the anterior end of a mononchoid nematode, showing the huge tooth in the stoma (NemaPix 2002). (Photo: Eisenback JD) **d** Light micrograph of a mononchid nematode feeding on another nematode (NemaPix 2000). (Photo: Eisenback JD)

are largely controlled by the biological and physical conditions of the soil. Although the body form of soil nematodes is basically the same in all stages, their greatest apparent morphological diversity can be seen in the head and mouth structures, which are closely related to their feeding habits (Fig. 20.2a, b). Most nematodes (herbivores, plant parasitic nematodes, or plant nematodes) use the energy fixed by plants through photosynthesis to feed directly on the primary producers (e.g., higher plants) and on unicellular algae. Other nematodes feed on microorganisms associated with decomposing cadavers, feces, and plant matter, such as bacterivores (feeding on microbes) and fungivores (feeding on fungal hyphae). Higher trophic levels feed as predators (Fig. 20.2c, d) on other nematodes and microinvertebrates, or as parasites of invertebrate and vertebrate animals that depend on plants themselves. Nematodes feeding on more than one trophic level are called omnivores. There is also growing awareness of nematodes found in anoxic environments that use the energy bound in chemicals as their resource, either directly or through symbiotic bacteria (Polz et al. 2000). Recently, Borgonie et al. (2011) discovered the 0.5-mm-long *Halicephalobus mephisto* 1.3 km below the surface at 37 °C in tunnel walls of the Beatrix Gold Mine, approximately 240 km southwest of Johannesburg, South Africa. The authors also recovered DNA from a second unknown monhysterid species in the TauTona Mine, 3.6 km below the surface, where temperatures remain around 48 °C.

The response of nematodes to stimuli is essential for their success in locating food resources, hosts, and mates. Thermotaxis, phototaxis, and geotropism (movement in response to temperature, light, and gravity) are important for host location of many taxa. Chemotaxis (movement in response to chemical stimulus) is also commonly involved in food selection and food finding by nematodes. Responses to different kinds of chemicals and/or bacterial food tend to be highly species specific and contribute to the small-scale patchiness of nematode populations (Moens et al. 1999). For example, CO_2 attracts many plant parasitic species, and ethylene (a gaseous plant hormone) attracts the very important plant parasitic *Heterodera* juveniles (McCallum and Dusenbery 1992; Wubben et al. 2001).

Given this range of feeding types, soil nematode fauna interacts with many other groups of soil organisms. According to Yeates et al. (2009), C:N:P ratios between nematodes and their food inevitably lead to their excreting minerals. In soil food webs, nematodes are involved in the transformation of OM into mineral and organic nutrients, which can be taken up by plants, as well as influencing plant growth and crop productivity (Ingham et al. 1985; Ferris et al. 2004). As such, nematode feeding activity contributes to soil food web stability. Entomophagous nematodes (consuming insects as food) may also influence pest damage to plants by regulating insect abundance (Viglierchio 1991). In natural ecosystems, terrestrial nematodes contribute to spatial and temporal diversity in plant communities and, therefore, to the diversity of any plant-associated communities both above- and belowground. Since nematodes are so abundant and omnipresent in ecosystems, they serve as elegant indicators of environmental disturbance (Bongers 1990; Heininger et al. 2007).

According to Yeates et al. (2009), nematodes feeding on their food sources, besides providing the required energy and nutrient resources, have the potential to regulate or even suppress the magnitude of those resources and consequently impact on ecosystem structure and function in the following ways:

1. *Plant-feeding nematodes (herbivores)* may affect the plant community in natural systems by reducing or even eliminating susceptible and less fit plants from the community. In agricultural systems, aggressive strains of plant-feeding nematodes have often been introduced with their susceptible hosts. A seeding rate designed for maximum production in the absence of nematodes will therefore

provide a less vigorous stand of the desired crop in the presence of these nematodes. This opens up the canopy and reduces competitiveness with weeds which then may outcompete the crop so that the resultant yield loss can be enormously magnified (Schroeder et al. 2005).

2. *Suppression of mycelial growth by fungivorous nematodes*: Nematodes grazing on fungal mycelia play a role in complex interactions in soil. In laboratory studies, the fungus-feeding nematodes, *Aphelenchoides* spp., constrained the efficacy of the biocontrol agent *Trichoderma harzianum* (Bae and Knudsen 2001). Other studies have suggested that nematodes feeding on mycorrhizal fungi could reduce exploration of the soil body by their mycelia. Current work suggests that the relative abundance of fungivorous and bacterivorous nematodes is sensitive to management changes and may be a good indicator of underlying changes in the composition of the nematode fauna. For instance, the ratio of fungi to bacteria rises at lower pH, owing to the greater tolerance of fungi to acidity. A fungal-dominated decomposition pathway and fungal-feeding nematodes as predominant secondary decomposers are therefore expected in the more acidic forest systems where cellulose- and lignin-rich litter material is the main source of nutrient input to the soil food web (Hohberg 2003). In recent studies in tropical north Queensland (Australia), soil biological activity was manipulated to reduce the impact of economically important plant parasitic nematodes (Stirling et al. 2005; Stirling and Eden 2008), but in both studies, this was achieved by using amendments and tillage practices that favored dominance of fungivorous nematodes over their bacterivorous counterparts.
3. *Roll of predacious and omnivorous nematodes*: The nematode faunal structure of undisturbed soils often has an abundance of specialist nematode predators, as well as generalist predators (Yeates et al. 2009). Such observations support the hypothesis that these predators have a regulatory, or even suppressive, effect on the abundance and stability of nematodes occupying the lower trophic levels of the food web, including herbivores, fungivores, and bacterivores. Predacious nematodes are, however, sensitive to soil disturbances and chemical amendments. Moreover, they are slow colonizers with long life cycles and lower productivity compared to other nematodes. Colonization and regulatory balance in the soil food web of agricultural systems by these nematodes may require considerable time (Korthals et al. 1996). According to Cobon et al. (2008), nematode community analyses showed that a low-till mulch system had a greater structure index (SI), a measure of the number of trophic levels in the soil food web. This gives the soil more potential for regulation by predators than the soil food web of conventional soil.
4. *Microbial-feeding nematodes (bacterivores) in an agricultural context*: Burial of plant material during cultivation provides resources for microbial-feeding nematodes whose populations may exceed 3000 g^{-1} dry matter (Sohlenius and Boström 1984). Initially, the populations tend to be dominated by bacterivorous genera of the Rhabditidae, Cephalobidae, and Panagrolaimida with fungivorous Aphelenchidae contributing during later stages of decomposition. Studies of the rhizosphere of peas, barley, turnips, and grass showed that the biomass of

microbial-feeding nematodes exceeded that of protozoa (Griffiths 1990) and led to the conclusion that nematodes are more important than protozoa in terms of nutrient cycling. Hendrix (1999) showed that no-tillage management favored food webs dominated by fungi and fungivores and high numbers of earthworms. In contrast, food webs in plowed soils show greater importance of bacteria and bacterivores, which colonize buried residues. As a consequence of these altered biotic communities, residue decomposition, OM mineralization, and nutrient release rates tend to be higher in plowed than in no-till soils. According to Yeates et al. (2009), the following study of the transition from conventional to organic farming was conducted in a Mediterranean climate. It involved crops planted in the spring, without fertilizer application but with a winter legume cover crop incorporated into the soil. Initially, the summer crop showed symptoms of nitrogen deficiency. Microbial biomass was at high levels following cover crop incorporation, but population levels of bacterial-feeding nematodes were very low. About 6 weeks after planting the summer crop, bacterial and fungal-feeding nematodes had increased on the newly available resources and with them nitrogen deficiency symptoms disappeared, with crop yield and mineral nitrogen concentrations strongly correlating. Likewise, Ferris et al. (1998) showed that when bacteria were grazed upon by bacterial-feeding nematodes in microcosm experiments, soil mineral nitrogen levels increased by 20% or more. Chen and Ferris (1999) indicated that fungal-feeding nematodes may also contribute to nitrogen mineralization. The opportunity to increase the abundance of bacterial- and fungal-feeding nematodes and other organisms in field soil is during the warm summer soil temperature, since winter soil temperatures are generally too cold for nematode reproduction and biological activity. Venette and Ferris (1998) demonstrated that not all bacteria are suitable food for bacterial-feeding nematodes and linked this, among other things, to the cell size of different bacterial species. Moens et al. (1999) also showed that four coexisting species of Monhysteridae, all responded differently to the presence of different bacteria. Such response differences relate not only to the bacterial strains offered but also to density, age, growth conditions, and activity of the bacteria. Of great interest is the work by Mikola and Setälä (1998) who demonstrated that bacterial-feeding nematodes perform species-specific functions rather than guild-specific functions in the soil food web. These studies have far-reaching implications, e.g., the effectiveness of soil enrichment by adding bacteria and fungi. Nematodes normally face two options to maximize energy gains: by moving to a better feeding location or by foraging within a given patch. The choice between these options depends on the nematode's functional response to a given type of food, and on the presence, suitability, and detectability of alternative food sources.

The abundance of each species in a nematode community can be transformed into ecological indices and parameters to measure changes in diversity and trophic structure in the community and to further assess soil disturbance levels and decomposition pathways (Gomes et al. 2003). Ecological indices based on the proportional contribution of each nominal taxon, such as the Shannon–Wiener index of diversity (H') and the Simpson index, are used to assess diversity (Baniyamuddin et al.

2007). Species richness is assessed by the Margalef's index (Baniyamuddin et al. 2007). The maturity index (MI) and plant parasitic index (PPI) provide focused tools for assessing the response of nematode populations to disturbance (Bongers 1990). MI values for soil subjected to various levels of disturbance range from > 2.0 in nutrient-enriched disturbed systems to ±4.0 in pristine environments (Bongers and Ferris 1999). The colonizer–persister values (cp values; Bongers 1990) of species reflect the perceived positions on an r–k spectrum based on their reproductive rate and correlated characteristics. The ratio between the abundance of two functional groups, such as bacterivores and fungivores, gives an index of the relative contribution of the two main decomposition channels (Baniyamuddin et al. 2007). It is expressed as the nematode channel ratio (NCR). Various functional feeding groups of nematodes have been described to compute the enrichment index (EI) and SI (Ferris et al. 2001). The EI is based on the expected responsiveness of the opportunistic guilds to the food source enrichment. Thus, EI describes whether a soil ecosystem is nutrient enriched (high EI) or depleted (low EI). The SI represents an aggregation of functional guilds with cp values ranging from 3 to 5. SI describes whether a soil ecosystem is structured/matured (high SI) or disturbed/degraded (low SI). While some authors recommend analysis at trophic group level, others emphasize the importance of identifying nematodes to species level.

Traditionally, nematode identification relied on taxonomic skill and a high-powered light microscope, which became problematic due to worldwide declining taxonomic skill and the time-consuming effort of identification. Many authors have thus proposed molecular methods as an alternative to morphological identification of nematodes. Neilsen et al. (2009) foresee routine analysis of nematode assemblages at an unprecedented scale (both numbers of specimens and sample numbers), whereby a wide range of changes in highly diverse and complex nematode assemblages would be better understood.

20.3 Influence of Three Key CA Principles on Soil Microbes

With global issues such as food security in a world with an exploding human population, arable land lost to urbanization forever available for agriculture, exhaustion of fossil fuels and natural resources, and climate change, we might be surprised to realize that the solution lies in something we walk on, and overlook, every day: our soils. There cannot be life without soil and agriculture. But traditional agriculture has left us with unhealthy soils depleted of nutrients, unable to naturally sustain crops, unless chemical fertilizers are applied—almost like a drug addict who cannot get through the day without a "chemical fix." Our soils are alive, but cannot function without their "chemical fix for the day." Just as a drug addict cannot be rehabilitated overnight, even more so, we cannot expect our soils to be rehabilitated in a matter of a few years after decades of chemical fertilizer abuse. Conventional intensive agriculture that resulted in declining crop yields, increased use of chemical fertilizers, increased crop disease due to monoculture, and soil erosion due to wind and rain have led farmers on the quest for alternative practices that would not leave arable land bare and unprotected after harvest, causing a loss of 24 billion tons of soil to erosion in 2011 alone (Global Soil Forum 2013).

These increased environmental concerns led farmers to the realization that fertile, healthy soils are urgently needed to increase yield dramatically on all available arable land (Johansson et al. 2004). This resulted in farming practices aimed at increased and sustainable SOM, crop rotation, integrated pest management, and other ecological-oriented farming practices (Karlen et al. 1992). The application of currently expanding knowledge led to CA by integrating three main principles, i.e., crop rotation (crop diversification) in combination with minimum soil disturbance (no-tillage) and permanent soil cover (mulching). Amendments applied to soil in terms of crop rotation, tillage, and residue management practices significantly impact soil biology, especially soil microbial diversity and activity (Govaerts et al. 2007).

In addition to all the benefits of CA discussed in other chapters of this book, this section aims to cast more light on the impact CA has on the soil's biological component.

20.3.1 Influence of Different Crops

Crop diversification encourages high soil microbial activity (Table 20.3) and diversity, initiating synergistic associations with other organisms such as rhizobia and mycorrhiza. Different crops have different root structures, placing OM in different soil strata, thus fertilizing the soil. Due to the interaction between plant roots and microorganisms in the rhizosphere through the release of root exudates, soil quality, crop health, and yield are affected by initiating improved nutrient cycling, disease resistance, and plant growth stimulation (Sturz and Christie 2003). Crop rotation and changes in planting dates might also contribute to disease control. Crop rotation with leguminous crops reduces the need for expensive nitrogen fertilizer. BNF can be enhanced by inoculating legume seeds with the appropriate *Rhizobium* strain for a specific legume (see *Biological Nitrogen Fixation*).

Table 20.3 Influence of cropping systems (MS, ML) and tillage practices (RT, CT) on microbial activity (β-glucosidase activity) over a period of three consecutive years (Habig 2014)

β-glucosidase activity (*p*-nitrophenol μg g^{-1} h^{-1})			
Treatment	2009	2010	2011
MS_RT	591.86	1184.62	2309.70
ML_RT	n/a*	1085.87	2432.72
MS_CT	603.66	762.00	1274.54
ML_CT	n/a*	1012.59	1413.65

MS maize–soybean rotation, *ML* maize–legume intercropping, *RT* reduced tillage, *CT* conventional tillage

* not applicable

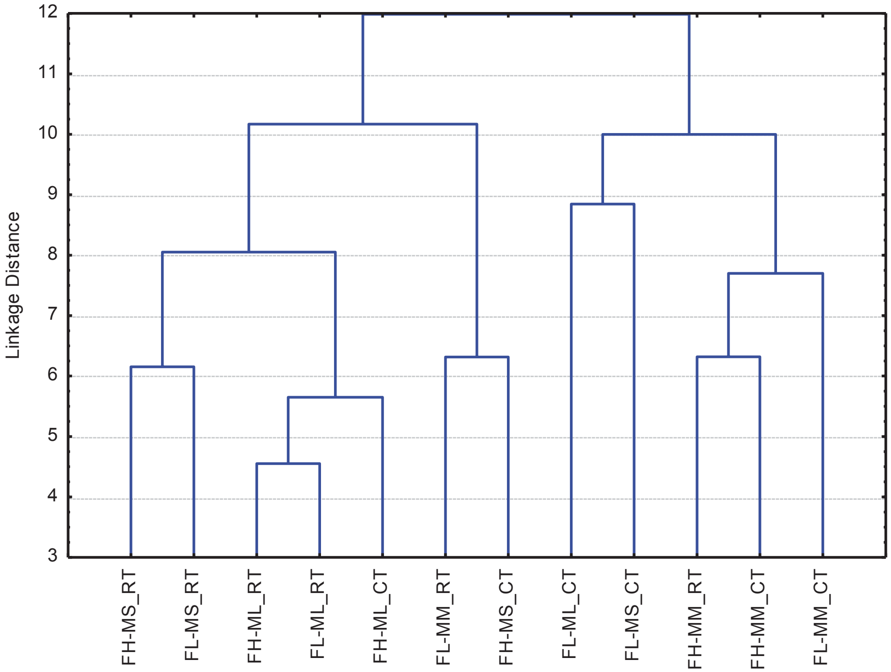


Fig. 20.3 Cluster analysis illustrating the influence of tillage practices (RT, CT) and cropping systems (MM, MS, ML) on soil microbial functioning. Cropping systems that included legumes under reduced tillage, clustered to the *left*, whereas maize monoculture under conventional tillage clustered to the *right*, thus indicating a difference in soil microbial functioning. *RT* reduced tillage, *CT* conventional tillage, *MM* maize monoculture, *MS* maize–soybean rotation, *ML* maize–legume intercropping. (Habig 2014)

20.3.2 Soil Disturbance

Tillage alters not only a soil's chemical and physical characteristics but also the spatial integrity of the soil as a support matrix for soil microbial community function (Fig. 20.3). Although tillage was supposed to substitute "biological plowing" by earthworms, tillage kills earthworms—no wonder earthworms constitute a vital part of the health status assessment of soils converted to CA after withdrawal of intensive plowing. SOM in a no-tillage system is mainly decomposed by fungi. As mentioned in the section on *Terrestrial Nematodes*, CT drastically alters SOM decomposition by breaking up crop residues into smaller pieces and redistributing it throughout the plowed layer, establishing bacteria as primary decomposers of SOM. Not only does the redistribution of broken-up crop residues increase microbial colonization but also it enhances aeration. SOM is consequently oxidized when exposed to air by tillage. Combined with the removal of produced OM during harvesting, tillage results in less OM content, unless additional OM is returned to the soil as residues or compost (Atlas and Bartha 1993; Hobbs 2007). Contrary to reduced (or no-) tillage (RT), CT accelerates nutrient cycling, consequently increasing nitrogen mineralization and soil carbon loss. Correct agricultural management practices can therefore be practiced to ensure effective nitrogen mineralization through minimum tillage, which minimizes soil erosion and compaction. Soil benefits are greater with continuous no-till compared to rotational tillage, i.e., 1 year no-till, tillage the next year.

Pores left by microbial activity and plant roots are also disrupted by tillage. Although the detrimental consequences of bare fallow soil after tillage are well known, the effect of tillage on soilborne diseases is still unclear. It is known, however, that a healthy soil with high microbial diversity does have a positive impact on disease suppression. Zero tillage has exhibited great potential to facilitate integrated pest management and biological control (Govearts et al. 2006).

20.3.3 Residue Retention (Mulching)

Forests and plants protect the soil. Every year, 13 million ha of forest is cut down. When these virgin (undisturbed) lands are converted for agricultural (disturbed) use, SOM content decreases annually until stabilizing at a much-reduced concentration, influencing soil microbial functioning. Buildup of SOM through residue retention retains nutrients and increases microbial diversity and activity in soil. The quality and quantity of SOM entering the soil greatly influences soil microbial processes as already mentioned. Care should be taken when high-carbon plant material is applied as a residue; it should be composted or mixed with manure prior to soil application since high-carbon compounds (high C:N ratio) take longer to decompose by soil microbial communities than compounds with a lower carbon content (higher nitrogen content).

Several long-term studies have shown that residue retention in combination with minimum soil disturbance created favorable conditions to promote ecological stability and develop antagonists and predators, contrary to the absence of residue retention which led to poor soil health (Govaerts et al. 2006). It is also important to note that while surface mulch moderates soil moisture and temperature, favorable conditions are also created for microbial activity and biological diversity with increased amounts of beneficial insects under ground cover to assist in insect pest management (Kendall et al. 1995). Several studies have found more soil fauna (microorganisms, earthworms, nematodes) under no-till and residue-preservation management practices compared to treatments subjected to CT. Unfortunately, CA is also associated with an increase in weed incidence, and residue retention could stimulate plant parasitic nematodes and fungal diseases “preserved” in the stubble, or pests and other diseases stimulated by the increased moisture. Increased pests and diseases inevitably lead to increased use of pesticides and herbicides. Fortunately, weeds could frequently contribute to nutrient dynamics by supplying extra organic material.

It is generally argued that a high diversity of soil microbial communities in an ecosystem will increase the ecosystem’s potential to function more efficiently under a variety of environmental conditions, implying an increased level of resilience (Kibblewhite et al. 2008).

20.4 Indicators of Ecosystem Status

The most relevant indicators of ecosystem status, irrespective of the extent of complexity, are relevant across sites or over time, easily measured, inexpensive, adaptable for specific ecosystems, able to demonstrate both positive and negative change, and are sensitive to changes induced by agricultural management practices (Arshad and Martin 2002; Schoenholtz et al. 2000). Due to the essential role microbial diversity and activity play in the condition of the soil's ecology, it can provide valuable information for determining the sustainability of an agricultural system (Pankhurst et al. 1995).

One of soil microbiology's biggest challenges is the application of appropriate techniques to study the small size and incredible diversity of microorganisms. Several techniques have therefore been developed to study soil microbial communities (Insam 2001), but, individually, each provides only limited information with regard to microbial community diversity and activity. Information is usually obtained regarding the microbial communities present, rather than providing insight into their activities. There are, however, techniques available to provide valuable information regarding the potential and actual activities of soil microbial communities, but then again, these techniques do not disclose which microbes are responsible. Due to this dilemma, it is clear that no single indicator will embrace all aspects of ecosystem status, and requires an integrative approach. Thus, a minimum data set (MDS) of indicators for ecosystem status should exhibit sensitivity towards various agricultural management practices such as fertilizer and pesticide application, soil disturbance, residue retention, and vegetation type (Ponge et al. 2013). Ponge et al. (2013) suggested a composite soil health index based mainly on a limited selection of easily identifiable soil organisms or bulk biological variables to detect soil community transformations after discarding the influence of factors not directly affected by anthropogenic activities. As a measure of evaluating the status of soil ecosystems, Kibblewhite et al. (2008) suggested the incorporation of abiotic assays as an indication of the state of the habitat (e.g., aggregate stability, pH, etc.) and the levels of key nutrient and energy reservoirs (e.g., ratios of SOM fractions), and biotic assays which explain soil microbial community diversity and function, as described below.

It should be kept in mind that these assays should be not only scientifically valid but also relevant to agricultural practices.

20.4.1 Conventional Techniques

Historically, microbiological techniques to obtain quantitative data relied on cell enumeration methods of specific bacterial and fungal groups. This was achieved by extracting microorganisms from soil and growing/cultivating them on a petri dish under specific conditions in a laboratory. Depending on the specific bacterial species, incubation time would vary from only 24–48 h for fast-growing bacteria to 10 days for slow-growing bacteria; after which, counting and describing microbial populations through direct microscopic counting and dilution plate counts commenced. Microorganisms isolated from soil were cultured on selective semisolid growth media that included all the necessary nutrients to sustain a specific microbial group. Eventually, researchers came to realize that these methods only detected culturable microorganisms, since a significant proportion of microorganisms remain unculturable—it was estimated that 90–99.9 % of the existing microbial diversity could not be cultured. It was difficult not only to assess soil microbial diversity but also to determine the contribution of the unculturable portion of the microbial diversity to the interactions in the soil ecosystem. Therefore, several useful community-level characterization techniques were developed that do not rely solely on culture-based assays. These quantitative, more representative and differentative, assays overcame the limitations of conventional microbiological techniques and contributed substantially to the characterization of soil microbial communities in their natural habitat.

20.4.2 Biochemical Assays

To improve their understanding regarding the actions of microbes in natural environments, microbial ecologists have developed several techniques to measure microbial community biomass, structure, metabolic status, and activity under "natural" conditions, thus attempting to reveal more closely the functional role of microbial communities (Vestal and White 1989). Several commonly used approaches to measure the diversity of decomposition functions performed by heterotrophic microorganisms have been developed.

Community-level physiological profiling (CLPP), first proposed by Garland and Mills (1991), tested the ability of whole microbial communities to degrade a set of 95 different carbon sources in a single assay on commercially available Biolog® microtiter plates. Biolog® EcoPlates (especially adapted for environmental applications) were designed with a reduced set of 31 discriminating carbon sources, but with three replicates on a single plate. The ability of microbial communities to use a specific substrate as an energy source was based on the reduction of tetrazolium violet dye as an indicator. Generally, whole soil samples are diluted, inoculated into Biolog® microtiter plates, and then incubated at 28 °C. The amount of carbon sources used, as well as the speed of utilization by microbial communities, reduces the tetrazolium dye, causing a color change that can be measured over a period of days at 590 nm (Fig. 20.4).

This consequently leads to a qualitative "metabolic fingerprint" that can be statistically analyzed. This technique has been successfully applied for better understanding of soil functions under the influence of plants, soilborne diseases (Fig. 20.5; Habig 2003), and in the development of sustainable agroecosystems (Das and Chakrabarti 2013).

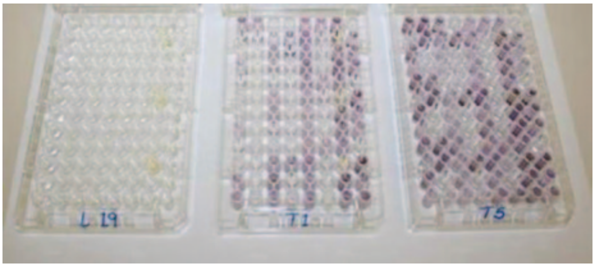


Fig. 20.4 Biolog® EcoPlates demonstrating differences in CLPP from three different agricultural sites. The purple represents carbon sources used by soil microbial communities. *CLPP* community-level physiological profiling. (Photo: Habig J, ARC-PPRI, South Africa)

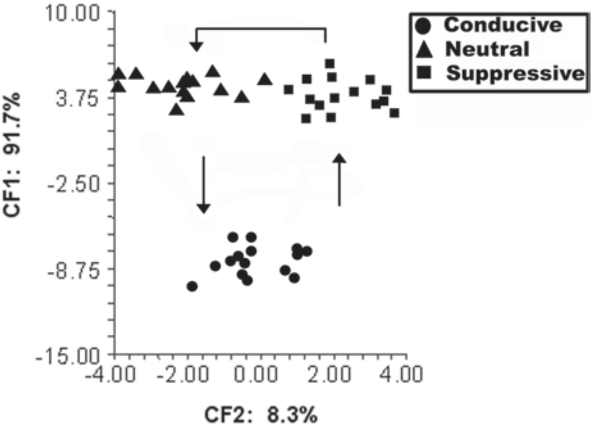


Fig. 20.5 Ordination plot generated by discriminant analyses of community-level physiological profile data obtained for functional diversity of soil microbial communities present in soils conducive (●), suppressive (■), and neutral (▲) to take-all disease of wheat. (Habig 2003)

Similar to the Biolog® method, the substrate-induced respiration (SIR) method, developed by Anderson and Domsch (1978), evaluates only the metabolically active portion of the microbial biomass by measuring the initial variation in soil respiration rates following the addition of an easily utilizable substrate, such as glucose.

The chloroform fumigation (CF) method is considered to measure both dead and alive microbial biomass, and consists of two indirect methods: the chloroform fumigation incubation (CFI) and the chloroform fumigation extraction (CFE) methods (Carter et al. 1999). These two methods are based on the killing and dissolving of microbial cells in a soil sample by chloroform vapors. CFI consequently estimates the size of the eradicated soil microorganisms by quantifying the respired CO_2 over a specified time period or by direct extraction of the soil directly after fumigation, consequently quantifying the extractable carbon (CFE). The respired CO_2 after fumigation indicates the utilization of the carbon source provided by the eradicated microbial cells, by germinating microbial spores.

It is clear that these techniques provide valuable information regarding the functioning of soil microbial communities, but no information is provided concerning the structural composition of the community. As a result, soil microbiologists concentrated more on phospholipid fatty acids (PLFA), structural components found in membranes of all living cells, to study and quantify specific microbial groups without cultivating them. Since bacteria and fungi differ in cell membrane composition, this technique can be used to provide a "structural fingerprint" of a soil microbial community. PLFA profiles in soils have been used significantly to estimate microbial biomass and to examine soil microbial community structure (Haack et al. 1994).

Since the mentioned techniques are not only laborious but are limited due to the culturing of microbial communities in the laboratory, measurements in nutrient fluctuation and quantification of enzyme activities have been proposed as alternatives.

Soil Enzymes Soil enzymes originate either intra- or extracellularly from bacteria, fungi, and plants. Since extracellular enzymes are responsible for the breakdown of organic macromolecules (e.g., lignin), and intracellular enzymes for the breakdown of the smaller molecules (e.g., carbohydrates, amino acids), these activities closely resemble microbial activity and abundance. Due to the important biochemical functions that enzymes fulfill in the general process of SOM decomposition, several enzymes have been studied on their suitability as indicators of soil quality. The ability of soil microbial communities to obtain carbon, phosphorus, nitrogen, and sulfur has been measured by determining the dehydrogenase, β-glucosidase, alkaline and acid phosphatase, urease, and arylsulfatase activities in the soil. The activities of these particular soil enzymes have been used as "biological fingerprints" of historical agricultural management practices (Dick 2000). Any disruption to the soil, i.e., soil disturbance, chemical additives, and removal or replacement of vegetation, has a significant impact on soil microbial diversity and activity.

Dehydrogenase is probably one of the most studied enzymes, as it is regarded as an accurate measure of viable microorganisms. Dehydrogenase assays have been applied to determine soil microbial activity, microbial biomass, and other ecological investigations (Smith and Pugh 1979).

β-Glucosidase has been found in bacteria, fungi, plants, and animals, and plays an important role in the cycling of SOM (Turner et al. 2002). Bandick and Dick (1999) have proposed β-glucosidase as a good indicator of soil quality due to its sensitivity to soil management practices.

Phosphatase plays an important role in the phosphorous cycle through soil organic phosphorous conversion. Due to the sensitivity of phosphatase activity to soil pH, it can be classified as alkaline phosphatase or acid phosphatase. Alkaline phosphatase (produced by microorganisms) and acid phosphatase (mainly detected in plant roots) activities are greatly influenced by agricultural practices, thus affecting their contribution to plant nutrition (Aon and Colaneri 2001).

Urease plays an important role in the nitrogen cycle. Although the urease enzyme is found in bacterial, fungal, plant, and animal cells, bacteria are known to convert urea to CO_2, water, and ammonia by means of urease activity (Heritage et al. 1999). It has been widely applied to evaluate soil quality due to its wide distribution in the soil environment (Turner et al. 2002).

Although the role of arylsulfatase in the cycling of sulfur in the soil surface is unclear, it is thought to play a crucial role in the breakdown of ester sulfates (found only in fungi) which contain 40–70 % of the total soil sulfur (Tabatabai 1994).

Despite the sensitivity of these enzymes to a wide variety of soil and environmental factors, these assays might provide valuable information regarding the functioning of soil microbial communities if monitored as trends over the long term (Aon and Colaneri 2001). If these indicators were included as part of an effective MDS or soil quality index (SQI), it should unravel the combination of measured soil characteristics to indicate whether productivity, health, and environmental protection are indeed positively affected by the various management practices (Granatstein and Bezdicek 1992). As a minimum requirement, an SQI should serve as an early warning system for soil degradation and differentiate between soil characteristics that would serve as indicators for rehabilitation of degraded soils (Sharma et al. 2005).

20.4.3 Molecular Techniques

Many of the soil and rhizosphere microorganisms are difficult to cultivate or enumerate using conventional culture-dependent techniques. To circumvent this problem, new frontiers in soil microbiology have been explored through molecular techniques over the last 20–25 years. Through the analysis of ribosomal DNA (rDNA) or ribosomal RNA (rRNA) extracted and purified from soil, an unimaginably diverse soil microbial composition was revealed (Franks et al. 2006). In principle, rDNA contains both conserved and variable regions—the conserved regions only differ among taxonomically distant groups, whereas the variable regions differ among strains of single species. The extracted DNA is then purified, amplified (multiplied), and analyzed by gel electrophoresis. The amplified products then separate from each other depending on their stability (guanine–cytosine (GC) content), thus yielding a distinct pattern of bands that differs between microbial communities (Fig. 20.6a). Apart from detecting the presence of a given strain of PGPR in a sample, the comparison of rRNA sequences is a very sensitive and powerful tool for deducing the phylogenetic and evolutionary relationship among bacteria (Weisburg et al. 1991; Fig. 20.6b).

20.5 Conclusion and Future Research Thrusts

The relationship between the soil's physical, chemical, and biological properties is exceptionally complicated, and, depending on existing soil conditions, these relationships can be either positive or negative. Ecosystem functioning is greatly influenced by SOM availability, activity, and diversity of soil microbial communities, and the flow of nutrients (Elliott and Coleman 1988). Plants respond to and alter their environment through root exudates. Exudates are also used as a means of communication between neighboring plants and rhizosphere microbial communities. Irrespective of the environments in which plants find themselves, they all rely on soil microbial communities for many crucial processes. Improved knowledge of the composition of different root exudates with regard to quality and quantity, according to plant species, environmental parameters, cropping systems, etc. is urgently

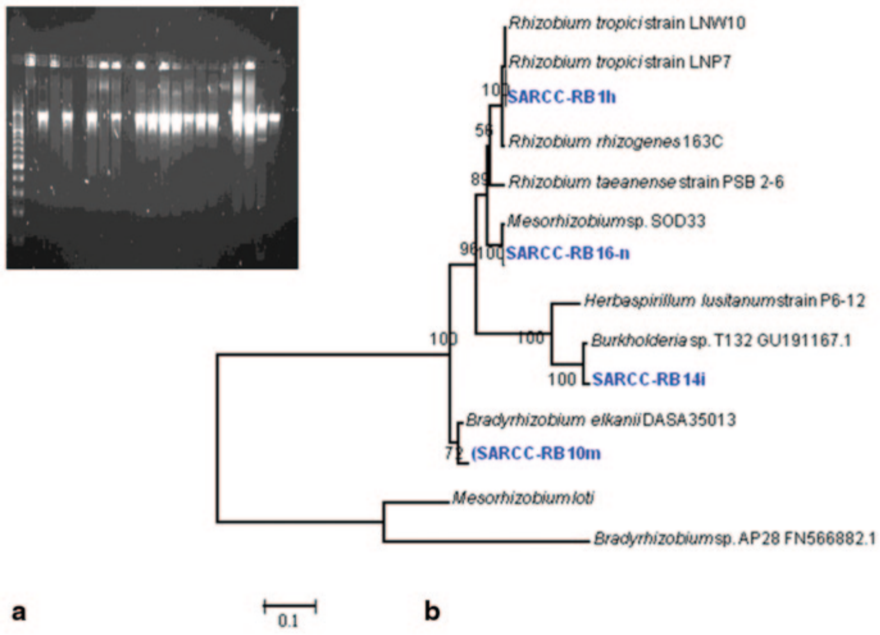


Fig. 20.6 Molecular indicators for PGPR. Samples of DNA obtained from unknown bacterial samples are amplified by the PCR and viewed on gel electrophoresis **a** The amplified ribosomal RNA could be sequenced and used to construct a phylogenetic tree that indicates either the evolutionary relationship of the samples or their identity to species and genus level **b** *PGPR* plant growth-promoting rhizobacteria, *DNA* deoxyribonucleic acid, *PCR* polymerase chain reaction, *RNA* ribonucleic acid (Hassen et al. 2013)

needed to promote beneficial interactions in the rhizosphere. The beneficial impact of soil microorganisms, especially that of symbiotic rhizobia in soil health maintenance and crop yield increase, has been widely studied and recognized for long. On the other hand, the use of PGPR as biocontrol agents and biofertilizers to enhance plant growth has gained momentum in recent years. As a result of current advances in the development of commercial PGPR inoculants for sustainable agriculture, several PGPR, such as *P. fluorescens*, *P. putida*, *Bacillus subtilis*, and other *Bacillus* species with a wide scope for commercialization, have been identified (Nakkeeran et al. 2005). With this taken into consideration, it can only be advantageous to crops to “optimize” their microbial allies in the rhizosphere. This knowledge can be applied by several means to enhance the sustainability of agricultural systems by favoring beneficial soil microbial communities to increase plant health, while enhancing defenses against pathogens (Badri and Vivanco 2009).

Although numerous techniques have been developed to provide valuable information regarding current soil activities and specific processes, few have been integrated to enhance our holistic understanding of ecosystem functions. Combining basic research/knowledge (i.e., ecology, molecular biology) with current knowledge of healthy ecosystems could lay the foundation for the development of microbe-based sustainable agriculture. By applying the correct agricultural practices as prescribed for CA, the soil ecosystem is granted the opportunity to nurture natural biological control measures during the buildup of soil cover and subsequent outbreaks of pests and diseases. This improved understanding will therefore be fundamental in the protection of our natural resources through the promotion of a balanced ecosystem that would inevitably lead to sustainable management of crop production and soil fertility through cropping systems that are resilient and sustainable.

References

Anderson TH (2003) Microbial eco-physiological indicators to assess soil quality. Agric Ecosyst Environ 98:285–293

Anderson JPE, Domsch KH (1978) A physiological method for the quantitative measurement of microbial biomass in soil. Soil Biol Biochem 10:215–221

Andrews M, Cripps MG, Edwards GR (2012) The potential of beneficial microorganisms in agricultural systems. Ann Appl Biol 160:1–5

Aon MA, Colaneri AC (2001) Temporal and spatial evolution of enzymatic activities and physico-chemical properties in an agricultural soil. Appl Soil Ecol 18:255–270

Arshad MA, Martin S (2002) Identifying critical limits for soil quality indicators in agro-ecosystems. Agric Ecosyst Environ 88(2):153–160

Atlas RM, Bartha R (1993) Microbial ecology-fundamentals and applications. Benjamin-Cummings, Redwood City

Badri DV, Vivanco JM (2009) Regulation and function of root exudates. Plant Cell Environ 32:666–681

Bae YS, Knudsen GR (2001) Influence of a fungus-feeding nematode on growth and biocontrol efficacy of *Trichoderma harzianum*. Phytopathology 91:301–306

Bakker PAHM, Pieterse CMJ, van Loon LC (2007) Induced systemic resistance by fluorescent *Pseudomonas* spp. Phytopathology 97:239–243

Balesdent J, Chenu C, Balabane M (2000) Relationship of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res 53(3–4):215–230

Bandick AK, Dick RP (1999) Field management effects on soil enzyme activities. Soil Biol Biochem 31:1471–1479

Baniyamuddin M, Tomar VVS, Ahmad W (2007) Functional diversity of soil inhabiting nematodes in natural forests of Arunachal Pradesh, India. Nematol Mediterr 35:109–121

Bashan Y, de-Bashan LE (2002) Protection of tomato seedlings against infection by *Pseudomonas syringae* pv. tomato using the plant growth promoting bacterium *Azosprillum brasilense*. Appl Environ Microbiol 68:2637–2643

Bashan Y, de-Bashan LE (2010) How the plant growth promoting bacterium Azosprillum promotes plant growth—a critical assessment. Adv Agron 108:77–130

Bashan Y, Holguin G (1998) Proposal for the division of plant growth-promoting rhizobacteria into two classification: biocontrol-PGPB (plant growth-promoting bacteria) and PGPB. Soil Biol Biochem 30:1225–1228

Bastida F, Zsolnay A, Hernandez T, Garcia C (2008) Past, present and future of soil quality indices: a biological perspective. Geoderma 147:159–171

Beneduzi A, Ambrosini A, Pasagila LMP (2012) Plant growth promoting rhizobacteria (PGPR): their potential as antagonistic and biocontrol agents. Genet Mol Biol 35(4):1044–1051

Berendsen R, Pieterse C, Bakker P (2012) The rhizosphere microbiome and plant health. Trends Plant Sci 17:478–486

Bhattacharyya PN, Jha DK (2012) Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World J Microbiol Biotechnol 28:1327–1350

Bohlool BB, Ladha JK, Garrity DP, George T (1992) Biological nitrogen fixation for sustainable agriculture: a perspective. Plant Soil 141:1–11

Bongers T (1990) The maturity index: an ecological measure of environmental disturbance based on nematode species composition. Oecologia 83:14–19

Bongers T, Ferris H (1999) Nematode community structure as a bio-indicator in environmental monitoring. Trends Ecol Evol 14:224–228

Borgonie G, García-Moyano A, Litthauer D, Bert W, Bester A, Van Heerden E, Möller C, Erasmus M, Onstott TC (2011) Nematoda from the terrestrial deep surface of South Africa. Nature 474:4. doi:10.1038/nature09974

Bot A, Benites J (2005) The importance of soil organic matter—key to drought-resistant soil and sustained food and production. Food and Agriculture Organization of the United Nations: Rome. FAO Soils Bulletin 80

Carter MR, Gregorich EG, Angers DA, Beare MH, Sparling GP, Wardle DA, Voroney RP (1999) Interpretation of microbial biomass measurements for soil quality assessment in humid temperate regions. Can J Soil Sci 79:507–520

Chen J, Ferris H (1999) The effects of nematode grazing on nitrogen mineralization during fungal decomposition of organic matter. Soil Biol Biochem 31:1265–1279

Cobon J, O'Niell W, Jones P, Pattison A (2008) Changes in soil nematode assemblages under low tillage, mulched vegetable production systems in Queensland. Proceedings of the 5th international congress of nematology, July 13–18, Brisbane, Australia

Compant S, Duffy B, Jerzy N, Clement C, Barka EA (2005) Use of plant growth promoting bacteria for biocontrol of plant diseases: principles, mechanisms of actions and future prospects. Appl Environ Microbiol 71:4951–4959

Das B, Chakrabarti K (2013) Assessment of community level physiological profiles and molecular diversity of soil bacteria under different cropping systems. Turk J Agric For 37:468–474

de Faria MR, Wraight SP (2007) Mycoinsecticides and mycoacaricides: a comprehensive list with worldwide coverage and international classification of formulation types. Biol Control 43:237–256

Dick R (2000) Soil enzyme stability as an ecosystem indicator. Oregon, United States. http://cfpub.epa.gov/ncer_abstracts. Accessed 13 July 2009

Döbereiner J, Day JM (1976) Associative symbiosis in tropical grasses: characterization of microorganisms and dinitrogen-fixing sites. In: Newton WE, Nyman CJ (eds) Proceedings of the 1st international symposium on nitrogen fixation. Washington State University Press, Pullman, pp 518–538

Eckardt NA (2006) The role of flavonoids in root nodule development and auxin transport in *Medicago truncatula*. Plant Cell 18:1539–1540

Elliott ET, Coleman DC (1988) Let the soil work for us. Ecol Bull 39:23–32

Ferris H, Venette RC, Van der Meulen HR, Lau SS (1998) Nitrogen mineralization by bacterial-feeding nematodes: verification and measurement. Plant Soil 203:159–171

Ferris H, Bongers T, De Goede RGM (2001) A framework for soil food web diagnostics: extension of nematode faunal analysis concept. Appl Soil Ecol 18:13–29

Ferris H, Venette RC, Scow KM (2004) Soil management to enhance bacterivore and fungivore nematode populations and their nitrogen mineralization function. Appl Soil Ecol 24:19–35

Franks A, Ryan RP, Abbas A, Mark GL, O'Gara F (2006) Molecular tools for studying plant growth promoting rhizobacteria (PGPR). In: Copper JE, Rao JR (eds) Molecular approaches to soil, rhizosphere and plant microorganisms. Biddles Ltd., Kings Lynn, pp 116–131

Garland JL, Mills AL (1991) Classification and characterization of heterotrophic microbial communities on the basis of patterns of community-level sole-carbon-source utilization. Appl Environ Microbiol 57:2351–2359

Glick BR (2012) Plant growth promoting bacteria: mechanisms and applications. Scientifica 1–15

Glick B, Cheng Z, Czarny J, Duan J (2007) Promotion of plant growth by ACC deaminase containing soil bacteria. Eur J Plant Pathol 119:329–339

Global Soil Forum (2013) Fertile soils: fundamental in the struggle against hunger and climate change! Institute for Advanced Sustainability Studies e. V. 2013 October, pp 1–5

Gomes GS, Huang SP, Cares JE (2003) Nematode community, trophic structure and population fluctuation in soybean fields. Fitopatol Bras 28:258–266

Goswami D, Dhandhukia P, Patel P, Thaker JN (2014) Screening of PGPR from saline desert of Kutch: growth promotion in *Arachis hypogea* by *Bacillus licheniformis* A2. Microbiol Res 169:66–75

Govaerts B, Mezzalama M, Sayre KD, Crossa J, Nicol JM, Deckers J (2006) Long-term consequences of tillage, residue management, and crop rotation on maize/wheat root rot and nematode populations. Appl Soil Ecol 32:305–315

Govaerts B, Mezzalama M, Unno Y, Sayre KD, Luna-Guido M, Vanherck K, Dendooven L, Deckers J (2007) Influence of tillage, residue management, and crop rotation on soil microbial biomass and catabolic diversity. Appl Soil Ecol 37:18–30

Granatstein D, Bezdicek DF (1992) The need for a soil quality index: local and regional perspectives. Am J Altern Agric 7:12–16

Grayston SJ, Vaughan D, Jones D (1997) Rhizosphere carbon flow in trees, in comparison with annual plants: the importance of root exudation and its impact on microbial activity and nutrient availability. Appl Soil Ecol 5:29–56

Griffiths BS (1990) A comparison of microbial-feeding nematodes and protozoa in the rhizosphere of different plants. Biol Fertil Soils 9:83–88

Gyanshewar P, Kumar GN, Pakekh LJ, Poole PS (2002) Role of soil microorganisms in improving phosphorous nutrition in plants. Plant Soil 245:83–89

Haack SK, Garchow H, Odelson DA, Forney LJ, Klug MJ (1994) Accuracy, reproducibility, and interpretation of fatty acid methyl ester profiles of model bacterial communities. Appl Environ Microbiol 60:2483–2493

Haas D, Defago G (2005) Biological control of soil-borne pathogens by fluorescent pseudomonads. Nature Rev Microbiol 3:307–319

Habig J (2003) Soilborne disease suppressiveness/conduciveness: analysis of microbial community dynamics [dissertation]. North-West University, Potchefstroom

Habig J (2014) Effects of conservation agriculture on soil microbial community dynamics. In: Book of condensed papers of the 1st Africa congress on conservation agriculture, March 18–21, Lusaka, Zambia

Hartley JL (1965) Mycorrhiza. In: Baker KF, Snyder WC (eds) Ecology of soil-borne plant pathogens. University of California Press, Berkeley, pp 218–229

Hassen AI, Bopape FL, Lamprecht SC (2013) Emergence of new root nodule bacteria from members of the β-Proteobacteria group. Proceeding of the 18th biennial conference of the South African Society of Microbiology. Forever Resorts, Warmbaths, Bela-Bela, South Africa, pp 24–27

Heininger P, Höss S, Claus E, Pelzer J, Traunspurger W (2007) Nematode communities in contaminated river sediments. Environ Pollut 146:64–76

Hendrix PF (1999) Proceedings of the 22nd Annual Southern Conservation Tillage Conference for Sustainable Agriculture, Tifton, GA, July 6–8. In: Hook JE (ed) Georgia Agricultural Experiment Station, Special Publication No 95, University of Georgia, Athens

Heritage J, Evans EGV, Killington RA (1999) Microbiology in action. Cambridge University Press, Cambridge

Hobbs PR (2007) Conservation agriculture: what is it and why is it important for future sustainable food production? J Agr Sci 145:127–137

Hohberg K (2003) Soil nematode fauna of affected mine sites: genera distribution, trophic structure and functional guilds. Appl Soil Ecol 22:113–126

Hugot JP, Baujard P, Morand S (2001) Biodiversity in helminths and nematodes as a field of study: an overview. Nematology 3:199–208

Ingham RE, Trofymow JA, Ingham ER, Coleman DC (1985) Interactions of bacteria, fungi and their nematode grazers on nutrient cycling and plant growth. Ecol Monogr 55:119–140

Insam H (2001) Developments in soil microbiology since the mid 1960s. Geoderma 100:389–402

Jetiyanun K, Kloepper JW (2002) Mixtures of plant growth promoting rhizobacteria for induction of systemic resistance against multiple plant diseases. Biol Control 24:285–291

Johansson JF, Paul LR, Finlay RD (2004) Microbial interactions in the mycorrhizosphere and their significance for sustainable agriculture (Minireview). FEMS Microbiol Ecol 48:1–13

Karlen DL, Eash NS, Unger PW (1992) Soil and crop management effects on soil quality indicators. Am J Altern Agric 7:48–55

Kendall DA, Chin NE, Glen DM, Wiltshire CW, Winstone L, Tidboald C (1995) Effects of soil management on cereal pests and their natural enemies. In: Glen DM, Greaves MP, Anderson HM (eds) Ecology and integrated farming systems, proceedings of the 13th Long Ashton international symposium, Chichester, UK. Wiley Press, New York, pp 83–102

Kibblewhite MG, Ritz K, Swift MJ (2008) Soil health in agricultural systems. Philos Trans R Soc B: Biol Sci 363(1492):685–701

Kidarsa TA, Goebel NC, Zabriskie TM, Loper JE (2011) Phloroglucinol mediates croos-talk bewteen the pyoluteorin and 2,4 diacetylphloroglucinol biosynthetic pathways in *Pseudomonas fluorescens* Pf-5. Mol Microbiol 81(2):395–414

Kloepper JW, Schroth MN (1978) Plant growth promoting rhizobacteria in radishes. In: Proceedings of the IVth international conference on plant pathogenic bacteria. Station de Pathologie Vegetaleet Phyto-Bacteriologie, pp 879–882

Kloepper JW, Schroth MN (1981) Relationship of in-vitro antibiosis of plant growth promoting rhizobacteria to plant growth and displacement of root microflora. Phytopathology 71:1020–1024

Kloepper JW, Ryu CM, Zhang S (2004) Induced systemic resistance and promotion of plant growth by *Bacillus* spp. Phytopathology 94:1259–1266

Konopka A (2009) Ecology, Microbial. In: Schaechter M (ed) Encyclopedia of microbiology. 3rd edn. Elsevier, London, Oxford

Korthals GW, Van de Ende A, Van Megen H, Lexmond TM, Kammenga JE, Bongers T (1996) Short term effects of cadmium, copper, nickel and zinc on soil nematodes from different feeding and life-history strategy groups. Appl Soil Ecol 4:107–117

Lei L, Stewart CN Jr, Tang ZX, Wei W (2011) Dynamic expression of green fluorescent protein and *Bacillus thuringiensis* Cry1Ac endotoxin in interspecific hybrids and successive backcross generations (BC1 and BC2) between transgenic *Brassica napus* crop and wild *Brassica juncea*. Ann Appl Biol 159:212–219

Lindstrom K, Koko Gonzales P, Terefework Z, Rasanen LA (2006) Differentiation of nitrogen fixing legume root nodule bacteria (Rhizobia). In: Copper JE, Rao JR (eds) Molecular approaches to soil, rhizosphere and plant microorganisms. Biddles Ltd., Kings Lynn, pp 236–257

Masciarelli O, LIanes A, Luna V (2013) A new PGPR co-inoculated with *Bradyrhizobium japonicum* enhances soybean nodulation. Microbiol Res 169(7–8):609–615

McCallum ME, Dusenbery DB (1992) Computer tracking as a behavioural gc detector—nematode responses to vapour of host roots. J Chem Ecol 18:585–592

Menna P, Hungria M, Barcellos FG, Bangel EV, Hess PN, Martinez-Romero E (2006) Molecular phylogeny based on the 16S rRNA gene of elite rhizobial strains used in Brazilian commercial inoculants. Syst Appl Microbiol 29(4):315–332

Mikola J, Setälä H (1998) Relating species diversity to ecosystem functioning: mechanistic backgrounds and experimental approach with a decomposer food web. Oikos 83:180–194

Moens T, Verbeeck L, De Maeyer A, Swings J, Vincx M (1999) Selective attraction of marine bacterivorous nematodes to their bacterial food. Mar Ecol Prog Ser 176:165–178

Morrissey J, Dow J, Mark G, O'Gara F (2004) Are microbes at the root of a solution to world food production? EMBO Rept 5(10):922–926

Mulder C, Schouten AJ, Hund-Rinke K, Breure AM (2005) The use of nematodes in ecological soil classification and assessment concepts. Ecotox Environ Safe 62:278–289

Nakkeeran S, Delantha Fernando WG, Siddiqui ZA (2005) Plant-growth-promoting rhizobacteria formulations and scope in commercialization for the management of pests and diseases. In: Siddiqui ZA (ed) PGPR: biocontrol and biofertilization. Springer, Dordrecht, pp 257–296

Neilsen R, Donn S, Griffiths B, Daniell T, Rybarczyk KD, Van den Elsen S, Mooyman P, Helder J (2009) Molecular tools for analysing nematode assemblages. In: Wilson MJ, Kakouli-Duarte T (eds) Nematodes as environmental indicators. CAB International, Wallingford, pp 188–202

NemaPix (2000) A journal of nematological images. In: Eisenback JD, Zunke U (eds), vol 1. Mactode Publications, Blacksburg, Virginia, USA and Hamburg, Germany

NemaPix (2002) A Journal of Nematological Images. In: Eisenback JD, Zunke U (eds), vol 3. Mactode Publications, Blacksburg, Virginia, USA and Hamburg, Germany

Newton AC, Gravouil C, Fountaine JM (2010) Managing the ecology of foliar pathogens: ecological tolerance in crops. Ann Appl Biol 157:343–360

Nicklin J, Graeme-Cook K, Paget T, Killington RA (1999) Instant notes in microbiology, BIOS. Scientific Publishers Ltd., Oxford

Pankhurst CE, Hawke BG, McDonald HJ, Kirkby CA, Buckerfield JC, Michelsen P, O'Brien KA, Gupta VVSR, Doube BM (1995) Evaluation of soil biological properties as potential bioindicators of soil health. Aust J Exp Agr 35:1015–1028

Patten CI, Glick BR (2002) Role of *Pseudomonas putida* indoleacetic acid in development of the host plant root system. Appl Environ Microbiol 68:3795–3801

Peoples MB, Craswell ET (1992) Biological nitrogen fixation: investments, expectations and actual contributions to agriculture. Plant Soil 141:13–39

Perez-Montano F, Alias-Villegas C, Bellogin del Cerro P, Espuny MR, Jimenez Guerrero, I, Baena-Lopez FJ, Ollero FJ, Cubo T (2014) Plant growth promotion in cereal and leguminous agricultural important plants: from microorganism capacities to crop production. Microbiol Res 169:325–336

Philippot L, Raaijmakers JM, Lemanceau P, Van der Putten WH (2013) Going back to the roots: the microbial ecology of the rhizosphere. Nat Rev—Microbiol Focus Plant-Microbe Interact 11:789–799

Pliego C, Ramos C, de Vicente A, Cazorla FM (2010) Screening for candidate bacterial biocontrol agents against soilborne fungal pathogens. Plant Soil 340:505–520

Polz MF, Ott JA, Bright M, Cavanaugh CM (2000) When bacteria hitch a ride. ASM News 66:531–539

Ponge JF, Pérès G, Guernion M, Ruiz-Camacho N, Cortet J, Pernin C, Villenave C, Chaussod R., Martin-Laurent F, Bispo A, Cluzeau D (2013) The impact of agricultural practices on soil biota: a regional study. Soil Biol Biochem 67:271–284

Raajmakers JM, Vlami M, de-Souza JT (2002) Antibiotic production by bacterial biocontrol agents. A van Leeuw 81:537–547

Schoenholtz SH, Van Miegroet H, Burger JA (2000) A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. Forest Ecol Manag 138(1–3):335–356

Schroeder J, Thomas SH, Murray LW (2005) Impacts of crop pests on weeds and weed-crop interactions. Weed Sci 53:918–922

Schweitzer JA, Bailey JK, Fischer DG, LeRoy CJ, Lonsdorf EV, Whitham TG, Hart SC (2008) Plant–soil–microorganism interactions: heritable relationship between plant genotype and associated soil microorganisms. Ecology 8:773–781

Sharma KL, Mandal UK, Srinivas K, Vittal KPR, Mandal B, Grace JK, Ramesh V (2005) Long-term soil management effects on crop yields and soil quality in a dryland Alfisol. Soil Tillage Res 83:246–259

Smith SN, Pugh GJF (1979) Evaluation of dehydrogenase as a suitable indicator of soil microflora activity. Enzyme Microb Technol 1:279–281

Sohlenius B, Boström S (1984) Colonization, population development, population development and metabolic activity of nematodes buried in barley straw. Pedobiologia 27:67–78

Stirling GR, Eden LM (2008) The impact of organic amendments, mulching and tillage on plant nutrition, *Pythium* root rot, root-knot nematode and other pests and diseases of capsicum, and implications for the development of more sustainable vegetable farming systems. Australas Plant Pathol 37:123–131

Stirling GR, Wilson EJ, Stirling AM, Pankhurst CE, Moody PW, Bell MJ, Halpin N (2005) Amendments of sugarcane trash induce suppressiveness to plant parasitic nematodes in sugarcane soil. Australas Plant Pathol 34:203–211

Sturz AV, Christie BR (2003) Beneficial microbial allelopathies in the root zone: the management of soil quality and plant disease with rhizobacteria. Soil Tillage Res 72:107–123

Tabatabai MA (1994) Soil enzymes. In: Weaver RW (ed) Methods of soil analysis. Part 2. SSSA Book, Ser. 5. SSSA and ASA, Madison, pp 775–833

Tate RL (2000) Soil microbiology, 2nd edn. John Wiley & Sons, New York

Tikhonovich IA, Provorov NA (2011) Microbiology is the basis of sustainable agriculture: an opinion. Ann Appl Biol 159:155–168

Turner BL, Hopkins DW, Haygarth PM, Ostle N (2002) Limitations of soil enzymes as indicators of soil pollution. Soil Biol Biochem 32:1867–1875

Venette RC, Ferris H (1998) Influence of bacterial type and density on population growth of bacterial-feeding nematodes. Soil Biol Biochem 30:949–960

Vessey JK (2003) Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255:571–586

Vestal JR, White DC (1989) Lipid analysis in microbial ecology: quantitative approaches to the study of microbial communities. Bioscience 39:535–541

Viglierchio DR (1991) The world of nematodes. Department of Nematology, University of California, Davis, California, U.S.A, pp 229–31

Wagenet RJ, Hutson JL (1997) Soil quality and its dependence on dynamic physical processes. J Environ Qual 26(1):41–48

Wander MM, Walter GL, Nissen TM, Bollero GA, Andrews SS, Cavanaugh-Grant DA (2002) Soil quality: science and process. Agron J 94(1):23–32

Wardle DA, Bardgett RD, Klironomos JN, Setälä H, van der Putten WH, Wall DH (2004) Ecological linkages between aboveground and belowground biota. Science 304:1629–1633

Weisburg WG, Barns SM, Pelletier DA, Lane DJ (1991) 16S ribosomal DNA amplification for phylogenetic study. J Bacteriol 173:697–703

Weller DM, Thomashow LS (1994) Current challenges in introducing microorganisms into the rhizosphere. In: O'Gara F, Dowling DN, Boesten B (eds) Molecular ecology of rhizosphere microorganisms. biotechnology and the release of GMO's. VCH, Weinheim, pp 1–18

Weller DM, Raaijmakers JM, Gardner BB, Thomashow LS (2002) Microbial populations responsible for specific soil suppressiveness to plant pathogens. Ann Rev Phytopathol 40:309–348

West CP, Mallarino AP (1996) Nitrogen transfer from legumes to grasses. In: Joost RE, Roberts CA (eds) Nutrient cycling in forage systems. Potash and Phosphate Institute and Foundation of Agronomic Research, Manhattan

Whipps JM (2001) Microbial interactions and biocontrol in the rhizosphere. J Exp Bot 52:487–511

Wubben MJE, Su H, Rodermel SR, Baum TJ (2001) Susceptibility to the sugar beet cyst nematode is modulated by ethylene signal transduction in *Arabidopsis thaliana*. Mol Plant Microbe Interact 14:1206–1212

Yeates GW (1979) Soil nematodes in terrestrial ecosystems. J Nematol 11:213–229

Yeates WY, Ferris H, Moens T, Van der Putten WH (2009) The role of nematodes in ecosystems. In: Wilson MJ, Kakouli-Duarte T (eds) Nematodes as environmental indicators. CAB International, Wallingford, pp 1–31

Chapter 21
Conservation Agriculture in Organic Farming: Experiences, Challenges and Opportunities in Europe

J. Peigné, V. Lefevre, J.F. Vian and Ph. Fleury

Abstract Conservation tillage includes a range of tillage practices, mostly non-inversion, which aim to reduce soil erosion by leaving the soil surface covered by crop residues. Despite conservation tillage having been promoted in organic farming (OF) to improve inherent soil quality, several factors hinder its development such as weed control and soil compaction. Consequently, to enhance the adoption of conservation tillage in OF, long-term experiments were established several years ago in Europe. Different tillage techniques have been assessed from mouldboard ploughing to direct drilling under cover crops. In all cases, the effects of conservation vs. conventional tillage on soil fertility and weed and crop development were compared. Preliminary results show that the effects of conservation tillage are closely related to soil and climatic conditions, practices conducted in the field, and initial experimental conditions (level of weeds, previous crop, soil structure, etc.). Direct seeding under a cover crop or mulch remains a major challenge in OF, since weeds are not mechanically controlled, which thus affect crop performance. However, with other reduced tillage techniques, such as using a layer cultivator, weed development has had minimal effects with no impact on yields. In addition, to improved soil fertility, reduced tillage can increase crop yields. Most of the results of conservation tillage effects were obtained from experiments conducted for less than 10 years under OF management. Assessment over longer periods is needed and then shared with organic farmers to design new cropping systems. Introduction of new equipment and knowledge exchanges between conventional farmers practising conservation tillage and organic farmers could improve the adoption of conservation tillage in OF.

Keywords Organic farming · Conservation tillage · Soil fertility · Weed control

---

J. Peigné (✉) · V. Lefevre · J.F. Vian
Department of Agroecology and Environment, ISARA-Lyon, 23 Rue Jean Baldassini,
69364 Lyon cedex 07, France
e-mail: jpeigne@isara.fr

Ph. Fleury
Department of Agriculture, Laboratoire d'Etudes Rurales, Food Systems and Rural Areas,
ISARA-Lyon, 23 Rue Jean Baldassini, 69364 Lyon cedex 07, France

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_21

21.1 Introduction

In organic farming (OF), the plough is traditionally used to prepare soil before seeding, for weed control, to bury intermediate crops, and to incorporate organic fertilizers and amendments. However, due to soil fertility problems such as poor soil structure (compaction, soil crust) and the negative impact of tillage on soil biological organisms, organic farmers have shown interest in adapting conservation agriculture (CA) techniques to avoid using the plough (Lefèvre et al. 2012). According to the FAO (http://www.fao.org/ag/ca/), CA relies on three main principles: (1) minimal soil disturbance or no tillage, (2) permanent soil cover, and (3) diversified crop rotation. However, no reports are available for CA applied as this three-principle package in OF. In this chapter, CA is described and analysed in regard to conservation tillage techniques.

21.2 Main Issues in Conservation Tillage

CA and conservation tillage, in particular, have been extensively studied in conventional farming (Soane et al. 2012). Conservation tillage includes many practices such as tillage with tined tools at depth down to 15–20 cm, or direct seeding without prior cultivation (Fig. 21.1). The differences in soil depth worked and degree of fragmentation due to different tools (teeth, disks) impact the soil differently. For instance, the distribution of organic matter (OM) repartition will be more or less homogeneous in the cultivated soil layer, and weed management resulting from seed burial will be more or less substantial, depending on the tools used. Whatever

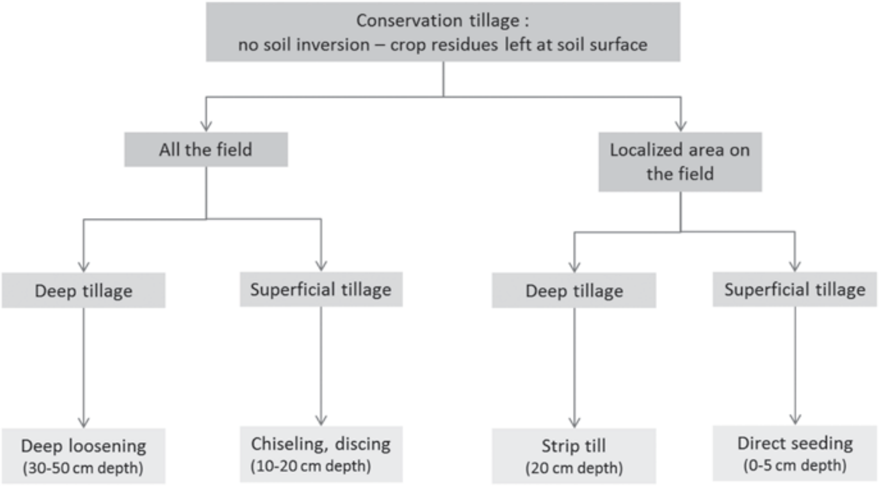


Fig. 21.1 Diagram of the different categories of conservation tillage techniques

the techniques, the first reason to stop ploughing is to protect the soil surface from crusting and erosion by leaving crop residues and OM at the soil surface. Consequently, more water-stable aggregates are measured in the uppermost soil layer under conservation tillage compared to ploughing (Holland 2004; Blanco-Canqui and Lal 2007). In addition, several studies have shown that conservation tillage increases carbon stock (C) as well as the quantity, activity, and diversity of microorganisms in the upper soil layers (Kladivko 2001). Conservation tillage also tends to increase earthworm biomass and diversity (Holland 2004; Pelosi et al. 2013). Conservation tillage preserves their habitat (burrows), especially anecic burrows, which favour water and root penetration (Holland 2004; Soane et al. 2012). Bohlen et al. (1995) reported that conservation tillage tends to increase earthworm densities, which then promotes macroporosity of biological origins in deeper soil layers (Kay and VandenBygaart 2002). Conservation tillage is also used to decrease labour time, energy consumption, and machinery cost (Soane et al. 2012).

Questions remain unsolved about the effect of conservation tillage on soil fertility and crop performance. For instance, Wu (1990) questioned the usefulness of increased OM concentration in the top 5 cm of soil for overall biological functioning in the soil. Indeed, OM tends to increase in the first 10 cm of the soil, but strongly decreases in deeper soil layers (Gál et al. 2007), which puts into question the impact of conservation tillage systems on soil carbon sequestration (Baker et al. 2007). Conservation tillage also tends to reduce total porosity in soil layers, which are not mechanically fragmented, especially in soils with low shrinking–swelling activity (sandy, silty soils; Rasmussen 1999; Soane et al. 2012). Conversely, in poorly drained soils such as clayey soils, conservation tillage tends to increase problems related to drainage (Soane et al. 2012). One of the challenges of conservation tillage techniques is to replace mechanical porosity with biological porosity, attributed to the burrowing activity of earthworms. But soil compaction and reduced OM in deeper soil layers may limit activity of soil organisms in conservation tillage systems, especially that of soil microorganisms (Vian et al. 2009). Two questions to consider over the long term are: (1) Is the burrowing activity of earthworms sufficient to maintain or improve total macroporosity in soil under conservation tillage compared to ploughed soil? And (2) what are the consequences of reduced microbial activity in deeper soil layers for sustainable nutrient management? In a European review, Soane et al. (2012) also raised several questions about the effect of conservation tillage on crop yields in Northern and Western Europe. They found that winter crops performed equally under conservation tillage and ploughed soils, but the yield performance of spring crops decreased. In conservation tillage, yields are strongly affected by the inherent soil fertility and use of herbicides for weed control.

21.3 Challenges in OF

All the questions raised in conventional agriculture also concern organic farmers. Moreover, these issues are particularly important in OF as crop growth depends primarily on soil biological processes for nutrient uptake (Watson et al. 2002).

The prohibition of herbicides and frequent organic amendments in OF influence particular soil features, especially the biological soil component (Shepherd et al. 2000). Several studies have shown that soil fertility under OF tends to be higher than under conventional farming, which is attributed to more OM and soil micro- and macrofauna (Flieβbach and Mäder 2000; Hole et al. 2005; Birkhofer et al. 2008) and earthworm activity and diversity (Gerhardt 1997; Scullion et al. 2002). Thus, conservation tillage techniques which modify soil fertility could strongly impact nutrient, water, and weed dynamics, and thus the whole cropping system in OF (yield stability, weed competition, etc.). The combination of conservation tillage advantages and OF specificities should improve soil fertility in OF. The effects, however, of conservation tillage systems as previously mentioned on soil OM, soil organisms, and soil compaction need to be studied further in OF (Peigné et al. 2007).

Weed control is an issue for conservation tillage in OF. Indeed, ploughing is considered an effective weed control practice. The abandonment of ploughing as weed control could present an obstacle to the use of conservation tillage in OF (Peigné et al. 2007; Mäder and Berner 2012). Without herbicides, conservation tillage tends to increase weed pressure to a critical level, where crop production could be compromised. Weed control must be well adapted to conservation tillage in OF, especially considering that crop residues left on the soil surface limit the practice of mechanical weeding. The main challenges for adopting conservation tillage in OF are therefore: (1) to preserve the soil fertility and main soil functions such as OM mineralization and (2) to control weeds and maintain crop yields.

21.4 Experiences in Europe

21.4.1 Long-Term Experiments

To enhance adoption of conservation tillage in OF, various long-term experiments have been recently established in Europe (Mäder and Berner 2012). In France, three experimental trials (Table 21.1) compared ploughing and conservation tillage techniques in OF; four tillage systems were tested: (1) traditional ploughing at 30 cm depth, (2) shallow ploughing at 18 cm depth, (3) reduced tillage with chisel between 12 and 15 cm depth, and (4) much reduced tillage at 5 cm depth. This last system was essentially direct seeding under a cover crop. This technique corresponds to no tillage or zero tillage (Fig. 21.1). Direct seeding was performed in a rolled cover crop. The main objective of this technique is to control weeds using a cover crop. The cover crop was rolled with a roller-crimper before sowing without soil disturbance (Fig. 21.2). The rolled cover crop became mulch and the cash crop was directly sown into the mulch with a direct seeder (Fig. 21.3). Direct seeding was tested three times at the different sites (in 2005 and 2008 for site A and in 2003 for site C) but, due to weed problems, the soil was superficially tilled again.

In Römmershein (southwestern Germany), the 'Stiftung Ökologie und Landbau' (SOEL) began a long-term experiment in 1994 on a clay loam soil (Vakali et al. 2011) to

Table 21.1 Details of experimental sites in France. (after Peigné et al. 2009)

Sites	Organic farming	Year started	Soil type (FAO classification)	Annual temperature (°C)	Annual rainfall (mm)	pH (H_2O)	Annual crop rotation
A: Thil	8 years	2004	Sandy loam (fluvisol)	10.7	730	8.3	Alfalfa (2001–2004)—maize[a] (oat) —soybean—wheat (rye)—soybean[a]—wheat (alfalfa)
B: Angers	7 years	2005	Silty (cambisol)	12.1	704	7.2	Faba bean (2004)—Winter wheat—lupine crop (clover)—winter wheat—maize
C: Kerguehennec	11 years	2003	Silty (cambisol)	11.5	891	6.2	Clover (2002)—maize[a]—triticale—buckwheat—winter pea—triticale

In bracket green manure between two crops

FAO Food and Agriculture Organization

[a] Direct seeding under an intercrop/previous crop

Fig. 21.2 Home-made roller-crimper used at site A (France): steel bars were welded to a roll. The aim of the roller-crimper is to roll over and damage the cover crop before sowing the cash crop. (Source J. Peigné—ISARA Lyon)

Fig. 21.3 Direct sowing of maize on a rolled alfalfa cover crop at site A (France). (Source J. Peigné—ISARA Lyon)

compare the effects of three tillage practices on crop performance and soil properties: (1) ploughing (inversion to 30 cm depth), (2) two-layer plough (soil inversion to 15 cm and loosening to 30 cm), and (3) layer cultivator (soil loosening to 30 cm). Three long-term field experiments were set up in 1998 (experiment 1) and in 2000 (experiments 2 and 3) by the University of Hohenheim (near Stuttgart) to identify the effects of different tillage operations on weeds (Gruber and Claupein 2009). The University of Kassel established another trial in 2002 at the experimental organic farm of Frankenhausen (central Germany) on a silty loess soil to evaluate whether reducing the depth of ploughing would affect earthworm communities. Three treatments were compared: deep ploughing (30 cm), shallow ploughing (10 cm), and a ridge culture system (Metzke et al. 2007).

In Switzerland, an experiment was established in 2002 by the Research Institute of Organic Farming (FiBL) in Frick (northern Switzerland) on a clayey soil to evaluate the effects of tillage (reduced vs. conventional), fertilization (slurry vs. manure compost), and biodynamic preparations (with vs. without) on crop performance, weed and soil properties (Berner et al. 2008; Krauss et al. 2010; Sans et al. 2011).

Finally, in Rugballegard, Denmark, a field trial was established in 1997 by the Danish Institute of Agricultural Science on a sandy loam soil to evaluate the short-term effects of converting a ploughed soil to a non-inversion tillage system (soil loosening to 35 cm) on soil physical properties (Munkholm et al. 2001).

Due to the different effects on soil, weeds, and yields, conservation tillage is split into three categories: (1) deep tillage (soil loosening to 30 cm without soil inversion), (2) reduced tillage, which corresponds to all the techniques without soil inversion that still constitute soil tillage (i.e. chisel, layer cultivator), and (3) no tillage, which corresponds to all the techniques without soil disturbance (direct seeding). In all of the long-term experiments outlined above, the objectives were to assess the effects of ploughing versus conservation tillage systems (deep, reduced, or no tillage) on soil fertility, as well as on weed and crop development. A large range of measurements were implemented to answer to the main issues raised by no till in OF. Soil fertility was assessed through the analysis of organic carbon content (OC), biological activity (microbial biomass and activity, earthworm biomass and activity), and physical components (soil compaction and soil aggregate stability). Assessments of vegetation, density, crop yields and biomass, or diversity of weeds were also conducted.

21.4.2 Soil Organic Matter and Biological Activities

In French experiments (sites A and C), OC, microbial carbon content (C_{mic}), and the potential activity of OC and nitrogen mineralization (C_{min} and N_{min}) were measured on soils sampled in compacted and non-compacted zones in three soil layers (0–5, 5–15, 15–30 cm) in four treatments (Vian et al. 2009). After 1 year, the distribution of OC, C_{mic}, C_{min}, and N_{min} soil contents (in g kg–^{1} of soil) differed throughout the soil profile depending on the tillage system (Fig. 21.4) and is due to the burial depth of crop residues and the presence of compacted areas (Vian et al. 2009). In ploughed soil profiles, OC, C_{mic}, C_{min}, and N_{min} were homogeneously distributed throughout the tillage depth (5–30 cm for traditional ploughing; 0–20 cm for shallow ploughing). In reduced tillage and no tillage techniques, there was vertical stratification with a higher concentration of OC, C_{mic}, C_{min}, and N_{min} in the topsoil horizons (Fig. 21.4). These results confirm previous work showing that microbial biomass preferentially grows in the horizons where crop residues are buried (Andrade et al. 2003). Moreover, this distribution is modified by the level of compaction generated by the different cultivation techniques. Thus, microbial biomass decreased in compacted areas, especially in the cultivated soil layer, where crop residues were buried (Fig. 21.4). Vian et al. (2009) showed that no-till techniques contain more C_{mic}, C_{min}, and N_{min} stocks (in t ha–^{1}) than tillage techniques to 0–30 cm soil depth.

Berner et al. (2008) and Gadermaier et al. (2012), working with the Frick experiment (Switzerland), confirmed the French observations. The authors showed that soil OC increased in the 0–10 cm soil layer with reduced tillage during the

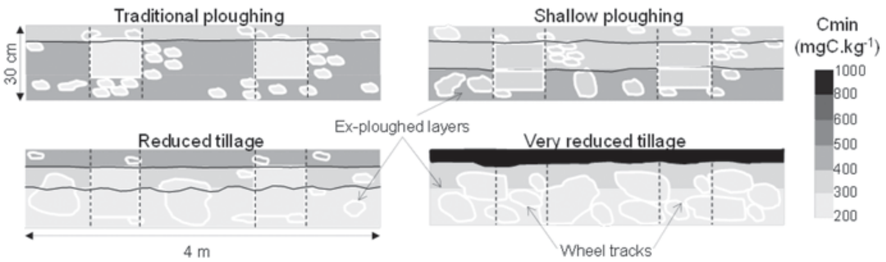


Fig. 21.4 Influence of crop residue distribution and soil structure on the distribution of the potential C mineralization rate (C_{min}) in the soil profile (0–30 cm) of the four tillage systems tested at site A (France). Compacted zones are outlined in white. (after Vian et al. 2009)

first 6 years of experimentation, whereas OC content remained stable in the ploughed treatment. Similarly, C_{mic} and dehydrogenase activity (DHA) increased by 37 and 57 %, respectively, with reduced tillage than with conventional tillage in the 0–10 cm soil layer. In the 10–20 cm soil layer, significant differences occurred between tillage systems for C_{mic} and microbial activities but not for OC content.

In Römmershein (southwestern Germany), globally soil respiration did not differ under reduced tillage or ploughing during 2 years of experiment (2000 and 2001) and two crops (Vakali et al. 2011). Higher soil respiration for reduced tillage was temporarily measured under barley (*Hordeum vulgare* L) in 2000 and 2001. These results were confirmed by Emmerling (2007), who observed that, after 10 years, reduced tillage had beneficial effects on microbial biomass and activity due to the increased quantity and quality of soil OM.

These results showed that conservation tillage tends to increase OC, microbial biomass, and its activities in the first 10–15 cm of the soil, which confirms previous results in conventional farming. These experiments also showed that microbial biomass and the potential activities of C and N mineralization are higher throughout the topsoil. These findings highlight that increased microbial biomass and their activities in the upper soil layers compensate for their decrease in deeper soil layers, due to the absence of fresh OM and more soil compaction. However, these results did not determine N nutrient availability for crops, only its potential availability. Soil microclimate at the soil surface (temperature and humidity) plays a crucial role in real N and C mineralization, and with conservation tillage, these soil conditions could decrease the mineralization rate (Peigné et al. 2007). For instance, in Frick (Switzerland), Berner et al. (2008) and Sans et al. (2011) observed a lack of available N in early spring in the reduced tillage treatment while N demand by cereals was high. Reduced tillage may retard N mineralization in early spring by reducing soil aeration.

In Frick (Switzerland), earthworm density or biomass did not differ between tillage treatments (Berner et al. 2008), confirmed the results found by Metzke et al. (2007) in Frankenhausen (middle Germany), who also observed less earthworms in ridge culture systems than in conventional tillage. This study concluded that reduced tillage depth alone is not sufficient to support earthworm communities.

In French experiments (sites A, B, and C), earthworm density and biomass were higher with no tillage (direct seeding under a cover crop; Peigné et al. 2009a), which is consistent with findings over the longer term under conventional agriculture (Jordan et al. 2004; Pfiffner and Luka 2007), and those of Johnson-Maynard et al. (2007) after 3 years' experimentation.

The development of earthworm populations in conservation systems over the years appears more correlated to the mixed effect of rotation, cover, and no tillage than solely no or reduced tillage. At site A in France—after 3 years of no tillage due to the presence of an alfalfa crop—ploughing and reduced tillage reduced earthworm biomass. Only direct seeding of maize (strict no tillage) in 2005 increased earthworm biomass, which is probably attributed to the live cover crop, a considerable food resource for earthworms. After destruction of this cover, much reduced tillage also resulted in a decline in earthworm biomass (Peigné et al. 2009a).

Conversely at site B, reduced tillage tended to increase earthworm biomass compared to the initial state of the earthworm population (before treatment differentiation). The field at site B was routinely ploughed before the start of the trial and was without a cover crop (Peigné et al. 2009a). Riley et al. (2008) observed similar results, highlighting the importance of rotation with a perennial legume to increase the earthworm population.

21.4.3 Soil Compaction and Soil Aggregate Stability

Studies by Munkholm et al. (2001) indicate that soil loosening at depth improved soil structure by reducing the plough pan during the first 2 years of conservation tillage. However, in the early stage of reduced tillage adoption, measurements of soil strength and friability indices in the topsoil indicated that the ploughed soil was more friable than conservation tillage soil (Munkholm et al. 2001). Indeed, conservation tillage equipment is less effective on soil loosening than the plough. In France, soil structure was measured by soil profile description (Roger-Estrade et al. 2004), bulk density and penetration resistance, and which increased compacted areas in the short term (2 years) and mid-term (5–6 years) of conservation tillage techniques (Vian et al. 2009; Peigné et al. 2009a, 2013). In both cases (Denmark and France), soils exhibited a low shrinking–swelling effect (silty and sandy soils). In these soils, and in the first years of adoption of conservation tillage, this technique tended to increase soil compaction in deeper soil layers compared to ploughing. Figure 21.5 shows increased compacted zones in the soil profile in the first 2 years of conversion from ploughing to reduced or much reduced tillage. However, it seems that after 5–6 years, earthworm activity and soil cracking helped roots pass though these compact zones (Peigné et al. 2013). More research is needed to draw conclusions on soil compaction with conservation tillage. For instance, in Frick, soil structure tended to improve with conservation tillage compared to ploughing in the first few centimetres of soil with a more favourable soil type (clayey soil; Berner et al. 2008).

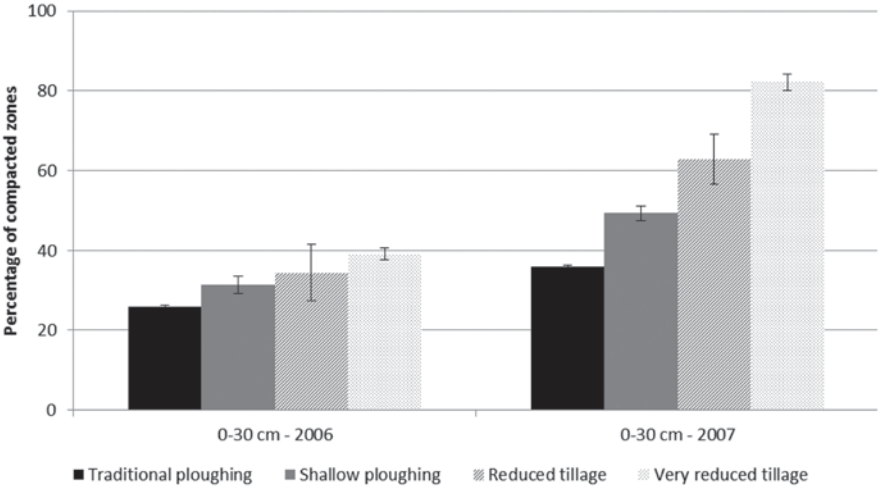


Fig. 21.5 Evolution of compacted zones in the soil profile during the first 2 years of tillage treatments at site A. (France; after Vian 2009)

After 5–8 years of treatment differentiation, Vakali et al. (2011) found that soil stability was higher with loosening cultivation (deep tillage) than with ploughing. Indeed, by turning the soil with a plough, more unstable aggregates are brought to the soil surface. The authors also drew connections with other soil properties: They suggested that the higher the soil aggregate stability, the higher the potential infiltration of water, gas exchange, and capacity of load-carrying. In addition, Krauss et al. (2010) reported that in dry conditions, topsoil offers better water retention under reduced tillage than under ploughing.

21.4.4 Weed Control

The main difficulty for conservation tillage in OF, as mentioned in many studies, is weed management (Peigné et al. 2007). Results are highly variable depending on conservation tillage techniques used, crop rotation, and climate.

Sans et al. (2011) observed that after 3 years of experiments in Frick (Switzerland), weed cover was two to three times higher in reduced tillage treatments than in ploughed treatments. Crop yields under reduced tillage were 14 and 8 % lower than under ploughed management for bread wheat (*Triticum aestivum* L.) and spelt (*Triticum spelta* L.), respectively. Also in Frick, Krauss et al. (2010) observed weed infestation two to three times higher with reduced tillage than with conventional tillage, but it was considered acceptable because no yield impact was observed. In a barley in Römmershein (southwestern Germany), shoot mass of the crop and weeds was lower and higher, respectively, with reduced tillage (Vakali et al. 2011). However, under rye (*Secale cereale*), there was no difference between tillage treatments.

In France, there was also a tendency for more weeds with reduced tillage compared to ploughing (Peigné et al. 2008, 2013). Consequently, weeds are controlled by intensive mechanical weeding (harrowing and hoeing), which can impact the soil structure. The practice can also offset positive effects of conservation tillage, when energy consumption requirements are considered.

Results were clearer in site A (France) with higher weed infestation under direct seeding of maize into a cover crop of alfalfa (*Medicago sativa)* compared to ploughing. In 2005 under direct seeding, weed biomass (dry matter) at harvest was about 4 t (Fig. 21.6). The cover crop under maize was heterogeneous. After using the roller, large parts of the plot under no tillage produced more dandelions (*Taraxacum* sp.) and white clover than the initial alfalfa (see Fig. 21.7). Such high infestations were not observed in 2008, which saw about 1.5 t/ha of weeds with direct seeding of soybean (*Glycine max)* into a rye cover crop. However, direct seeding still resulted in three times more weeds than ploughing (Fig. 21.6).

Research efforts for weed management under reduced tillage were initiated in Germany (Stuttgart; Gruber and Claupein 2009) with a study on different tillage intensities focusing on weed infestation in arable cropping systems. Results under reduced tillage, compared with ploughing, generally showed that with less soil disturbance came increased weed infestation. Further, this study pointed out that soil seed banks tend to be higher in conservation tillage. Gruber and Claupein (2009) also observed substantial increases in Canada thistle (*Cirsium arvense)* density, when the depth of primary tillage work was reduced (non-inversion tillage or shallow ploughing) and additional stubble tillage was omitted. After several years of reduced tillage, perennial weeds increased due to seed accumulation in the upper soil horizons and the lack of roots or rhizome disturbance. The authors proposed that weed management in OF must be generally integrated at a cropping system scale. Thus, crop rota-

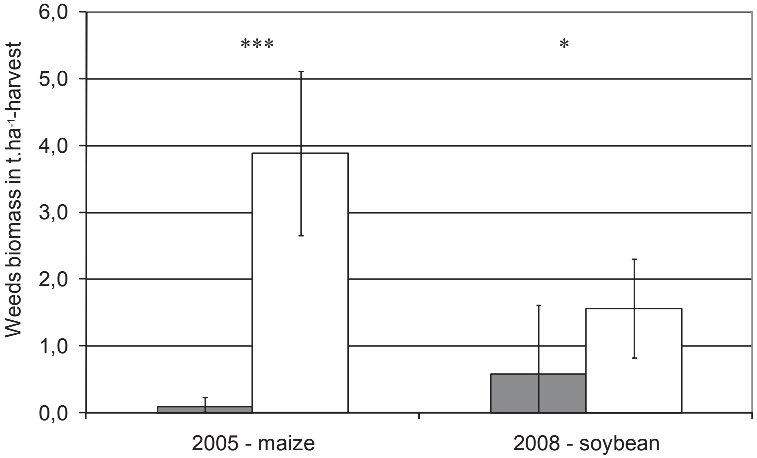


Fig. 21.6 Weed biomass (t DM ha–^{1}) in maize (2005) and soybean (2008) harvests with ploughing (*grey bar*) or no tillage (*white bar*) at site A (France; after Peigné et al. 2009b and unpublished data). ***ANOVA *p* value < 0.001 and *ANOVA *p* value < 0.05

Fig. 21.7 Direct seeding into a cover crop at site A (France). **a** Maize sown in alfalfa without dandelions—good emergence of maize but had crop growth problems compared to neighbouring ploughed plot, and **b** few maize plants emerged in the cover crop, which was infested with dandelions and clover

tion, alternating sowing seasons, perennial crops, and variety competitiveness must be considered in combination with conservation tillage practices in OF.

21.4.5 *Crop Yields*

In Frick (Switzerland), sunflower yield under reduced tillage was, on average, 5 % higher than under ploughing, even if there was double weed density in reduced tillage (Berner et al. 2008; Sans et al. 2011). These results may be explained by sunflower's late season need for N. Indeed, as reduced tillage retarded N mineralization in late spring, sunflower did not suffer from a lack of N. Regarding forage production, Krauss et al. (2010) reported that reduced tillage positively influenced grass clover and silage maize (*Zea mays)* yields. These results, obtained midway into the experiment (after 4–6 years), linked grass clover to better soil structure, increased soil moisture retention, and decreased water stress for the ley. For silage maize, higher yields were explained by better N supply with reduced tillage. Indeed, to remove the ley without inversion tillage, researchers began to clear grass clover in early autumn and sow a winter pea catch crop. This occurred only in this treatment and not in the ploughing treatment. This catch crop could partly explain the better N supply for silage maize under reduced tillage, as it was an excellent preceding crop. Results obtained in France (sites A, B, and C) for reduced tillage are less encouraging. Due to soil compaction and weed infestation, reduced tillage tended to lower crop performance (Peigné et al 2008, 2013). At all the sites, no yield reduction was observed for the first year of experiments. But over the long term, weeds and soil compaction impacted reduced tillage yields. This can be explained by wet spring seasons (difficulty controlling weeds) as well as an intensive crop rotation. The main differences between Switzerland and France were: (1) the soil type, with more clay and a better soil structure in Switzerland; and (2) the crop rotations, which were more intensive in French trials, with less frequency of leys.

For no tillage, yields tended to strongly decrease. At French site A in 2005, yields were 75 % lower with direct seeding of maize into a cover crop compared to ploughing (Fig. 21.8), but this difference was not observed in 2008. The yield decrease was due to: (1) no maize emergence in the area infested by dandelions and clover, and (2) a delay in maize emergence and growth in areas with less weeds (Fig. 21.7). Direct seeding of soybean into a rye cover crop resulted in 25 % lower yields than ploughing (Fig. 21.8). Direct seeding into a cover crop in OF has been widely studied in North America. In a review, Carr et al. (2012a) addressed the main issues for adopting 'no till' or 'zero tillage' with a cover crop. As in the French experiment, the main problem is weed control, perennial weeds in particular. To control cover crops and weeds before seeding, the timing of killing the cover crop by a mechanical method (roller-crimper) is fundamental. The cover crop must be destroyed at a late growth stage to obtain the thickest mulch possible and to prevent long-term damage. Altieri et al. (2008) had more conclusive results between direct sowing soybean into cover crops and ploughing. The yield reduction ranged from 5 to 10 % with direct sowing. In their trial in South America, the cover crop was rolled at the flowering stage, and was therefore more damaged than the cover crops in the experiments in Europe; the mulch at the soil surface was thick and the weeds were well controlled. In a study performed in Canada, Lefebvre et al. (2011) compared several treatments of direct sowing soybean in OF: without weed control, sown in a rolled rye cover crop (with a roller-crimper), and mechanical weed control. For a certain cultivars, they found that direct sowing of soybean in a rye cover gave better results than mechanical or no control of weeds, i.e. 2.67 t ha^{-1} (14 % water content) versus 2.29 and 1.76 t ha^{-1} (14 % water

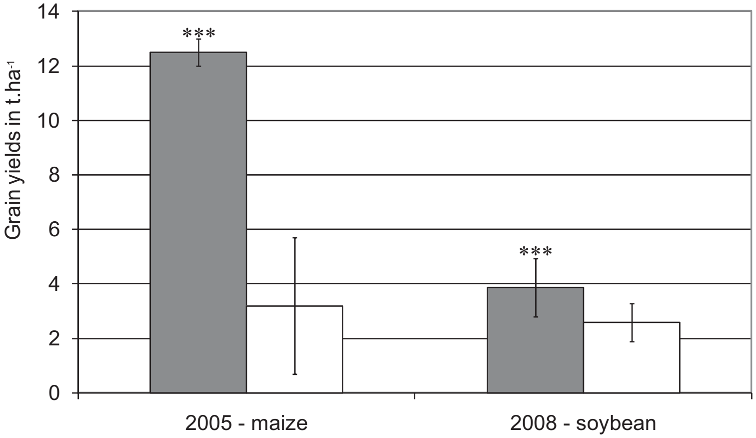


Fig. 21.8 Grain (at 15 % water content) yields (t ha^{-1}) of maize (2005) and soybean (2008) with ploughing (*grey bar*) or no tillage (*white bar*) at site A (France; after Peigné et al 2009b and Personnal data). ***ANOVA *p* value<↔0.001

content), respectively. This yield was close to that of direct sown soybean at site A in France (2.6 t ha^{-1} at 15 % water content).

21.5 Opportunities

21.5.1 New Equipment

Development of new equipment for the adoption of conservation tillage in OF is needed. As mentioned previously, weed control and soil preservation are key points for adopting these techniques in OF, and equipment should be adapted.

The roller-crimper associated with the direct seeder is promising for no tillage or zero tillage in OF. The roller-crimper has undergone continuous improvement in South and North America for the past 20 years, to improve not only the machines but also their potential in association with an efficient cash cover crop (Carr et al. 2012b; Mirsky et al. 2012; Reberg-Horton et al. 2012). In Europe, the use of the roller-crimper is not well developed and, of the few available reports, yields with this technique have not been satisfying (Peigné et al. 2009b). More research is needed for its adoption by organic farmers (Peigné et al. 2007). A new option for practising no tillage is strip till or zone till (Fig. 21.9), particularly for spring crops such as maize or soybean. Strip till consists of a tine, which works the soil at 15–20 cm depth, just below the seed line (Fig. 21.9). The soil is worked in a small part of the field, thus minimizing soil disturbance. The row can be mechani-

Fig. 21.9 Use of strip tillage where only seed line areas are tilled to a depth of 15–20 cm. In other parts of the field, the soil remains untilled with a permanent cover crop. (Photo courtesy of Arvalis Institut du Vegetal, France)

cally weed controlled to preserve favourable crop emergence. The inter-rows can be sown with a permanent cover crop to control weed development. Nowadays, however, no reference to such a system exists in OF, despite its promise. According to Luna et al. (2012), who refer to strip till as a 'hybrid system', strip tillage could solve weed problems in OF by integrating conventional and conservation tillage aspects. Indeed, strip tilling enables soil loosening for crop root development while maintaining soil fertility by reducing soil disturbance throughout the whole field.

Organic farmers also build new equipment on their own. In Germany, Alfred Wentz and his son, both organic farmers, stopped ploughing 30 years ago. Year by year, they built and adapted a machine called Eco-Dyn (http://www.eco-dyn.com/). The machine consists of a direct seeder associated with working utensils (tines, discs, and rollers). The main goal of the machine is to perform reduced tillage and sow at the same time. More organic farmers are modifying their own machines to adopt conservation tillage techniques in order to (1) minimize soil disturbance with reduced tillage systems and (2) control weeds. For instance, Eco-Dyn is fitted with duck-foot tines to scalp weeds or pasture roots at 10 cm depth.

Conservation tillage is based on no soil inversion. However, a new way of ploughing may interest organic farmers, who are not willing to completely stop ploughing. Traditionally, organic farmers plough their soil to 25–30 cm depth. New ploughs have been built to reduce the working depth, a practice known as shallow ploughing (Fig. 21.10). The main goal of shallow ploughing is to reduce the depth worked to 12–18 cm, depending on the machine. As the depth of soil worked decreases, the depth of fresh OM incorporation decreases, which limits soil OM diffusion throughout the soil profile. With this technique, the soil OM content at the soil surface tends to increase, thus limiting crusting and soil erosion. Shallow ploughs are often used for stubble tillage. The main benefit of shallow ploughing is weed control, and the same results as deep ploughing have been found in OF (Peigné et al. 2008). However, the soil is more disturbed than with reduced tillage, especially soil biological components.

Fig. 21.10 Shallow plough tested in at site A (France)—the plough is adapted to work at 18 cm depth, on-land and without skim coulters

21.5.2 Diffusion and Adoption of Conservation Tillage in Organic Farming

As mentioned in the introduction, CA has been widely studied under conventional conditions and has been increasingly adopted by farmers in Europe (Soane et al. 2012). This has not been the case for organic farmers. Long-time promoters of CA have expressed their differences with respect to OF. On one hand, organic farmers were suspicious and reluctant to adopt CA because of its herbicide use. On the other hand, 'conservation farmers' believed they preserved soil fertility better than organic farmers due to the intensive plough use by organic farmers (Goulet 2010). In some countries, there were clashes between farmers practising either CA or organic agriculture. Since the late 2000s, some promoters of conservation tillage have emphasized that organic agriculture and CA are actually complementary and convergent models. Simultaneously, some organic farmers are increasingly interested in CA techniques.

A survey based on semi-structured interviews with French organic and conservation farmers helped to understand the knowledge diffusion process and conservation tillage practices in OF (Fleury et al. 2014). Firstly, organic agriculture and CA remain distinct models with different values. For organic farmers, organic agriculture remains an alternative form of agriculture based on the prohibition of pesticides, and is ethically different from conventional farming. Consequently, OF is a community of practices with intensive internal exchanges of knowledge (Wenger 2005) both at local and regional levels. But, it has been observed that the exchanges concerning tillage practices are not yet delimited to an internal sphere. For about the past 10 years, a process of hybridization of crop management practices has been growing between OF and CA. These technical borrowings are related to different challenges: maintaining biological soil fertility and reducing tillage in organic agriculture versus reducing pesticide use in CA. Farmers facing these challenges are experimenting with new techniques on their farm and sharing experiences in their community, namely organic and conservation organizations. Organic and conservation farmers have been meeting more frequently and sharing common readings. For organic farmers, these exchanges with conservation farmers are a means to learn more about conservation tillage, the key point of discussion being the difficulties of weed control without tillage. The practical experience and know-how of conservation farmers helps organic farmers to gain confidence, some even testing new techniques such as reduced tillage on their farms. This process of conservation tillage diffusion in OF is equally, if not more so, a process involving collaboration between organic and conservation farmers (and agricultural advisors in some cases) than it is the result of institutional incentives and dissemination initiatives driven by research results.

21.6 Conclusions and Future Directions

The first results from studies on conservation tillage in OF are promising. The soil biological component, such as macroorganisms and microorganisms, improves with conservation tillage, and especially no tillage, when associated with cover crops. Nutrient availability and carbon stocks increase in the upper soil layers, but needs confirmation over the long term particularly in regard to the whole soil profile (down to 1.5 m). A negative aspect of conservation tillage in OF is soil compaction. Indeed, intensive machinery travel on soil sensitive to compaction induces soil compaction well below the upper soil layers. More long-term research is needed regarding the effect of soil macroorganisms such as earthworms on soil compaction.

In terms of weed and crop performance (crop yields), deep soil non-inversion tillage, such as subsoiling, presents similar results to ploughing. However, the effects of reduced tillage depend on soil, climate, crop rotation, and farmer practices. Research on weed control in no-tillage systems such as direct seeding is needed, particularly in regard to the design and adaptation of adequate equipment for organic farmers.

Much of the research has been done at experimental stations; however, farmer involvement is essential to develop conservation tillage in OF. Building upon this recognition, more research now uses participatory approaches to involve farmers from the beginning of the research process. As previously mentioned, organic and conservation farmers increasingly exchange knowledge and it is this hybridization of knowledge that should be incorporated into research. Efforts to design new cropping systems that take into account both farmer and researcher knowledge are in progress (Lefèvre et al. 2014). This work will help transfer innovative cropping systems, such as conservation tillage in OF, to real farms.

Acknowledgments French research was carried out within the framework of the TILMAN-ORG project (www.tilman-org.net), funded by CORE Organic II Funding Bodies, partners of the FP7 ERANet (www.coreorganic2.org). The French research was also part of the PEPITES project, funded by ANR (French Agency for Research).

References

Altieri MA, Lovato PM, Lana M, Bittencourt H (2008) Testing and scaling-up agroecologically based organic conservation tillage systems for family farmers in southern Brazil. In: Neuhoff D, Halberg N, Alfldi T, Lockeretz W, Thommen A, Rasmussen I, Hermansen J, Vaarst M, Lck L, Carporali F, Jensen Henning H, Migliorini P, Willer H (eds) Cultivating the future based on science. Proceedings of the 2nd scientific conference of the International Society of Organic Agriculture Research (ISOFAR) held at the 16th IFOAM Organic World Congress in Cooperation with the International Federation of Organic Agriculture Movements (IFOAM) and the Consorzio ModenaBio, Modena, 18–20 June 2008

Andrade DS, Colozzi-Filho A, Giller KE (2003) The soil microbial community and soil tillage. In: El Titi A (ed) Soil tillage in agroecosystems. CRC, LLC, pp 51–81

Baker JM, Ochsner TE, Venterea RT, Griffis TJ (2007) Tillage and soil carbon sequestration-What do we really know? Agric Ecosyst Environ 118(1–4):1–5

Berner A, Hildermann I, Fließbach A, Pfiffner L, Niggli U, Mäder P (2008) Crop yield and soil fertility response to reduced tillage under organic management. Soil Till Res 101(1–2):89–96

Birkhofer K, Bezemer TM, Bloem J, Bonkowski M, Christensen S, Dubois D et al (2008) Long-term organic farming fosters below and aboveground biota: implications for soil quality, biological control and productivity. Soil Biol Biochem 40(9):22–37

Blanco-Canqui H, Lal R (2007) Soil structure and organic carbon relationships following 10 years of wheat straw management in no-till. Soil Tillage Res 95(1–2):240–254

Bohlen PJ, Edwards WM, Edwards CA (1995) Earthworm community structure and diversity in experimental agricultural watersheds in Northeastern Ohio. The significance and regulation of soil biodiversity. Plant and soil 170:233–239

Carr PM, Mäder P, Creamer NG, Beeby JS (2012a) Overview and comparison tillage practices and organic farming in Europe and North America (Review). Renew Agric Food Syst 27(1):2–6

Carr PM, Anderson RL, Lawley YE, Miller PR, Zwinger SF (2012b) Organic zero-till in the northern US great plains region: opportunities and obstacles. Renew Agric Food Syst 27(1):12–20

Emmerling C (2007) Reduced and conservation tillage effects on soil ecological properties in an organic farming system. Biol Agric Hortic 24(4):363–377

Fleury P, Chazoule C, Peigné J (2014) Ruptures et transversalités entre agriculture biologique et agriculture de conservation. Écon Rurale 339–340:95–112 (French)

Flieβbach A, Mäder P (2000) Microbial biomass and size-density fractions differ between soils of organic and conventional agricultural systems. Soil Biol Biochem 32(6):757–768

Gadermaier F, Berner A, Fließbach A, Friedel JK, Mäder P (2012) Impact of reduced tillage on soil organic carbon and nutrient budgets under organic farming. Renew Agric Food Syst 27:68–80

Gál A, Vyn TJ, Michéli E, Kladivko EJ, McFee WW (2007) Soil carbon and nitrogen accumulation with long-term no-till versus moldboard ploughing overestimated with tilled-zone sampling depths. Soil Tillage Res 96(1–2):42–51

Gerhardt RA (1997) A comparative analysis of the effects of organic and conventional farming systems on soil structure. Biol Agric Hortic 14(2):139–157

Goulet F (2010) Nature et Ré-enchantement du monde. In: Hervieu Bertrand (ed), Mayer Nonna (ed), Muller Pierre (ed), Purseigle François (ed), Rémy Jacques (ed). Les mondes agricoles en politique: de la fin des paysans au retour de la question agricole. Paris: Presses de Sciences Po, p. 51–71

Gruber S, Claupein W (2009) Effect of tillage intensity on weed infestation in organic farming. Soil Tillage Res 105(1):104–111

Hole DG, Perkins AJ, Wilson JD, Alexander IH, Grice F, Evans AD (2005) Does organic farming benefit biodiversity? Biol Conserv 122(1):113–130

Holland JM (2004) The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agric Ecosyst Environ 103(1):1–25

Johnson-Maynard JL, Umiker KJ, Guy SO (2007) Earthworm dynamics and soil physical properties in the first three years of no-till management. Soil Tillage Res 94(2):338–345

Jordan D, Miles R, Hubbard V, Lorenz T (2004) Effect of management practices and cropping systems on earthworm abundance and microbial activity in Sanborn Field: a 115-year-old agricultural field. Pedobiologia 48(2):99–110

Kay BD, VandenBygaart AJ (2002) Conservation tillage and depth stratification of porosity and soil organic matter. Soil Tillage Res 66(2):107–118

Kladivko EJ (2001) Tillage systems and soil ecology. Soil Tillage Res 61(1–2):61–76

Krauss M, Berner A, Burger D, Wiemken A, Niggli U, Mäder P (2010) Reduced tillage in temperate organic farming: Implications for crop management and forage production. Soil Use Manag 26(1):12–20

Lefebvre M, Leblanc M, Gilbert PA, Estevez B, Grenier M, Belzile L (2011) Semis direct sur paillis de seigle roulé en régie biologique. Institut de recherche et de développement en agroenvironnement. IRDA inc. (French), Quebec: Canada

Lefèvre V, Capitaine M, Peigné J, Roger-Estrade J (2012) Soil conservation practices in organic farming : overview of French farmers' experiences and contribution to future cropping systems design. In Proceedings of the 10th European IFSA Symposium, Aarhus, 1–4 July 2012

Lefèvre V, Capitaine M, Peigné J, Roger-Estrade J (2014) Farmers and agronomists design new biological agricultural practices for organic cropping systems in France. Agron Sustain Dev 34:623–632

Luna JM, Mitchell JP, Shrestha A (2012) Conservation tillage for organic agriculture: evolution toward hybrid systems in the western USA. Renew Agric Food Syst 27(1):21–30

Mäder P, Berner A (2012) Development of reduced tillage systems in organic farming in Europe. Renew Agric Food Syst 27(1):7–11

Metzke M, Potthoff M, Quintern M, Heß J, Joergensen RG (2007) Effect of reduced tillage systems on earthworm communities in a 6-year organic rotation. Eur J Soil Biol 43(Suppl 1):S209–S215

Mirsky SB, Ryan MR, Curran WS, Teasdale JR, Maul J, Spargo JT et al (2012) Conservation tillage issues: cover crop-based organic rotational no-till grain production in the mid-Atlantic region, USA. Renew Agric Food Syst 27(1):31–40

Munkholm LJ, Schjonning P, Rasmussen KJ (2001) Non-inversion tillage effects on soil mechanical properties of a humid sandy loam. Soil Tillage Res 62(1–2):1–14

Peigné J, Ball B, Roger-Estrade J, David C (2007) Is conservation tillage suitable for organic farming? A review. Soil Use Manag 23(2):129–144

Peigné J, Aveline A, Cannavaciuolo M, Giteau JL, Gautronneau Y (2008) Soil tillage in organic farming: impacts of conservation tillage on soil fertility, weeds and crops. In: Neuhoff D, Halberg N, Alfldi T, Lockeretz W, Thommen A, Rasmussen I, Hermansen J, Vaarst M, Lck L, Carporali F, Jensen Henning H, Migliorini P, Willer H (eds) Cultivating the future based on science. Proceedings of the 2nd scientific conference of the International Society of Organic Agriculture Research (ISOFAR) held at the 16th IFOAM Organic World Congress in Cooperation with the International Federation of Organic Agriculture Movements (IFOAM) and the Consorzio ModenaBio, Modena, 18–20 June 2008

Peigné J, Cannavaciuolo M, Gautronneau Y, Aveline A, Giteau JL, Cluzeau D (2009a) Earthworm populations under different tillage systems in organic farming. Soil Tillage Res 104(2):207–214

Peigné J, Védie H, Demeusy J, Gerber M, Vian JF, Gautronneau Y, Cannavaccuiolo M, Aveline A, Giteau JL, Berry D (2009b) Techniques sans labour en agriculture biologique. Innov Agronom 4:23—32 (French)

Peigné J, Vian JF, Cannavacciuolo M, Lefevre V, Gautronneau Y, Boizard H (2013) Assessment of soil structure in the transition layer between topsoil and subsoil using the profil cultural method. Soil Tillage Res 127:13–25

Pelosi C, Capowiez Y, Caro G, Guernion M, Hedde M, Peigné J et al (2013) Reducing tillage in cultivated fields: a way to improve soil functional diversity. Appl Soil Ecol (Forthcoming), DOI: 10.1016/j.apsoil.2013.10.005

Pfiffner L, Luka H (2007) Earthworm populations in two low-input cereal farming systems. Appl Soil Ecol 37(3):184–191

Rasmussen KJ (1999) Impact of ploughless soil tillage on yield and soil quality: a Scandinavian review. Soil Tillage Res 53(1):3–14

Reberg-Horton CS, Grossman JM, Kornecki TS, Meijer AD, Price AJ, Place GT (2012) Utilizing cover crop mulches to reduce tillage in organic systems in the southeastern USA. Renew Agric Food Syst 27(1):41–48

Riley H, Pommeresche R, Eltun R, Hansen S, Korsaeth A (2008) Soil structure, organic matter and earthworm activity in a comparison of cropping systems with contrasting tillage, rotations, fertilizer levels and manure use. Agric Ecosyst Environ 124(3–4):275–284

Roger-Estrade J, Richard G, Caneill J, Boizard H, Coquet Y, Defossez P et al (2004) Morphological characterisation of soil structure in tilled fields: from a diagnosis method to the modelling of structural changes over time. Soil Tillage Res 79(1):33–49

Sans FX, Berner A, Armengot L, Mäder P (2011) Tillage effects on weed communities in an organic winter wheat-sunflower-spelt cropping sequence. Weed Res 51(4):413–441

Scullion J, Neale S, Philipps L (2002) Comparisons of earthworm populations and cast properties in conventional and organic arable rotations. Soil Use Manag 18:293–300

Shepherd M, Harrison R, Cuttle S, Johnson B, Shannon D, Gosling P et al (2000) Understanding soil fertility in organically farmed soils. In: UK Ministry of Agriculture, Fisheries and Food report

Soane BD, Ball BC, Arvidsson J, Basch G, Moreno F, Roger-Estrade J (2012) No-till in northern, western and south-western Europe: a review of problems and opportunities for crop production and the environment. Soil Tillage Res 118:66–87

Vakali C, Zaller JG, Köpke U (2011) Reduced tillage effects on soil properties and growth of cereals and associated weeds under organic farming. Soil Tillage Res 111(2):133–111

Vian JF (2009) Comparaison de différentes techniques de travail du sol en agriculture biologique: effet de la structure et de la localisation des résidus sur les microorganismes du sol et leurs activités de minéralisation du carbone et de l'azote. Dissertation. Institut des Sciences et Industries du Vivant et de l'Environnement (Agro Paris Tech) (French, Paris)

Vian JF, Peigne J, Chaussod R, Roger-Estrade J (2009) Effects of four tillage systems on soil structure and soil biomass in organic farming. Soil Use Manag 25(1):1–10

Watson CA, Atkinson D, Gosling P, Jackson LR, Rayns FW (2002) Managing soil fertility in organic farming systems. Soil Use Manag 18:239–247

Wenger E (2005) La théorie des communautés de pratique. Apprentissages, sens et identité. Les presses de l'université Laval, Québec

Wu J, Joergensen RG, Pommerening B, Chaussod R, Brookes PC (1990) Measurement of soil microbial biomass C by fumigation-extraction: an automated procedure. Soil Biol Biochem 22:1167–1169

Chapter 22
Conservation Agriculture and Climate Change

M. Pisante, F. Stagnari, M. Acutis, M. Bindi, L. Brilli,
V. Di Stefano and M. Carozzi

Abstract This chapter review aims at developing a clear understanding of the impacts and benefits of conservation agriculture (CA) with respect to climate change, and examining if there are any misleading findings at present in the scientific literature. Most of the world's agricultural soils have been depleted of organic matter and soil health over the years under tillage-based agriculture (TA), compared with their state under natural vegetation. This degradation process can be reversed and this chapter identifies the conditions that can lead to increase in soil organic matter content and improvement in soil health under CA practices which involve minimum soil disturbance, maintenance of soil cover, and crop diversity. The chapter also discusses the need to refer to specific carbon pools when addressing carbon sequestration, as each carbon category has a different turnover rate. With respect to greenhouse gas emissions, sustainable agricultural systems based on CA principles are described which result in lower emissions from farm operations as well as from machinery manufacturing processes, and that also help to reduce fertilizer use. This chapter describes that terrestrial carbon sequestration efficiently be achieved by changing the management of agricultural lands from high soil disturbance, as TA practices to low disturbance, as CA practices, and by adopting effective nitrogen management practices to provide a positive nitrogen balance for carbon sequestration. However, full advantages of CA in terms of carbon sequestration can usually be observed only in the medium to longer term when CA practices and associated carbon sequestration processes in the soil are well established.

M. Pisante (✉) · F. Stagnari
Agronomy and Crop Sciences Research and Education Center—Via C.R.Lerici,
University of Teramo, 1–64023 Mosciano S.Angelo, Italy
e-mail: mpisante@unite.it

M. Acutis
Department of Agricultural and Environmental Sciences—Production, Landscape,
Agroenergy—Via G. Celoria, University of Milano, 2–20133 Milano, Italy

M. Bindi · L. Brilli · V. D. Stefano
Department of Agri-food Production and Environmental Sciences,
University of Florence -Piazzale delle Cascine, 18–50144 Firenze, Italy

M. Carozzi
INRA, AgroParisTech, UMR 1091 Environnement et Grandes Cultures,
rue de la ferme, 78850 Thiverval-Grignon, France

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_22

Keywords Farm machinery · Greenhouse gas emissions · Soil health · Tillage-based agriculture

22.1 Introduction

Agronomy management in agricultural landscapes should deploy production practices in harmony with soil-mediated ecosystem functions in order to deliver a broad range of ecosystem services (Kassam et al. 2013). Conventional agriculture is tillage-based in industrialized as well as developing countries and relies, as a key operation for seedbed preparation, on mechanical soil tillage with no organic mulch cover. It is generally considered to speed up the loss of soil organic matter (SOM) by increasing its mineralization and through soil loss by erosion. In addition, tillage is a high energy-consuming operation that uses large amounts of fossil fuel per hectare in mechanized systems. In contrast, conservation agriculture (CA) is an agroecological approach to resource-conserving agricultural production that complies with three practical principles, namely (1) minimum mechanical soil disturbance (with no-till and direct seeding), (2) maintenance of permanent organic soil cover (with crops, cover crops, and/or crop residues), and (3) species diversification through crop rotation and association (involving annual and/or perennial crops including tree and pasture crops) FAO (2012). CA facilitates good agronomy such as timely operations, improves overall land husbandry for rainfed and irrigated production, and is complemented by other good practices such as the use of quality seeds and integrated pest management (Pisante et al. 2012).

Anthropogenic climate change (i.e., that resulting from human activities) is probably the most serious environmental challenge facing us today. Human activities contribute significantly to increased concentrations of atmospheric greenhouse gases (GHGs), which in turn alter the way in which thermal radiation is absorbed by the planet and reradiated, changing global temperatures, and climatic patterns. As a consequence, we are faced with two parallel imperatives in order to deal with what could be a very damaging situation:

- Climate change adaptation: we must make changes to the way we do things to ensure that the ecosystem services upon which we rely on are sustained as conditions change.
- Climate change mitigation: the emission of GHGs must be reduced and the sequestration of atmospheric carbon increased (removal from the atmosphere to soil and vegetative stores).

The combined environmental benefits of CA at the farm and landscape level can contribute to global environmental conservation and provide a low-cost option to help offset emissions of the main GHGs. This chapter tackles CA and climate change as well as what solutions are being implemented in different parts of the world for an efficiently sustainable farming and landscape management.

22.2 CA and Climate Change

22.2.1 Impacts of Climate Change

The conclusions of the recent Working Group I contribution to the AR5-IPCC (IPCC 2013) confirmed that human activity has played a primary role in the observed global warming since the mid-nineteenth century, and indicated that future increases in GHG concentration may further increase global mean surface temperature and amplify changes in precipitation patterns and amounts. Proof of these changes has been widely observed through several instrumental data on both local and global scales. According to the latest IPCC report (IPCC 2013), the globally averaged combined land and ocean surface temperature data, as calculated by a linear trend, show a warming of 0.85 °C from 1880 to 2012. This increase was observed mostly since 1950.

Moreover, on a global scale, several changes in the frequency and intensity of daily temperature extremes have been observed since the mid-twentieth century. In particular, averaged maximum and minimum temperatures over land have both increased by in excess of 0.1 °C per decade. Significant multi-decadal variability was highlighted, including a recent period (1997–2004) of no change. In addition, a significant increase in daily minimum temperature rather than maximum has been observed (Alexander et al. 2006; IPCC 2013).

Global mean precipitation has increased annually by about 2% from 1900 to 1998 (Dai et al. 1997; Hulme et al. 1998) which corresponds to approximately 1.1 mm per decade (IPCC 2007). The precipitation trend varied worldwide, with higher increases in specific areas (from +7 to +12%, between 30 and 85°N) and less in others (+2% between 0 and 55°S; IPCC 2007). In addition, a considerable decrease in snowfall events has occurred. In particular *in situ* observations showed significant reductions in the extent of snow cover over the past 90 years particularly in June, when the average extent of snow cover decreased by 53 % (40–66 %) from 1967 to 2012 (IPCC 2013).

Recent years have been also characterized by a large number of extreme episodes as heat waves, cold spells, and floods. Globally, while cold spells decreased, heat waves significantly increased (Alexander et al. 2006). In particular, a significant reduction in cold spells was observed over central and northern Russia, parts of China and northern Canada, while warm spells increased over central and eastern USA, Canada, and parts of Europe and Russia (Alexander et al. 2006).

Looking at climate projections, simulations developed for IPCC's Fifth Assessment Report (AR5) projected increases in mean surface temperature for the end of the twenty-first century is likely to exceed 1.5 °C relative to 1850–1900. More specifically, this projected increase is likely to range from 0.3 to 4.8 °C depending on the new Representative Concentration Pathways (RCPs) scenarios. However, warming above 4 °C by 2081–2100 is unlikely in almost all RCPs scenarios. It is also virtually certain that many areas will be characterized by an increase in hot temperature extremes and a decrease in cold temperature extremes as global mean temperatures increase.

The AR5 also confirmed an increase in global mean precipitation with increasing global mean surface temperature. According to the four RCPs scenarios, this increase is likely to range from 0.5 to 4 % $°C^{-1}$ at the end of the twenty-first century. Generally, the pattern of change indicates that high latitudes and moist midlatitude regions are likely to experience more precipitation. Conversely, many midlatitude and subtropical arid and semiarid regions are likely to experience less precipitation by the end of this century. The latest IPCC report (IPCC 2013) also indicated an increase in extreme precipitation events in terms of intensity and frequency, especially over most midlatitudes and wet tropical regions.

These changes in climate regimes may have severe consequences especially in sectors like agriculture, where the lifecycle of crops is mainly determined by climate conditions. Therefore, changes in temperature and precipitation trends can bring shifts in phenology, yield changes, modification of crop physiology, and resilience (Parmesan 2006; IPCC 2007; Cleland et al. 2007; Zhao and Running 2010, Olesen et al. 2011).

Expected increases in temperature can lead to positive or negative impacts on crop growth and yield depending on several factors (i.e., region, crop type, etc.). Generally, at high and middle latitudes, global warming is expected to increase the length of the growing season especially with the advance of spring sowing. The lengthening of the growing season is expected to increase crop growth and productivity, thus resulting in higher crop yields (Easterling and Apps 2005). In particular, for countries at latitudes > 60°N, advances in sowing time are estimated to proceed very rapidly (Peltonen-Sainio et al. 2009; Rötter et al. 2011). Similarly, Olesen et al. (2012) indicated an advance of spring cereal sowing from 1 to 3 weeks by 2040. Moreover, warmer climate conditions are expected to increase potential cultivated areas of commonly grown major and/or minor crops, especially above their current northern limits for cultivation (Peltonen-Sainio et al. 2009). In particular, crops with higher thermal need (e.g., soybean and sunflower) are expected to move towards northern areas (Harrison et al. 1995; Bindi et al. 1996; Moriondo et al. 2010; Bindi and Olesen 2011). These crops, however, may encounter some limitations when adapting their photoperiod to different summer light conditions. Conversely, warmer conditions may be detrimental for crop growth and productivity over southern regions. In these areas, the temperature increase may result in faster physiological development, thus shortening the growing season and consequently the time for biomass accumulation (e.g. Lobell and Field 2007; Battisti and Naylor 2009; Giannakopoulos et al. 2009; Supit et al. 2010; Confalonieri et al. 2012).

The negative effect of higher temperatures on crop growth and productivity may be counterbalanced by the higher atmospheric CO_2 concentration, which is expected to increase crop productivity through a higher photosynthetic rate (Kimball et al. 2002; Ainsworth and Long 2005; Qaderi and Reid 2005; Franzaring et al. 2008). The benefit of higher CO_2 concentration is mainly expected for C3 species (i.e., almost all cereals and legumes, etc.), compared with C4 species (e.g., maize, sorghum, sugarcane, etc.; Kimball et al. 2002; Ainsworth and Long 2005; Southworth et al. 2000; Yano et al. 2007). Elevated atmospheric CO_2 concentrations are expected to reduce the vulnerability of pasture and forage production to climate variability and increase crop roots yields (Farrar 1996; Soussana and Lüschert 2007).

Nevertheless, increases in CO_2 may be insufficient to completely recover yield losses due to higher temperatures. Tubiello et al. (2007) suggested that in the most vulnerable areas such as the Mediterranean basin the benefit offered by higher CO_2 concentration might be nullified if temperatures increase by about 2 °C.

Besides temperature and the CO_2 concentration, crop growth and productivity are also determined by water availability; therefore, changes in precipitation trends (total amount, frequency, and intensity) are expected to have devastating effects on agricultural systems in many regions. For instance, in the Mediterranean basin, the expected decrease in precipitation by up to 20 % (Del Río et al. 2011) coupled with increased rainfall frequency and intensity may lead to prolonged water deficit. This condition may be extremely harmful during the most sensitive growth phases (i.e., flowering, pollination, and grain filling), especially if coupled with the expected increase in evaporation rate, which can lead to negative consequences such as the complete failure of potential yield. Furthermore, crop systems may suffer higher competition with other plants (i.e., weeds, trees, etc.) for freshwater availability, while the expected increase in evaporation rate will also contribute to increased soil salinization risk, preventing cultivation of highly sensitive crops (e.g., vegetables, fodder, root, and tuber crops).

Finally, further increases in extreme events (i.e., drought and heat stress) are expected to be detrimental for cropping systems. Drought affects yields by reducing grain number and the amount of dry matter produced during flowering, or decreasing grain number and size through the reduction and limitation of ovule function and nutrient supply during the reproductive stage (Wheeler et al. 1996; Prasad and Staggenborg 2008). Conversely, heat stress influences seed-filling duration, resulting in smaller seeds and lower yields (Prasad and Staggenborg 2008). Although these events can occur independently, their combined impact are the most detrimental for crop systems affecting almost all plant physiological processes (i.e., growth, productivity, area expansion, number and final size of leaves, photosynthesis, etc.; Jagtap et al. 1998; Jiang and Huang 2001; Alves and Setter 2004; Rizhsky et al. 2004; Prasad et al. 2006a, b). These observed and predicted changes in climate and, in turn, crop systems have raised further concern about how to reduce, or at least limit, further impacts over the next decades (IPCC 2007). In order to deal with the evolution of these changes, adaptation and mitigation strategies may be applied.

Adaptation strategies are aimed at minimizing the consequences of climate change and variability on crop systems. These strategies tackle the effects of climate change through policies, planning, and measures that are efficient in the short term by maintaining suitable yields. Adaptation options need both global and local coordination; however, they can be independently developed and applied by individual farmers.

Conversely, mitigation strategies aim to reduce or stabilize GHG emissions from anthropogenic activities. They constitute an economic benefit by reducing the impacts of climate change and its consequent costs. These strategies deal with the causes of climate change through a long-term activity, which should be coordinated at a global scale and involve several countries and institutions. Among the agricultural adaptation and mitigation strategies that can be combined to reduce climate change impacts, CA may represent a good option to obtain sustainable crop production and cope with climate change.

22.2.2 Adaptation

CA systems tend to offer more climate change adaptation benefits than conventional farming systems. Most of these benefits are related to increasing both soil fertility and water conservation. The application of CA principles should produce changes in soil properties and physical, chemical, and biological processes, thus enhancing water supply and soil quality (Palm et al. 2013). These improvements are fundamental for minimizing yield variability and maintaining suitable productivity, especially under climate change conditions.

According to several studies (Stockfisch et al. 1999; Tebrügge and Düring 1999; Horáček et al. 2001), both reduced tillage (RT) and no-tillage (NT)—by modifying biological activity, topsoil physical properties, and soil erosion (Dennis et al. 1994; Balabane et al. 2005; Riley et al. 2005)—allow considerable accumulation of SOM on topsoil as well as carbon vertical stratification (Hernanz et al. 2002; Moreno et al. 2006), thus resulting in improved soil fertility and, in turn, higher productivity. Moreover, RT and NT can also contribute to reduce soil erosion that is widely accepted as detrimental for crop productivity. According to Tebrügge and Düring (1999) and Hernanz et al. (2002), these practices can improve the stability of soil aggregates and avoid soil surface sealing. This change in soil structure improves soil fertility and, as a consequence, the crop's productivity efficiency.

Permanent soil organic cover is another main principle of CA. While RT and NT can limit water infiltration in soil due to surface crust formation, the presence of residues on the soil surface can increase water storage (Lampurlanés and Cantero-Martínez 2006). Moreover, cover crops can also avoid runoff by reducing the overland flow velocity, thus improving soil structure (Sudhishri et al. 2008; Dass et al. 2010). The improved soil structure and increased water availability is mainly due to the increased bio-pores, which should maximize the effect of rainfall and recharge groundwater, and therefore reducing the impacts of drought (Wuest 2001; Herrero et al. 2001; Akbolat et al. 2009; Ben Moussa-Machraoui et al. 2010). Therefore, permanent soil organic cover is a fundamental strategy for limiting expected yield losses under climate change, especially in dry areas.

Despite the role of cover crops being considered fundamental for erosion mitigation, many studies (Friebe and Henke 1991; Puget et al. 1995; Frielinghaus 2002; Balabane et al. 2005) concur that there are even further benefits when soil cover is coupled with RT or NT. This combination may increase aggregate stability and soil water infiltration rate, which are closely linked to SOM, soil organic carbon (SOC), and earthworm activity. Therefore, the coupling between soil cover and RT or NT is expected to be fundamental, especially over those regions where climate change results to be very detrimental for crop growth. In particular, for Mediterranean areas, several studies on annual and perennial crops suggested that the combined effect of minimum soil disturbance and soil cover seems to reduce both water and wind erosion but also increase precipitation storage (De Alba et al. 2001; López et al. 2001; Gómez et al. 2005; López and Arrúe 2005; De la Rosa et al. 2005; Cantero-Martinez et al. 2007).

Even diversification of crop species and rotations may be functional as adaptation strategies to cope with climate change. In particular, the role of legumes is expected to gain more importance due to the biological nitrogen fixation process, an efficient way to supply large amounts of nitrogen to the soil and to build SOM.

22.2.3 Mitigation

According to several studies (i.e., Lal et al. 2007; FAO 2011; Kassam et al. 2009), the application of CA over wide areas may have the potential to slow/reverse the rate of emissions and enhance the sinks of CO_2 and other GHG by agriculture. This was confirmed by Smith and Olesen (2010) who found that the proper application of the main CA pillars can contribute to reduce GHG emissions particularly through improved nitrogen use efficiencies and enhanced soil carbon storage. In particular, a study carried out by Baker et al. (2007) estimated that the global conversion of all croplands to conservation tillage could sequester 25 Gt C over the next 50 years.

In regard to minimum soil disturbances (i.e., RT and NT), both practices can contribute to reducing GHG emissions by reducing SOM oxidation into CO_2, which increases under conventional tillage (FAO 2011). However, the C sink response varies under both RT and NT depending on the area considered (Eagle et al. 2011). RT and NT can increase soil C sequestration by improving whole soil structure. In particular, increasing the number and quality of soil aggregates coupled with less soil compaction reduces CO_2 losses from soil, thus enhancing the passive C pools in soil. Moreover, as an indirect consequence especially of NT, a strong reduction in CO_2 emissions can result from lower fuel energy inputs due to less machinery use (FAO 2008).

In addition, permanent soil organic cover is useful for increasing long-term carbon sequestration processes (West and Post 2002). Improved soil structure will contribute to reduced CO_2 fluxes from soil. For instance, soil organic cover can reduce the risk of erosion episodes and limit C losses for soil respiration through the reduction of the impact of rain drops with high energy during intense rainfall events. Soil C storage can increase due to the presence of abundant root biomass. This was confirmed by Kassam et al. (2009) who identified roots as the main source of CO_2 sequestration due to their capacity to partially stock C above- and belowground as a resistant SOM pool.

Permanent soil organic cover can also limit GHG emissions indirectly. First, it can decrease CO_2 emissions through increased inter-species competition. This reduces the presence of invasive species and, in turn, CO_2 emissions due to less use of machinery for weed treatments. Second, permanent soil organic cover helps maintain high nitrogen levels close to roots, thus lower fertilization requirements and, in turn, N emissions.

Finally, the diversification of crop species and rotation should enhance SOC concentration in soil (Gregorich et al. 2001), especially when the soil nitrogen balance is positive (Bayer et al. 2000a, b). In this context, the ability of legumes to provide sufficient N supply can increase C stock in soil, thus increasing atmospheric C sequestration. The role of mineral N as fertilizer in SOC improvement was confirmed in several studies (Mrabet et al. 2001; Baker et al. 2007; Mrabet 2008; López-Fando et al. 2007; Akbolat et al. 2009; López-Bellido et al. 2010). In addition, legumes increase soil N content, thus reducing the need to apply energy inputs such as fertilizer.

22.3 CA for Carbon Storage in Cropland

22.3.1 SOC Accumulation

SOC constitutes on average about 58 % SOM. Several SOM pools can be distinguished in the soil on the basis of size, state of decomposition, and chemical and physical properties. A labile pool, also known as the active pool, is the least decomposed organic matter smaller than 2 mm but larger than 0.25 mm. It consists mainly of young SOM (such as plant debris), is partially protected in macroaggregates, characterized by a rapid turnover or transformation, sensitive to land and soil management and environmental conditions. It consequently plays an important role in short-term carbon and nitrogen cycling in terrestrial ecosystems and can be used as a sensitive indicator of short- and medium-term changes in soil carbon in response to management practices (Chan 1997; Whitbread et al. 1998).

The pool of SOM, smaller than 0.25 mm and larger than 0.053 mm (250–253 μm), is a labile, insoluble intermediate in the SOM continuum from fresh organic materials to humified SOC, ranging from recently added plant and animal debris to partially decomposed organic material. The stable pool, the recalcitrant SOM, contains particles less than 0.053 mm (< 53 μm). The organic matter has reached the highest level of transformation and is incorporated into aggregates, where its further decomposition is protected. It holds moisture, retains cations for plant use, and acts as a recalcitrant binding agent preventing nutrients and soil components from being lost through leaching.

Several factors which determine the soil carbon budget are influenced by land management practices; in this context, the reasons for the positive influence of CA in SOC accumulation is related to the permanent and total protection of the soil through species diversity, a similar pattern to that of the most stable natural ecosystems. These conditions are inherent in CA principles, i.e., minimum mechanical soil disturbance, permanent soil organic cover, and species diversification. The permanent presence of abundant, undisturbed (above- and belowground) biomass fosters the buildup of new SOC (Stagnari et al. 2009) and carbon losses from decomposition are reduced by SOC inclusion within soil aggregates, as enhanced by the low soil disturbance (Table 22.1; de Moraes Sà et al. 2001).

With respect to the first principle of CA, SOC accumulation is a reversible process and any short-term disturbance, in a system which aims to improve carbon

Table 22.1 SOC accumulation in deeper soil layers under the CA management system

Location	Experiment duration	Results	Author
USA, north	22 years	The carbon stock under CA to a depth of 122 cm is 10.6 t ha^{-1} greater than that under TA	Doran et al. 1998
Brazil, south	13 years	Where complex rotations are adopted, soil carbon stocks under CA are approximately 17 t ha^{-1} higher than under TA, and that 46–68 % of carbon gains occurs at 30–85 cm depth	Sisti et al. 2004
Brazil, south	17 years	Samplings to 107.5 cm depth in an Acrisol demonstrate the significant potential of legume crops and nitrogen fertilization under CA to improve SOC stocks: the average carbon sequestration rate of legume-based cropping systems (with N-fertilizer) in the whole 0–107.5 cm layer was 1.42 t ha^{-1} y^{-1} when considering the soil profile down to 100 cm depth	Diekow et al. 2005
Brazil, south	15–26 years	The experiments on free-draining Ferralsols under rotations containing intercropped or cover-crop legumes show annual SOC accumulation rates of between 0.04 and 0.88 t ha^{-1} to 30 cm and from 0.48 to 1.53 t ha^{-1} y^{-1} when considering the soil profile down to 100 cm depth	Boddey et al. 2009
Brazil, south	13 years	When green-manure cover crops are part of the rotation soil carbon stocks were approximately 17 t ha^{-1} higher under CA than under TA	Sisti et al. 2004
USA, Indiana	28 years	10 t ha^{-1} greater SOC content under CA than in moldboard plowed trials at 0–100 cm depth in a dark-colored Chalmers silty clay loam in Indiana	Gál et al. 2007
Australia		Higher SOC cncentrations at 230 cm depth in Vertisols when compared with other soil types in Australia	Knowles and Singh 2003

CA conservation agriculture, *TA* tillage-based agriculture, *SOC* soil organic carbon

status as a long-term management tool, will not achieve significant improvement in SOC accrual (Jarecki and Lal 2003; Al-Kaisi 2008). The formation of stable microaggregates within macroaggregates is inhibited under tillage-based agriculture (TA; Six et al. 1998). Even with a single tillage event, sequestered soil carbon and years of soil restoration may be lost, and the damage to soil life is considerable (Grandy et al. 2006). In general, the mixing of litter in tilled soils favors bacteria (hence quick degradation processes), while the higher presence of fungi in undisturbed systems like CA (Beare et al. 1992, 1993; Frey et al. 1999; Guggenberger et al. 1999; Drijber et al. 2000) is responsible for a buildup of soil carbon in the form of polymers of

Table 22.2 Percentage of carbon in the crop residues released from the soil after different treatments (Reicosky 1997)

Tillage practice	Percentage of carbon in the crop residues released as CO_2
Moldboard plow	134
Moldboard plow and disc harrow	70
Disc harrow	58
Chisel plow	54
Sod seeding	27

Table 22.3 Carbon costs of the variables that intervene in the CA and the TA systems. (Smith et al. 1998; Tebrügge 2000; FAO 2001, 2008, 2009)

Variables	Cost of the variable under CA as compared to TA
Fuel consumption per unit area output	35–80 % less
Number of passes	50–54 % less
Size of machinery	50 % lower power requirement
Depreciation rate of machinery	Two to three times lower (i.e., two to three times longer lifetime)

melanin and chitin, which are relatively stable and resist degradation (Stahl et al. 1999; Bailey et al. 2002). Beyond its effect on the oxidative breakdown of SOM through mineralization, tillage has a direct effect on CO_2 exchange between the soil and atmosphere. The amount of CO_2 lost is directly correlated to the disturbed soil volume; consequently plowing, by disturbing the greatest soil volume, produces the maximum CO_2 flux, while NT causes the least CO_2 loss (Reicosky and Lindstrom 1993, Reicosky et al. 1995; Reicosky 1997, 1998; Table 22.2). In addition, plowing is an energy-intensive process: On average, tillage agriculture uses up to 80 % more energy (fuels) than CA (Table 22.3). Studies have also identified tillage-induced soil erosion as the major cause of severe soil carbon loss and soil translocation on convex upper slope positions of cultivated, upland landscapes (Lobb et al. 1995; Lobb and Lindstrom 1999; Reicosky et al. 2005).

The amount of SOC is limited by the availability of sufficient plant residue. In conventional agricultural systems, aboveground production is removed (harvested or used as livestock feed) or burned, leaving only root biomass for incorporation into SOM. Sometimes above- and belowground inputs are mechanically mixed (e.g., by disking or chiseling) into the soil with the residues rapidly decaying (Magdoff and Weil 2004). Such decay of SOM depends on the composition of the material: Readily decomposable carbon (e.g., low C/N ratio residues or liquid manure) generally induces a priming effect and increases CO_2 emissions. The composition of residues not mixed into the soil does not affect the decay of accumulated SOM (Chadwick et al. 1998; Flessa and Beese 2000; Kuzyakov et al. 2000; Chantigny et al. 2001; Bol et al. 2003; Fontaine et al. 2004; Sisti et al. 2004; Fontaine 2007). In no-tilled soils over long periods, SOM decomposition on the soil surface is reduced and increasing active fractions of SOM are observed (Franzluebbers et al. 1995a, b; Stockfisch et al. 1999; Tebrügge and During 1999; Horáček et al. 2001). The accumulation of SOM in surface layers influences carbon vertical stratification (Hernanz et al. 2002; Moreno et al. 2006), water infiltration, erosion resistance, and nutrient availability.

There is also clear evidence that species diversification, the third pillar of CA, positively influences SOC storage. Indeed, some authors found negative SOC accumulation rates under repeated monocropping in conventional systems (Angers et al. 1997; Wanniarachchi et al. 1999, VandenBygaart et al. 2003). Changing from monocropping to a multicrop rotation positively influences SOC concentration. Several studies comparing SOC concentration under multicropping with monocropping systems support this theory (Havlin et al. 1990; Entry et al. 1996; Mitchell et al. 1996; Robertson et al. 1994; Robinson et al. 1996; Buyanovsky and Wagner 1998; Gregorich et al. 2001; Lopez-Fando and Pardo 2001). In addition, soil type and climatic conditions are important variables which can strongly modify the effects of cropping pattern on SOC (VandenBygaart et al. 2003). Each type of rotation has a different potential to induce carbon sequestration. Generally, carbon accumulates when the nitrogen balance of the crop rotation is positive (Sidiras and Pavan 1985; Bayer and Mielniczuck 1997; Boddey et al. 1997; Alves et al. 2002, 2003, 2006; Sisti et al. 2004; Bayer and Bertol 1999; de Maria et al. 1999; Amado et al. 1999, 2001; Bayer et al. 2000a, b). Negative SOC accumulation rates under CA are associated with specific rotations, i.e., with fallow-, barley- and soybean-based rotations. In any case, fallow-based rotations should not be associated with the concept of CA (Black and Tanaka 1997; VandenBygaart et al. 2003; Hernanz et al. 2009; López-Bellido et al. 2010). A barley–wheat–soybean rotation does not seem to allow SOC accumulation (Angers et al. 1997). Barley, as a versatile species, is often cultivated, where growing conditions (e.g., climate and soil fertility) are most difficult for cereal crops as well as for SOC accumulation. Further negative SOC accumulation rates under CA were observed in a maize–wheat–soybean rotation (Yang and Kay 2001; VandenBygaart et al. 2002). Including soybean in the rotation does not appear sufficient to enhance SOC accumulation: Most of the fixed nitrogen was exported with the grain (Sisti et al. 2004) and, while its residues may improve nitrogen availability, they decomposed very quickly, returning insufficient biomass to the soil.

Agricultural systems such as CA that rely on permanent organic soil cover and NT to maintain crop residues on the surface layer lead to superficial SOC accumulation, and offer potential benefits in controlling some negative environmental effects traditionally associated with agroecosystems.

22.3.2 Soil Biodiversity

The positive impact of CA is not restricted to SOC accumulation, but more generally it induces enhancements in terms of soil quality, i.e., the capacity of the soil to function within ecosystem boundaries to sustain biological productivity, to maintain environmental quality, and to promote plant and animal health (Doran and Parkin

1994). One fundamental aspect of soil quality is “biodiversity,” which had not been appropriately considered until some years ago. Soil biodiversity is normally described as the variability of living forms—soil fauna, flora, vertebrates, birds, and mammals—within a habitat or management system of a territory involved in agricultural activity.

It has been largely demonstrated that in undisturbed soil or soil managed following CA techniques, biomass diversity and biological activity are higher compared to those under deep cultivation (Lupwayi et al. 2001; Spedding et al. 2004). Bacteria, actinomycetes, fungi, earthworms, and nematodes are higher in mulched fields than in those where residues are incorporated. The rate of organic C input from plant biomass is generally considered the dominant factor controlling the amount of microbial biomass in soils (Campbell et al. 1997); as the total organic C pool expands or contracts, the microbial pool also expands or contracts (Franzluebbers et al. 1999).

Microfauna, such as protozoa (Cochran et al. 1994), are favored by those management practices that are expected to also favor bacteria, since bacteria are their main food source. In addition, the abundance of mesofauna, in particular potworm, is greater where CA is practiced than in compacted soil (Röhrig et al. 1998). The negative effects on microarthropod populations are caused in part by the physical disturbance of the soil by tillage. Some individuals may be killed initially by abrasion during tillage operation or being trapped in soil clods after tillage inversion (Wardle 1995).

Soil mesofauna are mainly represented by springtails (Collembola) and mites (Acari; Kladivko 2001). Springtails are usually inhibited by tillage disturbances (Miyazawa et al. 2002; Wardle 1995). Mites exhibit more extreme responses to tillage than microbial groups: moderate to extreme increases or decreases have been observed (Wardle 1995). Interestingly, the mite population seems more affected by cover crop than tillage practice (Reeleder et al. 2006). Another important mesofauna group is the enchytraeids, thanks to their burrow which increases aeration, water infiltration, and root growth (Cochran et al. 1994). They may be inhibited or apparently stimulated by tillage in contrast with most other groups, probably due to their ability to recover from disturbances (Wardle 1995).

Large organisms (macrofauna) appear to be especially sensitive to agroecosystem management (Chan 2001; Folgarait 1998; Black and Okwakol 1997; Kladivko et al. 1997; Robertson et al. 1994; Holt et al. 1993; Barnes and Ellis 1979) with less negative impacts on species with high mobility and higher population growth potential (Decaëns and Jiménez 2002). Earthworms play a crucial role in mixing plant residues and other materials into the soil, particularly important in no-till systems due to the lack of mechanical mixing (House and Parmelee 1985). Earthworm species differ in their ecological behavior thus having different effects on soils. Large earthworms produce large-sized and compact aggregates, whereas small eudrilid earthworms produce small, fragile castings; both groups appear essential for maintaining soil structure (Blanchart et al. 2004). Their abundance, diversity, and activity increase under CA when compared to conventional agriculture (Kladivko 2001; Chan 2001; Kladivko et al. 1997; Barnes and Ellis 1979; Gerard and Hay 1979; Table 22.4). The few exceptions (Nuutinen 1992; Wyss and Glasstetter 1992)

Table 22.4 Abundance of earthworms (number m^{-2}) under no-tillage, conventional tillage, and permanent pasture

No-tillage	Conventional tillage	Permanent pasture	Remarks	Reference
270	90	–	On a very poorly drained soil, cultivation by normal plowing	Boone et al. 1976
137	67	–	Cultivation by deep plowing	Gerard and Hay 1979
913	213	–	Cultivation involved moldboard plowing, three disk plowing and two rotary tilling	House and Parmelee 1985
342	130	–	Lupin/wheat rotation, three cultivation to 7 cm with a duck food scarifier	Rovira et al. 1987
275	117	–	Cultivation involved scarifying (10 cm) two to three times and light harrowing (7 cm)	Haines and Uren 1990
266	48	477	–	Deibert et al. 1991
467	52	1017	–	Springett 1992
250	175	825	Lismore site, after 8 years of cropping	Francis and Knight 1993
–	52	168	–	Mele and Carter 1999

are probably related to type and timing of tillage as well as original species assemblage (Chan 2001). Tillage is the main factor perturbing earthworm populations, but mulched crop residues are fundamental, since earthworms are unable to maintain a constant water content (Edwards and Bohlen 1996).

Although ants are as important as earthworms in soil transformation, there is a lack of literature on ants in agroecosystems (Gotwald 1986). In general, ants increase infiltration by improving soil aggregation and porosity (Nkem et al. 2000) even in situations of low organic matter and clay contents (Mando and Miedema 1997). Management options favoring ant populations, such as residue mulch and reduced or zero tillage, have been identified as key factors in improving topsoil in agroecosystems, even in the degraded conditions of the Sahel (Mando and Miedema 1997). Most arthropods concentrate their activities above or within the topsoil and take part, at least partially, in organic matter incorporation through burrowing and food relocation (Zunino 1991). Theoretically, arthropods (Coleoptera and Araneae) favor CA conditions given the litter presence on the soil surface, which constitutes a food source for many arthropods (Kladivko 2001), and the higher niche availability (Ferguson and McPherson 1985). Nevertheless, many studies conducted in North America and Europe report inconsistent results with increased (Andersen 1999; Holland and Reynolds 2003), decreased (Andersen 1999; Holland and Reynolds 2003) or no effect (Holland and Reynolds 2003) on arthropod abundance. Generally, species diversity of all arthropod guilds is higher in CA compared to conventional agriculture (Stinner and House 1990). Interestingly, various authors (Holland and

Reynolds 2003; Marasas et al. 2001; Stinner and House 1990; House and Stinner 1983) found an increased presence of predators (spiders as well as carabid and staphylinids beetles) compared to phytophagous species under zero tillage systems.

22.3.3 Soil Moisture

Eighty percent of the world's cultivated land depends on "green water" for its production, which is defined as water located in the soil. Agriculture which depends only on green water is called "rainfed agriculture." Green water resources will, in the foreseeable future, be the dominant source for human food production. However, only 15 % of actual rainfall is productively used for crop growth, while the pressure on "blue water resources" is increased. The ground water, or surface water bodies, is limited; consequently, it will be difficult to increase the size of areas under irrigation. More pragmatically, it would be necessary to increase the efficiency of green water resources.

Improves soil and water management is possible through CA; data indicate increased crop yields of 10–100 % with water requirements for crop production reduced from 2500 to 1250 m^3 ton^{-1}. Conversely, conventional farming favors the loss of soil moisture by reducing the ability of the soil to capture, drain, and store rainwater. Unproductive losses take place through surface runoff, unproductive soil evaporation in bare soil surfaces, and unproductive evaporation due to soil aeration during tillage operations. There is evidence that long-term use of conventional tillage leads to soil compaction, increased runoff, and poor infiltration (Hussain et al. 1999b; Ferreras et al. 2000), ultimately determining the risk of soil erosion. Indeed, the destruction of the original soil structure alters many soil physical proprieties including the stability of aggregates > 2 mm (Chan et al. 2001), pore space and size distribution, water-holding capacity, and soil water content. CA, which favors improved soil structure and continuous soil pores, enables higher infiltration and ultimately increases available water for crop production (Roth et al. 1988; Thierfelder et al. 2005). Azooz and Arshad (1996) found that both saturated and unsaturated hydraulic conductivities were higher under zero tillage conditions than under conventional tillage on two luvisols (silty loam and sandy loam soils). Chan and Heenan (1993) found that, despite similar bulk densities, hydraulic conductivity under ponded infiltration of zero tillage with residue retention was one to four times that of conventional tillage with residues burnt. In the USA, CA reduced runoff by between 15 and 89 % and reduced dissolved pesticides, nutrients, and sediments within it (Clausen et al. 1996). Besides lower runoff intensity, numerous studies have shown significant reductions in soil erosion rates with CA or NT (Govaerts et al. 2007; Li et al. 2007; Pinheiro et al. 2004; Chan et al. 2002; Filho et al. 2002).

The effects of CA on soil evaporation are significant. Tillage moves moist soil to the surface, increasing drying losses (Hatfield et al. 2001). It has been demonstrated that tillage disturbance of the soil surface increases soil water evaporation more than untilled areas (Blevins et al. 1977; Papendick et al. 1973). The amount of energy the soil surface receives is influenced by canopy and residue cover. Greb (1966) found that residue and mulches reduce soil water evaporation by reducing soil temperature, impeding vapor diffusion, absorbing water vapor into mulch tissue, and reducing the wind speed gradient at the soil–atmosphere interface; residue thickness (volume) is more important than mass per unit area for controlling evaporation (Unger and Parker 1976; Steiner 1989). It has been estimated that the presence of residues on the surface lowers evaporation by 34–50 % (Sauer et al. 1996). Besides residue thickness, the rate of drying is determined by the atmospheric evaporative potential (Tolk et al. 1999). In general, residue characteristics, which affect energy balance components, have a large impact on evaporation fluxes and are strongly influenced by the effect of the year and by the nonuniform distribution (Sauer et al. 1997).

As a direct beneficial effect, soil moisture is conserved under CA systems and more water is available for crops. Azooz and Arshad (1996) found higher soil water contents under zero tillage compared with moldboard plow in British Columbia. In Zimbabwe, mulching helped conserve soil water in a season with long periods without rain at several experimental sites (Mupangwa et al. 2007). Gicheru (1994) showed that crop residue mulching resulted in more moisture down the profile (0–120 cm) during two consecutive crop periods (the short rains and the long rains) than conventional tillage and tied ridges in a semiarid area of Kenya. Thus, tillage and residue management may significantly affect crop yields during years of poor rainfall distribution (Johnson and Hoyt 1999) making permanent soil cover essential for cropping systems aimed at long-term agricultural sustainability.

22.3.4 Soil Nutrients

Maintenance of soil nutrient availability and soil fertility, in general, is the first condition of any permanent system of agriculture. Under conventional agriculture, soil chemical fertility is steadily lost—as crops and crop residues are removed, SOM is plowed and uncovered land oxidizes into carbon dioxide (a GHG) and water.

In CA, cover crops contribute to accumulate organic matter in the surface soil horizon (Alvear et al. 2005; Diekow et al. 2005)—this effect is more significant when cover crops are combined with NT—which is important due to the regulatory role of organic matter in most biological, physical, and chemical processes, which collectively determine soil health. Besides favoring infiltration and water retention, helping to stabilize soil structure to mitigate the impact of wheel traffic and cultivators, and reducing the potential for wind and water erosion, organic matter is an important source of C and a major reservoir for plant nutrients.

Consequently, increased stratification and nutrient availability is generally observed in CA soils (Duiker and Beegle 2006; Franzluebbers and Hons 1996) due to surface placement of crop residues (Unger 1991). Slower decomposition of surface-placed residues (Balota et al. 2004) may prevent rapid leaching of nutrients through the soil profile; however, the possible development of more continuous pores under zero tillage leads to more rapid passage of soluble nutrients deeper into the soil profile (Kay 1990).

N availability is strictly dependent on the rate of C mineralization. CA is normally associated with lower N availability due to greater immobilization of residues (Bradford and Peterson 2000); however, the net immobilization phase is transitory while the higher, but temporary immobilization of N in CA systems over the long term reduces leaching and denitrification losses. Residues from legume cover crops—which are associated with belowground biological agents and provide food for microbial populations—generally provide more carbon and nitrogen under NT compared with plowing (Campbell et al. 1996a, b).

The composition of residues, indeed, will affect their decomposition and consequent nutrient release; the C/N ratio, initial residue N, lignin, polyphenols, and soluble C concentrations are among the most used criteria for residue quality (Moretto et al. 2001). N immobilization can occur as a consequence of cereal residue retention, particularly during the first years of implementation (Erenstein 2002). Several studies have shown that P extractable levels are higher in no-tilled soils principally due to the reduced mixing of P fertilizers with soils, leading to lower P fixation (Duiker and Beegle 2006; Du Preez et al. 2001; Edwards et al. 1992). Higher P tends to accumulate in the topsoil of no-tilled soils in the absence of surface residues. If mulch is present, the soil surface is likely to be moister than conventionally tilled soils.

CA conserves and increases the availability of nutrients such as K near the soil surface where roots are present (Franzluebbers and Hons 1996). However, most research has shown that tillage does not affect Ca and Mg levels especially in clay soils (Govaerts et al. 2007; Duiker and Beegle 2006; Du Preez et al. 2001). Other authors reported increased available Ca and Mg concentrations to 60 cm depth in both oxisol and alfisol under CA (Sidiras and Pavan 1985). Micronutrient cations (Zn, Fe, Cu, and Mn) are usually present in higher levels under CA systems compared to conventional tillage due to surface placement of crop residues (Franzluebbers and Hons 1996). The higher organic matter content at the soil surface, commonly observed under CA, can increase the cation exchange capacity (CEC) of the topsoil (Duiker and Beegle 2006; Govaerts et al. 2007).

In CA, reduced nutrient leaching is not only linked to NT or crop residues but also to the use of catch crops grown during the wetter periods. In general, CA practices tend to favor soil biota, which are important not only because they favor the fast recycling of nutrients (Van Kessel et al. 1994; Drinkwater et al. 1998; Lafond et al. 2008) but also because they help to immobilize most residual nitrogen (along with organic carbon) in the soil (Amado and Costa 2004).

22.4 Climate Change and Gaseous Emission Dynamics

22.4.1 Methane

Methane (CH_4) is the third most important and abundant GHG after H_2O and CO_2 and is 34 times more potent as a heat-trapping gas than CO_2 over a 100-year time scale (IPCC, 2013). Despite a short residence in the atmosphere (ca. 10 years), CH_4 is chemically reactive in the troposphere and stratosphere. Biogenic sources, which account for more than 70 % of the global total, are mainly northern and tropical wetlands, rice paddies, enteric fermentation, forests, oceans, and landfills. Non-biogenic CH_4 includes mainly industry related and geological sources, biomass, and waste treatments (IPCC 2007).

Methanogenesis is a form of anaerobic respiration, where CO_2 or a simple organic carbon compound serves as the final electron acceptor; this activity is performed by *Archaea*, a domain of single-celled microorganisms. Conversely, the primary sinks of CH_4 are the oxidation of the gas to CO_2 in the troposphere (Wuebbles and Hayhoe 2002) and oxidation by methanotrophic bacteria in the aerobic zone of methanogenic soils and in upland soils, called methanotrophy (Hütsch 2001; Xu et al. 2003). Methanotropy activity, more effective in often-submerged or water-saturated soils (Nesbit and Breitenbeck 1992), can contribute up to 15 % of the total CH_4 removal (Born et al. 1994). When the soil is submerged, dissolved oxygen rapidly decreases causing development of facultative anaerobic, then microaerophilic, and finally strict anaerobic microorganisms. As a direct consequence, reducing conditions are established and when Eh is around –200 mV, the reduction of CO_2 into CH_4 occurs. Soils can act as a net source or sink for CH_4 depending on the oxidative state of the matrix, hence land use and management practices directly affect CH_4 release to the atmosphere (Yang and Chang 2001).

Conservation tillage techniques are a key strategy to reduce CH_4 emissions, since they can act as a CH_4 sink (Mojeremane et al. 2011). In fact, the disturbance of soil by tillage causes a significant reduction of CH_4 oxidation capacity through the damage of soil structure that influences negatively gaseous diffusivity and perturbs the physicochemical and biological properties that promote growth of oxidizing agents (Lessard et al. 1994). In long-term NT, the potential oxidation of CH_4 was considerably higher, from 2 to 11 times more than conventional tillage and minimum tillage (MT; Hansen et al. 1993; Hütsch 1998; Ussiri et al. 2009; Le Mer and Roger 2001). Soil porosity is a main factor affecting CH_4 emissions and is directly related to soil tillage practices. Lower values of bulk density, as seen in long-term NT when compared with conventional tillage andMT, improve gas diffusion. Furthermore, oxidative activity is more pronounced in topsoil under NT, while beyond the layer characterized by soil tillage in conventional tillage, methanotrophic activity is higher and equivalent to NT soils. The conversion of cropping systems from conventional tillage to NT improves the potential for soil CH_4 abatement, but it is a slow process, which can take some decades to quantitatively align methanotrophic activities (Regina and Alakukku 2010).

The fertilizer application and the management of crop residuals directly affect soil microbial activity and composition. Ammonium-based fertilizers or urea can reduce the soil potential for CH_4 oxidation activity, while nitrate-based applications have no direct effects. Fertilizers containing ammonium (NH_4^+) lead to increased N_2O emissions due to the change of methanotrophic bacteria activity, which begins to oxidize NH_4^+ with consequent increases in N_2O and CH_4 (Acton and Baggs 2011). The surface spreading of fertilizers, compared with incorporation, increases

CH_4 emissions due to direct inhibition of oxidase activity (Bronson et al. 1997). The effect of soil pH in methanogenesis indicates that emission tends to slightly increase at acid pH (Levy et al. 2012), with the optimum between 5.5 and 7.

The effect of soil incorporation of organic material, such as manure or green manure, in upland soils varies depending on the C/N ratio of the material. The state of degradation of the carbon supplied to the soil is relevant and, if anaerobic conditions occur, the more degraded the carbon, the greater the potential CH_4 production (Mudge and Adger 1995). The production of CH_4 and emission to the atmosphere decreases, when the C content and C/N ratio of incorporated residues decrease. Green legume manure releases an abundance of NH_4^+ that competes with monooxygenases enzymes increases the release of CH_4 (Nesbit and Breitenbeck, 1992). Conversely, the incorporation of manure, characterized by a higher C content and a relative low C/N ratio, has the potential to stimulate the work of methanogen communities (Hütsch et al. 1993), without affecting CH_4 oxidizers. A high C/N ratio, as in rice straw, corresponds to organic material abounding in labile C, which is readily usable by microflora.

Management of crop residues in the field, together with the addition of soil conditioners, affects the activity of methanogenic communities, which can be ten times more than without these additions (Schütz et al. 1989; Cicerone et al. 1992; Nouchi et al. 2010). The dose of fertilizer applied, as well as the green material, straws, or residues of crop fermentation, has a proportional effect with increasing doses (Denier van der Gon and Neue 1995). In general, increasing SOM by roots exudates and soil residues, together with improved soil structure and microorganism activity, promotes the activity of methanotrophs (Seghers et al. 2003). Conversely, a large microbial activity, especially if related to an organic matter contribution to the soil, results in oxygen consumption, which creates suitable environmental conditions for methanogenic growth (Baggs et al. 2006). Gas emission from surfaces is therefore balanced by these two processes.

Rice paddies are the most studied methanogenic ecosystems; in this environment, methanogenesis and methanotrophy are noticeable. Methane emissions derived from the passive transfer of gas produced in the soil, through aerenchyma and micropores on the leaf blade, vary depending on the variety of rice and are a function of the morphological differences in aerenchyma and roots (Butterbach-Bahl et al. 1997). Organic fertilizers (rice straw, green manure, or farmyard manure)—preferred due to their richness in C—promote CH_4 production more than synthetic fertilizers. Water management can significantly decrease emissions from 60 to more than 90 % if one or more drainage periods are observed (Cai et al. 1997). Conversely, intermittent drainage may increase nitrification and losses of nitrogen by denitrification with the subsequent emission of N_2O. Varietal selection in the case of rice can be a potential strategy to reduce CH_4 emissions, since the composition of various exudates acts directly on methanotrophic communities (Wassmann et al. 1993). In general, soil tillage in paddy fields or transplantation can potentially release CH_4 trapped in soil, while the use of direct seeding can reduce total emissions (Neue 1997). Farmland releases of CH_4, together with nitrous oxide (N_2O), ammonia (NH_3), and nitrates (NO_3^-), are presented in Fig. 22.1.

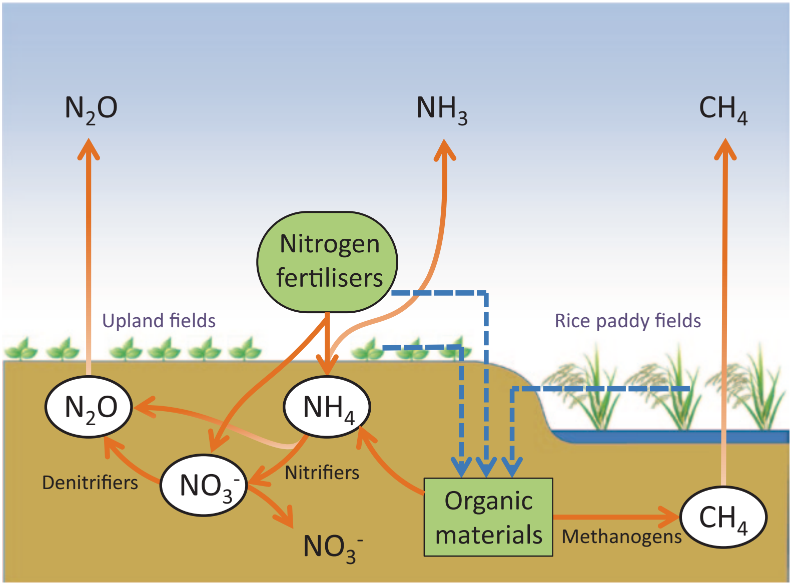


Fig. 22.1 Nitrous oxide (N_2O), methane (CH_4), ammonia (NH_3), and nitrate (NO_3^-) release in farmland. Solid lines are carbon or nitrogen fluxes, dotted lines represent organic materials

22.4.2 Nitrous Oxide

Field crop agriculture is estimated to be the main source of anthropogenic N_2O (IPCC 2001) which contributes more than 61 % of total global N_2O emissions (Montzka et al. 2011). N_2O is 21 times more potent as a heat-trapping gas than CH_4 over a 100-year time scale (IPCC 2007). Once released into the troposphere, N_2O acts as a GHG and takes part in ozone (O_3)-depleting reactions in the stratosphere (Phillips et al. 2007). N_2O is produced from nitrification and denitrification biological processes together with non-biological chemodenitrification. Soil tillage, together with the addition of N compounds as ammonium or nitrate, stimulates microbial activities which produces this reactive gas. Mineral and organic N-fertilizers, together with crop residues and green manures, are recognized as major drivers of N_2O emissions (Bøckman and Olfs 1998). The presence of labile C forms also stimulates denitrification activity due to molecular oxygen consumption in the soil. Moreover, the relationships among soil temperature and pH, soil texture and structure, soil water content, landform and land use, and meteorological conditions are decisive in N_2O emissions.

CA, through zero tillage and MT and practices, directly affects N_2O soil production with highly variable effects (Rochette et al. 2008). In humid climates, in the first 10 years of NT after the conversion from conservation tillage, N_2O emissions were higher and this tendency was counterbalanced by reduced emissions after another 10 years of continuous NT (Six et al. 2004). This variability is related to soil physical, chemical, and biological modifications induced by CA, such as lower soil temperatures reducing N_2O emissions (van Kessel et al. 2013) or progressive increases in water-filled pore spaces (WFPS) that, initially, promote emissions (Smith et al. 2001) and, finally, decrease them once that the soil macroporosity is definitively formed. This effect is also related to soil depth, where nitrification and denitrification activities are greater in the topsoil layer (first 0–10 cm) under NT, whereas at greater depths, denitrification activity is less abundant in conventional tillage (Linn and Doran, 1984). Furthermore, changes in soil pH directly influence the microbial communities that exponentially produce more N_2O from moderate to very strong soil acidity (Blevins et al. 1977; van den Heuvel et al. 2011). In humid climates, increasing soil moisture content detected after conversion from NT or MT practices can be insufficient to significantly increase N_2O emissions by denitrification; in dry climates, increased soil moisture and WFPS with respect to conventional tillage can enhance the denitrification process under humid conditions. Finally, NT practices lead to a general increase in N_2O emissions in poorly aerated soils, while no increase in emissions is observed in well-aerated soils (Rochette 2008).

Crop residue incorporation is a significant source of N_2O with an inverse proportionality between C/N ratio and N_2O emissions. In general, cereal straw incorporation results in higher losses of N_2O with respect to residuals remaining on the soil as mulch (Gregorich et al. 2005). NT practices can increase both nitrification and denitrification processes compared to conventional tillage; straw incorporation in NT significantly increased both processes (Hu et al. 2013). Crop residuals can have a positive effect in reducing soil surface temperature; on the other hand, residuals reduce water evaporation creating in some cases temporarily anaerobic environments that could enhance denitrification and consequently N_2O emissions. Denitrification rates, in fact, are positively correlated with soil moisture (Chen et al. 2011). Although the effects may be controversial, under climate change scenarios where an increase of temperature, CO_2 and a variation in the precipitation distribution are forecast, the role of crop residues as an increasing C source may stimulate denitrification (Butterbach-Bahl and Dannenmann 2011). In some types of grassland, even those with a high potential for C storage, the presence of legumes and their residuals create a higher potential of N_2O emission related to N biological fixation (Rochette and Janzen 2005; Berntsen et al. 2006). The size of crop residues plays an important role, e.g., with pea residues cut into <3 mm lengths, emissions were two times higher than uncut residues, while emissions were not affected by high C/N ratio crop residues such as barley (Ambus et al. 2001). The soil freeze–thaw cycle stimulates C and N mineralization that increases N_2O emissions. The addition of crop residues leads to rapid immobilization of N and a consequent reduction in N_2O emissions if the soil is not C limiting, otherwise addition of C stimulates N_2O production (Pelster et al. 2013). However, cropping systems involving cover crops and characterized by high N-use efficiency had reduced N_2O gaseous emissions (van Groenigen et al. 2011).

N-fertilization placement in CA is relevant; N_2O emissions were significantly reduced, if fertilizers were located below the most biologically active zone (ca. 5 cm depth) with general agronomic advantages (van Kessel et al. 2013). In NT

Table 22.5 Effects on GHG and ammonia (NH_3) emissions on mitigation options at the crop production stage. (modified from Novak and Fiorelli 2010)

Mitigation options for crop production		CH_4	N_2O	CO_2	NH_3
Crop rotation	Increase diversity in crop rotation	–	–	↘	–
	Introduce perennial crops	–	↘	↘	–
	Prolong lifespan of temporary leys	–	↗ after plowing	↘ ↗ after plowing	–
	Cultivate catch crop	–	↘ in short term; ↗? in long term	↘ in short term; ↗? in long term	–
Genetic selection	Breed crops to improve N use efficiency	–	↘?	–	↘?
Fertilization	Synchronize N inputs with crop uptake	–	↘	–	-
	Time effluent application with soil wetness	–	↘	–	↘ or ↗
	Improve fertilization	↘	↘	↘? or ↗?	↘
Soil tillage	Reduce tillage	↘	↘? or ↗?	↘	↗?
	Avoid soil compaction	↘	↘	↘	↘?
	Incorporate crop residues	↗	↗	↘	↘?

↘: mitigation option decreases emissions
↗: mitigation option increases emissions
↘ or ↗: both tendencies have been shown
–: no information given on this compound
?: result needs to be confirmed by more studies

systems, surface spreading of fertilizers leads to greater N_2O emissions than conventional tillage (Ball et al. 1999), while band injection or band placement increases N_2O emissions compared to homogeneous surface spreading, due to the toxic effect of NH_3 release on nitrifying bacteria (Venterea et al. 2010). Finally, NT and MT practices should be practiced for prolonged periods, particularly in dry climates, to efficiently mitigate N_2O emissions. Table 22.5 summarizes the effects of different agricultural management systems in CH_4, N_2O, CO_2 and NH_3 emission potentials.

22.4.3 Ammonia

Ambient NH_3 assumes an important role and growing interest among different atmospheric N reactive species, as a key for future negative impacts of N on terrestrial ecosystems (Sutton 2006). In particular, environmental issues due to NH_3 include soil acidification, water eutrophication with subsequent loss of biodiversity, particulate matter formation, and long-range transport of sulfur (S) and N (Harper 2005). Dry or wet deposition of NH_4^+ particles to the ground contributes to increased environmental loads, such as NO_3^- in groundwater and production of indirect GHG emissions as N_2O and O_3 (Galloway et al. 2008). Most NH_3 emissions in the atmosphere are due to agricultural activities that contribute to more than 50 % of global emissions (Bouwman et al. 1997). NH_3 is mainly produced by conversion of N present in urea and uric acid, excreted by livestock or supplied by mineral fertilizers, to NH_4^+. This transformation occurs rapidly (often within a few days) and requires a key enzyme, urease, which is present in faeces and soil. Furthermore, NH_3 can be produced by conversion of complex organic N forms contained in soil or manures, but this process is slower and could take months.

The main factors influencing the total amount of NH_3 lost from organic and inorganic fertilizers are: typology and concentration of fertilizer, physicochemical characteristics of soil and transfer of NH_3 from surface to atmosphere, and function of the meteorological conditions, i.e., air temperature, wind speed, and solar radiation (Webb et al. 2010). While increased air temperature has a direct impact on the increase in volatilization, rain has an inverse relationship, keeping NH_3 in the aqueous phase in the soil and reducing overall emissions (Sommer and Hutchings 2001).

In dry soils, NH_3 emissions are generally reduced due to ammoniacal solutions, which may be adsorbed and infiltrated through the pores, reducing its contact with air (van der Molen et al. 1989). In contrast, wet or very dry soils reduce infiltration facilitating NH_3 emissions due to the longer fertilizer–air contact. Therefore, increasing the WPFS by reduction tillage or NT can be a helpful agronomical practice to deepen NH_3 solutions into the subsoil. Furthermore, lower temperatures—typical of CA tillage practices—can decrease surface water evaporation, discouraging emissions.

Soil placement and application timing may affect the agronomic efficiency of fertilizer and the relative losses in the atmosphere as NH_3 (Carozzi et al. 2013a). Tillage operations, such as plowing or deep harrowing, after application of organic fertilizers or green manures, contribute to reducing NH_3 emissions by burying the material into the soil. NH_3 abatement efficiency can range up to 90 %, if soil incorporation occurs rapidly compared to surface spreading (Huijsmans et al. 2003, Carozzi et al. 2013b). Consequently, NH_3 emissions are crucial in NT and MT systems, where fertilizers are placed on the soil surface or mixed in the topsoil layer.

NH_3 volatilization from broadcasted urea has a slower dynamic than manure, since the hydrolysis process has to take place under favorable conditions of soil water content and temperature (Terman 1979). NH_3 losses may be greater when urea is applied to residue-covered soil because: (1) urease is active on the crop residual surface, (2) the effect of mulch makes the soil moist and helps the hydrolysis process not in close contact with the soil, and (3) it is more difficult for the urea to reach the soil due to the physical barrier caused by residues. In addition, residues may have a different thermal inertia with respect to the soil by potentially increasing chemical reactions. Moreover, losses tend to be higher from coarse- than fine-textured soils, since fine-textured soils have a higher cation exchange capacity, which can sequestrate more NH_4^+ from soil solution. Therefore, NT may enhance NH_3 volatilization losses from urea-based fertilizers due to the high urease activity associated with residue retention on the soil surface (Sommer et al. 2004). Since nitrate-based fertilizers are less subject to volatilization than ammonium-based ones and soil water retention is enhanced in NT and MT to limit leaching, nitrate-based fertilizers are preferred in CA practices. Moreover, under climate change conditions, it is even more important to avoid keeping ammonium-based fertilizers (both organic or urea forms) on soil surface, especially in CA systems. In this regards, it is useful to consider N-sulfate or nitrate forms, and to develop technologies for direct injection of ammonium-based fertilizer into the soil, or to avoid the contact between ammonium-based fertilizer and crop residues. Variations in meteorology and overall climate can significantly affect NH_3 emissions. The main motivation is that the volatilization phenomenon is directly correlated with increasing temperatures (Skjøth and Geels 2013). This effect is reflected in atmospheric aerosol concentrations, radiative forcing (Xu and Penner 2012), and atmospheric chemistry (Seinfeld and Pandis 2006).

22.5 CA and Water Quality

22.5.1 Runoff and Erosion, Nutrient Losses in Surface Water

Soil erosion represents a threat for agricultural sustainability worldwide (Laflen and Roose 1998). In Europe, soil erosion is one of the most important environmental problems particularly in agricultural systems of the Mediterranean basin (Fig. 22.2). In East and Southeast Asia, available water resources are limiting factors; while there is water available for irrigation, agricultural land resources are becoming scarce (Pisante et al. 2010).

Despite the economic impact on a world-scale, soil erosion is difficult to estimate; it is a function of erosivity and erodibility. Erosivity is related to the physical characteristics of rainfall at the soil surface and runoff velocity: It is therefore affected by crop residues. Erodibility is related to the physical features of soil (Blevins et al. 1998). It is now well acknowledged that long-term use of conventional tillage in certain situations leads to soil compaction and therefore lower yields, increased runoff, and poor infiltration (Hussain et al. 1999a; Ferreras et al. 2000; Raper et al. 2000), ultimately determining the risk of soil erosion. In erosion-prone environments (wet or dried warm zones), inversion of soil by tillage promotes unnecessary moisture loss; at the same time, crop residues that should protect soil from erosion by wind or water and slow soil moisture loss after rain are buried (Pisante 2002).

The higher aggregate stability in CA practices, when compared to conventionally tilled fields or NT fields without residue retention, results in lower soil erosion potential (Govaerts et al. 2007; Li et al. 2007; Pinheiro et al. 2004; Chan et al. 2002; Filho et al. 2002; Hernanz et al. 2002). The positive effect of CA on reduced erodibility is further enhanced by the reduced runoff (Rao et al. 1998, Rhoton et al. 2002). Soil sediments, as a consequence of soil erosion, represent the main contaminants of water flows (Tebrügge and Düring 1999); it is estimated that 27–86 % of eroding sediment leaves the field (Quine and Walling 1993). Associated with this movement of soil and water are nutrients, agrochemicals, pathogens, organic

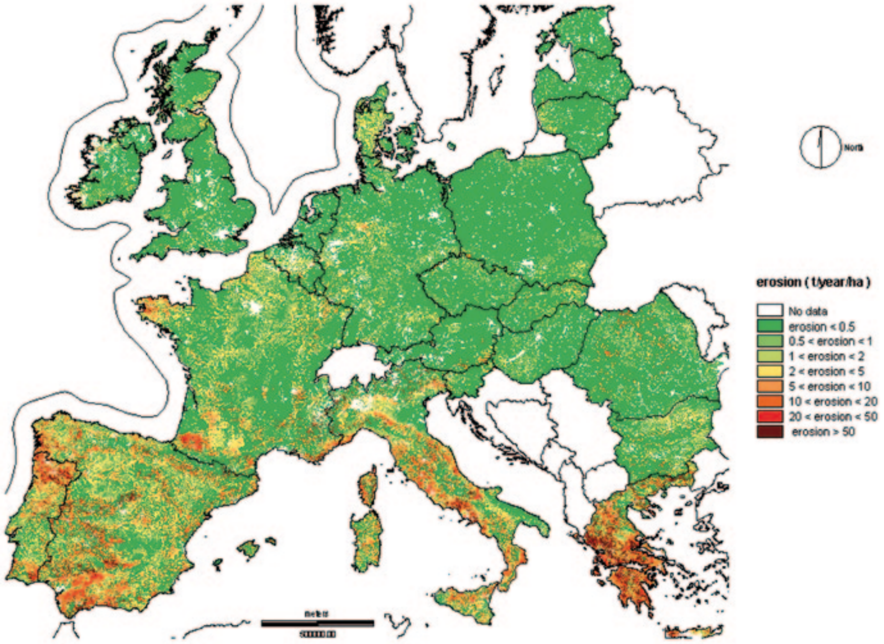


Fig. 22.2 Soil erosion map in Europe. (Kirkby et al. 2004)

matter, and heavy metals (Christensen et al. 1995), all of which frequently damage the water ecosystem (Uri et. al. 1998). Sediments cause sublethal and lethal responses in fresh water fish, aquatic invertebrates, and periphyton (Newcombe and MacDonald 1991). A direct consequence of inorganic fertilizers, organic matter, and pesticides leaching into the water is eutrophication, a widespread phenomenon throughout the world (Harper 1992).

CA is a possible way to reduce the risk of these pollutants reaching surface and ground water. In a 15-year study, comparing different CA techniques, sediment loss was 532, 82, and 1152 kg ha^{-1} per year for chisel-plow and disk versus no-till, respectively (Owens et al. 2002). Soil management affects the rate and proportion of water infiltration and therefore river flow rates and the need for irrigation (Evans 1996). In areas of low rainfall, CA helps retain water in the upper soil layers (Rasmussen 1999). Direct drilling combined with stubble retention increased rain infiltration, leading to reduced runoff compared to cultivated soil (Carter and Steed 1992).

22.5.2 Nitrate Leaching

Nitrate leaching from agricultural systems is one of the most important negative externalities of agricultural systems. Nitrate leaching depends on several interacting factors such as organic and mineral fertilization, cropping system, crop nitrogen uptake, amount of rain, temperature, and soil characteristics (Acutis et al. 2000; Beaudoin et al. 2005; Perego et al. 2012; Zavattaro et al. 2012). All these factors are subject to the effects of climate change and conservation tillage systems; no-till has the possibility to reduce nitrate losses through leaching under climate change conditions (Soane et al. 2012). Tebrügge (2001) supposed lower nitrate leaching in no-tilled soils and Van Den Bossche et al. (2009) showed higher N efficiency in reduced and no-till systems compared to conventional systems as a result of slower organic matter decomposition and therefore slower mineralization and less leaching. Greater nitrogen use efficiency (NUE) in conservation systems has been observed in the USA; this increase in NUE allows for a reduction in leaching when comparison with conventional agriculture, without increasing N_2O emissions (Robertson et al. 2012). These results were partially confirmed by Hansen et al. (2010) who identified situations where leaching was lower in no-tilled soils, while others had lower leaching under conventional tillage. Klein et al. (2013) used the CropSyst model to highlight increases in N-leaching by 30–45 % for two climate scenarios for 2050 in a catchment on the Swiss Central Plateau, and to identify RT as an important option for reducing leaching and erosion.

Another possible impact of climate change is increased cracking in dry periods and increased infiltration during more frequent, intense rainfall events (Stuart et al. 2011), and surface sealing due to the impact of raindrops on the soil surface, causing soil aggregate breakdown and production of fine particles, which reduce macroporosity. In both situations, conservation tillage offers more surface residues to protect soil from raindrops, conserves soil moisture by reducing the shrinking and swelling phenomena in clay soil, reduces the risk of high concentrations of P and N in runoff water, and often reduces leaching by reducing the macroporosity.

22.6 Research and Knowledge Transfer

Scientific research is the main driver of innovation, creating new knowledge and technology that can be transferred and adapted to different situations. This view is usually described as the “linear” or “transfer of technology” model. The second view, while not denying the importance of research and technology transfer, recognizes innovation as an interactive process. Innovation involves the interaction of individuals and organizations possessing different types of knowledge to include not only knowledge creation but also the whole system of technological diffusion, adoption processes and interaction adjustments. Future solutions will require interactive relationships among basic science, applied science, and technology development (OECD 2009). The important role of agronomy research and effort technology transfer system for enhancing the effect of CA in relation to climate change, as in other areas, is strongly linked to the quantity and quality of available data. In the contemporary agricultural sector, competitiveness depends on collaboration for innovation. Increasingly, “innovation systems” are viewed as a network of knowledge flows with considerable two-way flows of information upstream and downstream and knowledge spillover among participants that are connected in formal and informal ways. This more systemic approach suggests that innovation policy goes far beyond research expenditure and involves a wide range of institutions that can affect incentives, knowledge sharing, and the processes used for commercialization. The estimated benefits of agricultural research generally far exceed its costs, with the literature reporting annual internal rates of return that range between 20 and 80 % (Alston 2010).

A conceptual framework containing elements of an agricultural innovation system for adaptation to climate change could be developed, as well as multiple indicators that would help assess the performance of each aspect of an innovation system in agriculture across countries. Knowledge, information, and technology are increasingly generated, diffused, and applied through the private sector. Exponential growth in information and communications technology (ICT), especially the Internet, has transformed the ability to take advantage of knowledge developed in other places or for other purposes. The knowledge structure of the agricultural sector in many countries is changing markedly (OECD 2011). Evidence of linkages between research, productivity growth, and competitiveness also stress the need to adopt an approach with more innovation systems, like in agriculture.

The mitigation of adverse effects of climate change and exploration of new solutions for agriculture in an increasingly globalized comparison could help to identify the most appropriate policy directions in support of research and development (Nisbet 2009). Future work should take a closer look at institutional arrangements in agricultural innovation and knowledge systems, and examine the respective roles of governments and the private sector in strengthening innovation systems and facilitating technological adoption. In this respect, some measures to take are (1) presence of research collaboration across sectors, (2) protection of intellectual property rights, and (3) knowledge flow. A comprehensive effort should be undertaken to measure the different stages of an innovation system, for example, by testing its technological adoption and diffusion at the farm level, and to investigate the impact of agricultural policies on technological change and technical efficiency. The nature of production systems, within contemporary climate change, has been the transformation from high-disturbance production systems with a high environmental impact to low-disturbance agroecological systems, where production technologies and practices (i.e., CA) are more in harmony with the ecosystem process and where both productivity and environmental services can be harnessed. Multi-stakeholder innovation systems have an important role to play in generating relevant technologies that can be adopted and adapted by farmers, who must be an integral part of any effective innovation system. Training actions creating the possibility for "fast track" applications and evaluations under different specific conditions could be considered, though are more common for students and less common for farmers and more popular among research institutions and extension offices, where they exist. The spread of CA worldwide has been achieved where: (1) farmers have been informed of the system and convinced of its benefits by experience; (2) training and technical support to early adopters have been provided; and (3) adequate support policies exist (e.g., funding through carbon sequestration contracts with farmers).

22.7 Conclusions

This chapter reviews the main interactions of CA systems with climate change, especially on sectors like agriculture, where the lifecycle of crops is mainly determined by climate conditions. At national and state levels, the adoption of CA policies is often congruent and supportive of other policies related to the environment, natural resources, energy efficiencies, and more recently, climate change.

The adoption of CA can significantly affect the emission of GHG and NH_3, especially if good agricultural practices, mainly related to the efficient use of fertilizers, are observed. Reduced or NT leads to direct drops in N_2O emissions, CH_4 and CO_2 sinks, while the incorporation of crop residues causes a general increase in N_2O and CH_4, and a potential reduction in NH_3 and NO_3^-. Improved NUE can greatly reduce the emission of N reactive forms, as N_2O, NH_3, and NO_3^-, towards the atmosphere and groundwater. In relation to increasing temperatures, the emissions of N_2O and NH_3 are directly correlated, while CH_4 is negatively correlated, to air and soil temperatures. The changes in precipitation frequency and intensity in some areas may noticeably affect the release of these pollutants, because they are directly correlated to NO_3^- leaching and the emission of N_2O and CH_4, mainly due to conditions of soil aeration. In this regard, CA techniques which greatly improve soil porosity and reduce soil temperature are advantageous practices to mitigate these releases into the environment.

For productive and remunerative agriculture, which at the same time preserves and enhances the natural resource base and environment, and positively contributes to harnessing environmental services, CA represents a task for Sustainable Crop Production Intensification (SCPI) to not only reduce the impact of climate change on crop production but also mitigate the factors that cause climate change by reducing emissions and by contributing to carbon sequestration in soils. Hence, it adapts to and mitigates climate change and leads to a more efficient use of inputs to reduce production costs. Intensification should also enhance biodiversity—above- and belowground level—in crop production systems to improve ecosystem services for better productivity and a healthier environment (Pisante et al. 2012). Investments in knowledge—especially in the form of science and technology—have featured prominently and consistently in most strategies to promote sustainable and equitable agricultural development at the national level.

In crux, CA as a basis for SCPI is essential and practicable, but depends on both how and what crops are grown, as well as on the engagement of all stakeholders who are aligned towards transforming the unsustainable tillage-based farming systems to CA systems regardless of soil, climate, and ecosystem services. This transformational change is now occurring worldwide on all continents and ecologies and covers nearly 10 % of global arable land. In any case, there is the need to standardize research activities because often contradictory results are due to incomplete implementation of the basic principles of CA (Derpsch et al. 2014). In the authors' opinion, well-managed experiments indicate greater resistance and resilience of CA systems to climate changes, and that the most critical point could be the control of gaseous emissions of N_2O, and that this is a specific requirement.

An example of ecosystem services operating in different parts of the world and including a carbon offset scheme for agricultural land use is in Alberta, Canada. The province of Alberta, which has a strong agriculture-based economy and also the highest GHG emissions in the country (due to oil and gas production), first adopted a climate change action plan in 2002. Since 2007 this has included the implementation of a CA system protocol on agricultural lands as an opportunity for direct and indirect reductions of GHG emissions through carbon offset trading with industry (Goddard et al. 2009). These important lessons learnt from around the world regarding the high potential for carbon sequestration with CA systems and the associated opportunity for carbon trading and reduction in GHGs emissions should be taken into consideration in any climate change mitigation and sustainable crop production strategy for the future.

References

Acton SD, Baggs EM (2011) Interactions between N application rate, CH_4 oxidation and N_2O production in soil. Biogeochemistry 103:15–26

Acutis M, Ducco G, Grignani C (2000) Stochastic use of the LEACHN model to forecast nitrate leaching in different maize cropping systems. Eur J Agron 13:191–206

Ainsworth EA, Long SP (2005) What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. New Phytol 165:351–372

Akbolat D, Evrendilek F, Coskan A, Ekinci K (2009) Quantifying soil respiration in response to short-term tillage practices: a case study in southern Turkey. Acta Agric Scand Sect B Plant Soil Sci 59:50–56

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG (2006) Global observed changes in daily climate extremes of temperature and precipitation (1984–2012). J Geophys Res Atmos 111(D5)

Al-Kaisi M (2008) Impact of tillage and crop rotation systems on soil carbon sequestration. Iowa State University, Iowa

Alston J (2010) The benefits from agricultural research and development, innovation, and productivity growth. OECD Food, agriculture and fisheries working papers, No. 31. OECD Publ., Paris, France

Alvear M, Rosas A, Rouanet JL, Borie F (2005) Effects of three soil tillage systems on some biological activities in an Ultisol from southern Chile. Soil Till Res 82:195–202

Alves AC, Setter TL (2004) Response of cassava leaf area expansion to water deficit: cell proliferation, cell expansion and delayed development. Ann Bot 94:605–613

Alves BJR, Zotarelli L, Boddey RM, Urquiaga S (2002) Soybean benefit to a subsequent wheat cropping system under zero tiIlage In: Nuclear techniques in integrated plant nutrient, water and soil management: proceedings of a Symposium held in Vienna, 16–20 October 2000 Vienna: IAEA 2002, pp 87–93

Alves BJR, Boddey RM, Urquiaga S (2003) The success of BNF in soybean in Brazil. Plant Soil 252:1–9

Alves BJR, Zotarelli L, Fernandes FM, Heckler JC, Macedo RAT, Boddey RM, Jantalia CP, Urquiaga S (2006) Biological nitrogen fixation and nitrogen fertilizer on the nitrogen balance of soybean, maize and cotton. Pesq Agrop Bras 41-3:449–456

Amado TJC, Costa CN (2004) Solos sob sistema Plantio Direto no Brasil podem atuar como importante tampão ambiental. Jornal Direto no Cerrado 37:21–22

Amado TJC, Mielniczuck J, Fernandes SBV, Bayer C (1999) Culturas de cobertura, acúmulo de nitrogenio total no solo e produtividade de milho. Rev Bras Ciência Solo 23:679–686

Amado TJC, Bayer C, Eltz FLF, Brum AC (2001) Potencial de culturas de cobertura em acumular carbono e nitrogenio no solo no plantio direto e a melhoria da qualidade ambiental. Rev Bras Ciência Solo 25:189–197

Ambus P, Jensen ES, Robertson GP (2001) Nitrous oxide and N-leaching losses from agricultural soil: influence of crop residue particle size, quality and placement, Phyton-Ann. REI Bot 41:7–15

Andersen A (1999) Plant protection in spring cereal production with reduced tillage. II. Pests and beneficial insects. Crop Prot 18:651–657

Angers DA, Bolinder MA, Carter MR, Gregorich EG, Drury CF, Liang BC, Voroney RP, Simard RR, Donald RG, Beyaert RP, Martel J (1997) Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. Soil Till Res 41:191–201

Azooz RH, Arshad MA (1996) Soil infiltration and hydraulic conductivity under long-term no-tillage and conventional tillage systems. Can J Soil Sci 76:143–152

Baggs EM, Chebii J, Ndufa JK (2006) A short-term investigation of trace gas emissions following tillage and no-tillage of agroforestry residues in western Kenya. Soil Till Res 90:69–76

Bailey VL, Smith JL, Bolton HJ (2002) Fungal-to-bacterial ratios in soils investigated for enhanced carbon sequestration. Soil Biol Biochem 34:1385–1389

Baker JM, Ochsner TE, Venterea RT, Griffis TJ (2007) Tillage and soil carbon sequestration-what do we really know? Agric Ecosyst Environ 118:1–5

Balabane M, Bureau F, Decaens T, Akpa M, Hedde M, Laval K, Puget P, Pawlak B, Barray S, Cluzeau D, Labreuche J, Bodet JM, Le Bissonnais Y, Saulas P, Bertrand M, Guichard L, Picard D, Houot S, Arrouays D, Brygoo Y, Chenu C (2005) Restauration de fonctions et proprietes des sols de grande culture intensive: effets de systemes de culture alternatifs sur les matieres organiques et la structure des sols limoneux, et approche du role fonctionnel de la diversitè biologique des sols. GESSOL/projet Dmostra. Rapport final, p 119

Ball BC, Scott A, Parker JP (1999) Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil Till Res 53:29–39

Balota EL, Colozzi A, Andrade DS, Dick RP (2004) Long-term tillage and crop rotation effects on microbial biomass and C and N mineralization in a Brazilian Oxisol. Soil Till Res 77:137–145

Barnes BT, Ellis FB (1979) Effects of different methods of cultivation and direct drilling and disposal of straw residues on populations of earthworms. J Soil Sci 30:679

Battisti DS, Naylor RL (2009) Historical warnings of future food insecurity with unprecedented seasonal heat. Science 323:240–244

Bayer C, Bertol I (1999) Características químicas de um Cambissolo húmico afetadas por sistemas de preparo, com enfase à matéria organica. Rev Bras Ciência Solo 23:687–694

Bayer C, Mielniczuck J (1997) Nitrogênio total de um solo submetido a diferentes métodos de preparo e sistemas de culturas. Rev Bras Ciência Solo 21:235–239

Bayer C, Martin-Neto L, Mielniczuck J, Ceretta CA (2000a) Effect of no-tillage cropping systems on SOM in a sandy clay loam Acrisol from Southern Brazil monitored by electron spin resonance and nuclear magnetic resonance. Soil Till Res 53:95–104

Bayer C, Mielniczuck J, Amado TJC, Martin-Neto L, Fernandes SBV (2000b) Organic matter storage in a sandy clay loam Acrisol affected by tillage and cropping systems in southern Brazil. Soil Till Res 54:101–109

Beare MH, Parmelee RW, Hendrix PF, Cheng W, Coleman DC, Crossley DA (1992) Microbial and faunal interactions and effects on litter nitrogen and decomposition in agroecosystems. Ecol Monogr 62:569–591

Beare MH, Pohlad BR, Wright DH, Coleman DC (1993) Residue placement and fungicide effects on fungal communities in conventional and no-tillage soils. Soil Sci Soc Am J 57:392–399

Beaudoin N, Saad JK, Van Laethem C, Machet JM, Maucorps J, Mary B (2005) Nitrate leaching in intensive agriculture in Northern France: effect of farming practices, soils and crop rotations. Agric Ecosyst Environ 111:292–310

Ben Moussa-MachraouiS, Errouissi F, Ben-Hammouda M, Nouira S (2010) Comparative effects of conventional and no-tillage management on some soil properties under Mediterranean semiarid conditions in North-Western Tunisia. Soil Till Res 106:247–253

Berntsen J, Grant R, Olesen JE, Kristensen IS, Vinther FP, Molgaard JP, Petersen BM (2006) Nitrogen cycling in organic farming systems with rotational grass-clover and arable crops. Soil Use Manage 22:197–208

Bindi M, Olesen JE (2011) The responses of agriculture in Europe to climate change. Reg Environ Change 11:S151–158

Bindi M, Fibbi L, Gozzini B, Orlandini S, Miglietta F (1996) Modeling the impact of future climate scenarios on yield and yield variability of grapevine. Clim Res 7:213–224

Black HIJ, Okwakol MJN (1997) Agricultural intensification, soil biodiversity and agroecosystem function in the tropics: the role of termites. Appl Soil Ecol 6:37–53

Black AL, Tanaka DL (1997) A conservation tillage-cropping systems study in the Northern Great Plains of the United States. In: Paul EA et al (eds) Soil organic matter in temperate agroecosystems—Long-term experiments in North America. CRC, New York, 335–342

Blanchart E, Albrecht A, Brown G, Decaens T, Duboisset A, Lavelle P, Mariani L, Roose E (2004) Effects of tropical endogeic earthworms on soil erosion. Agric Ecosyst Environ 104:303–315

Blevins RL, Thomas GW, Cornelius PL (1977) Influence of no-tillage and nitrogen fertilization on certain soil properties after 5 years of continuous corn. Agron J 69:383–386

Blevins RL, Lal R, Doran JW, Langdale GW, Frye WW (1998) Conservation tillage for erosion-control and soil quality. In: Pierce FJ, Frye WW (eds) Advances in soil and water conservation. Ann Arbor Press, Michigan, pp 51–68

Bøckman OChr OHW (1998) Fertilizers, agronomy and N_2O. Nutr Cycl Agroecosyst 52:165–170

Boddey RM, de Moraes SJC, de Alves M, Urquiaga BJR (1997) The contribution of biological nitrogen fixation for sustainable agricultural systems in the tropics. Soil Biol Biochem 29:787–799

Boddey RM, Alves BJR, Soares LH deB, Jantalia CP, Urquiaga S (2009) Biological nitrogen fixation and mitigation of greenhouse gas emissions. In: Emerich DW, Krishnan HB (eds) Agronomy Monograph Nitrogen Fixation in Crop Production. Am Soc Agron, Crop Sci Soc Am, and Soil Sci Soc Am Madison, Wisconsin, pp 387–413

Bol R, Kandeler E, Amelung W, Glaser B, Marx MC, Preedy N, Lorenz K (2003) Short-term effects of dairy slurry amendment on carbon sequestration and enzyme activities in a temperate grassland. Soil Biol Biochem 35:1411–1421

Boone FR, Slager S, Miedema R, Eleveld R (1976) Some influences of zero-tillage on the structure and stability of fine textured river levee soil. Neth J Agric Sci 24:105–119

Born M, Dorr H, Levin J (1994) Methane consumption in aerated soils of the temperate zone. Tellus B 42:2–8

Bouwman AF, Lee DS, Asman AH, Dentener EJ, Van Der Hoe KW, Olivier JGJ (1997) A global high-resolution emission inventory for ammonia. Global Biogeochem Cycles 11:561–587

Bradford JM, Peterson GA (2000) Conservation tillage. In: Summer ME (ed) Handbook of soil science. CRC, Boca Raton, pp G247–269

Bronson KF, Neue HU, Singh U, Abao EB Jr (1997) Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil: I. Residue nitrogen and water management. Soil Sci Soc Am J 61:981–987

Butterbach-Bahl K, Dannenmann M (2011) Denitrification and associated soil N_2O emissions due to agricultural activities in a changing climate. Curr Opin Environ Sustain 3:389–395

Butterbach-Bahl K, Papen H, Rennenberg H (1997) Impact of gas transport through rice cultivars on methane emission from rice paddy fields. Plant Cell Environ 20:1175–1183

Buyanovsky GA, Wagner GH (1998) Carbon cycling in cultivated land and its global significance. Global Change Biol 4:131–141

Carter MR, Steed GR (1992) The effects of direct-drilling and stubble retention on hydraulic-properties at the surface of duplex soils in North-Eastern Victoria. Aust J Soil Res 30:505–516

Cai ZC, Xing GX, Yan XY, Xu H, Tsuruta H, Yagi K, Minami K (1997) Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilizers and water management. Plant Soil 196:7–14

Campbell CA, McConkey BG, Zentner RP, Dyck FB, Selles F, Curtin D (1996a) Longterm effects of tillage and crop rotations on soil organic C and total N in a clay soil in southwestern Saskatchewan. Can J Soil Sci 76:395–401

Campbell CA, McConkey BG, Zentner RP, Selles F, Curtin D (1996b) Tillage and crop rotation effects on soil organic C and N in a coarse-textured Typic Haploboroll in southwestern Saskatchewan. Soil Till Res 37:3–14

Campbell CA, Lafond GP, Moulin AP, Townley-Smith L, Zentner RP (1997) Crop production and soil organic matter in long-term crop rotations in the sub-humid northern Great Plains of Canada. In: Paul EA et al. (eds) Soil organic matter in temperate agroecosystems-Long-term experiments in North America. CRC, New York, 297–315

Cantero-Martinez C, Gabina D, Arrue JL (2007) Evaluation of conservation agriculture technology in Mediterranean agriculture systems. In: Fares SB, Asfary A, Belloum A, Steiner K, Friedrich T (eds) Proceedings of the International Workshop on Conservation Agriculture for Sustainable Land Management to Improve the Livelihood of People in Dry Areas 2007 May 7–9, Damascus, Syria. ACSAD and GTZ, p 157–164

Carozzi M, Loubet B, Acutis M, Rana G, Ferrara RM (2013a) Inverse dispersion modelling highlights the efficiency of slurry injection to reduce ammonia losses by agriculture in the Po Valley (Italy). Agric Forest Meteorol 171-172:306–318

Carozzi M, Ferrara RM, Rana G, Acutis M (2013b) Evaluation of mitigation strategies to reduce ammonia losses from slurry fertilisation on arable lands. Sci Total Environ 449:126–133

Chadwick DR, van der Weerden T, Martinez J, Pain BF (1998) Nitrogen transformations and losses following pig slurry applications to a natural soil filter system (Solepur process) in Britany, France. J Agr Eng Res 69:85–93

Chan KY (1997) Consequences of changes in particulate organic carbon in vertisols under pasture and cropping. Soil Sci Soc Am J 61:1376–1382

Chan KY (2001) An overview of some tillage impacts on earthworm population abundance and diversity—implications for functioning in soils. Soil Till Res 57:179–191

Chan KY, Heenan DP (1993) Surface hydraulic-properties of a red earth under continuous cropping with different management-practices. Aust J Soil Res 31:13–24

Chan KY, Bowman A, Oates A (2001) Oxidizible organic carbon fractions and soil quality changes in an oxic paleustalf under different pasture leys. Soil Sci 166:61–67

Chan KY, Heenan DP, Oates A (2002) Soil carbon fractions and relationship to soil quality under different tillage and stubble management. Soil Till Res 63:133–139

Chantigny MH, Rochette P, Angers DA (2001) Short-term C and N dynamics in a soil amended with pig slurry and barley straw: a field experiment. Can J Soil Sci 81:131–137

Chen YT, Borken W, Stange CF, Matzner E (2011) Effects of decreasing water potential on gross ammonification and nitrification in an acid coniferous forest soil. Soil Biol Biochem 43:333–338

Christensen B, Montgomery JM, Fawcett RS, Tierney D (1995) Best management practices for water quality. Conservation Technology Information Center, West Lafayette, pp 1–3

Cicerone RJ, Delwiche CC, Tyler SC, Zimmerman PR (1992) Methane emissions from California rice paddies with varied treatments. Global Biogeochem Cycles 6:233–248

Clausen JC, Jokela WE, Potter FI, Williams JW (1996) Paired watershed comparison of tillage effects on runoff, sediment, and pesticide losses. J Environ Qual 25:1000–1007

Cleland EE, Chuine I, Menzel A, Mooney HA, Schwartz MD (2007) Shifting plant phenology in response to global change. Trends Ecol Evol 22:357–365

Cochran VL, Sparrow SD, Sparrow EB (1994) Residue effect on soil micro- and macroorganisms. In: Unger PW (ed) Managing agricultural residues. CRC, Boca Raton, pp 163–184

Confalonieri R, Donatelli Bregaglio S, Tubiello FN, Fernandes E (2012) Agroecological zones simulator: A component based, open-access, transparent platform for climate change - crop productivity impact assessment in Latin America. iEMSs 6th International Congress, Leipzig, 1–5 July

Corsi S, Friedrich T, Kassam A, Pisante M, Sà J de M (2012) Soil organic carbon accumulation and greenhouse gas emission reductions from conservation agriculture: a literature review. Integrated crop management, vol 16. Plant Production and Protection Division, Food and Agriculture Organization of the United Nations, Rome

Dai A, Fung IY, DelGenio AD (1997) Surface observed global land precipitation variations during 1900-1998. J Climate 10:2943–2962

Dass A, Sudhishri S, Lenka NK, Patnaik US (2010) Runoff capture through vegetative barriers and planting methodologies to reduce erosion, and improve soil moisture, fertility and crop productivity in southern Orissa. India Nutr Cycl Agroecosyst 10:1–13

De Alba S, Lacasta C, Benito G, Perez-Gonzalez A (2001) Influence of soil management on water erosion in a Mediterranean semi-arid environment in Central Spain. In: Garcıa-Torres L, Benites J, Martınez-Vilela A (eds) Conservation agriculture, a worldwide challenge, vol 2. ECAF and FAO, Spain

De laRD, Diaz-Pereira E, Mayol F, Czyz EA, Dexter AR, Dumitru E, Enache R, Fleige H, Horn R, Rajkay K, Simota C (2005) SIDASS project Part2. Soil erosion as a function of soil type and agricultural management in Sevilla olive area, Southern Spain. Soil Till Res 82:19–28

de Maria IC, Nnabude PC, de Castro OM (1999) Long-term tillage effects on soil chemical properties of a Rhodic Ferralsol in Southern Brazil. Soil Till Res 51:71–79

De MSàJCM, Cerri CC, Dick WA, Lal R, Filho SPV, Piccolo MC, Feigl BE (2001) Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian Oxisol. Soil Sci Soc Am J 65:1486–1499

Decaëns T, Jimenez JJ (2002) Earthworm communities under an agricultural intensification gradient in Colombia. Plant Soil 240:133–143

Deibert EJ, Utte RA, Schwert DP (1991) Tillage system influence on earthworms (Lumbricidae) in North Dakota. N Dak Farm Res 48:10–12

Del Río S, Herrero L, Pinto-Gomes C, Penas A (2011) Spatial analysis of mean temperature trends in Spain over the period 1961–2006. Glob Planet Change 79:65–75

Denier vanderGHAC, Neue HU (1995) Influence of organic matter incorporation on the methane emission from a wetland rice field. Glob Biogeochem Cycles 9:11–22

Dennis P, Thomas MB, Sotherton NW (1994) Structural features of field boundaries which influence the overwintering densities of beneficial arthropod predators. J Appl Ecol 31:361–370

Derpsch R, Franzluebbers AJ, Duiker SW, Reicosky DC, Koeller K, Friedrich T, Sturny WG, Sa´ JCM, Weiss K (2014) Why do we need to standardize no-tillage research? (Letter to the Editor). Soil Till Res 137:16–22

Diekow J, Mielniczuk J, Knicker H, Bayer C, Dick DP, Kogel-Knabner I (2005) Soil C and N stocks as affected by cropping systems and nitrogen fertilisation in a Southern Brazil Acrisol managed under no-tillage for 17 years. Soil Till Res 81:87–95

Doran JW, Parkin TB (1994) Defining and assessing soil quality. In: Doran JW, Coleman DC, Bezdicek DF, Stewart BA (eds) Defining soil quality for a sustainable environment. SSSA special publication no. 35, Madison, pp 3–21

Doran JW, Liebig MA, Santana DP (1998) Soil health and global sustainability. In: Transactions of the 16th World Congress of Soil Science. Montepellier. 20–26 August, France

Drijber RA, Doran JW, Parkhurst AM, Lyon DJ (2000) Changes in soil microbial community structure with tillage under long-term wheat-fallow management. Soil Biol Biochem 32:1419–1430

Drinkwater LE, Wagoner P, Sarrantonio M (1998) Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396:262–265

Du Preez CC, Steyn JT, Kotze E (2001) Long-term effects of wheat residue management on some fertility indicators of a semi-arid Plinthosol. Soil Till Res 63:25–33

Duiker SW, Beegle DB (2006) Soil fertility distributions in long-term no-till, chisel/disk and moldboard plow/disk systems. Soil Till Res 88:30–41

Eagle AJ, Henry LR, Olander LP, Haugen-Kozyra KH, Millar N, Robertson GP (2011) Greenhouse gas mitigation potential of agricultural land management in the United States: a synthesis of the literature, 2nd edn. Nicholas Institute for Environmental Policy Solutions, Durham, North Carolina

Easterling W, Apps M (2005) Assessing the consequences of climate change for food and forest resources: a view from the IPCC. Clim Change 70:165–189

Edwards CA, Bohlen PJ (1996) Biology and ecology of earthworms. Chapman and Hall, London

Edwards JH, Wood CW, Thurlow DL, Ruf ME (1992) Tillage and crop-rotation effects on fertility status of a hapludult soil. Soil Sci Soc Am J 56:1577–1582

Entry IA, Mitchell CC, Backman CB (1996) Influence of management practices on soil organic matter, microbial biomass and cotton yield in Alabama's "Old Rotation". Biol Fertil Soils 23-4:353–358

Erenstein O (2002) Crop residue mulching in tropical and semi-tropical countries: an evaluation of residue availability and other technological implications. Soil Till Res 67:115–133

Evans R (1996) Soil erosion and its impacts in England and Wales. Friends of the Earth, London, p 121

FAO (2001) World Soil Resources Reports 96: Soil carbon sequestration for improved land management. Food and Agriculture Organization of the United Nations, Rome, Italy

FAO (2008) The case for improving soil health. In: Proceedings of the International Technical Workshop on Investing in Sustainable Crop Intensification, 22–24 July. Integrated Crop Management, vol 6. FAO, Rome

FAO (2009) Food security and agricultural mitigation in developing countries: options for capturing synergies. Food and Agriculture Organization of the United Nations, Rome, Italy

FAO (2011) What is conservation agriculture? FAO conservation agriculture website. http://www.fao.org/ag/ca/1a.html

FAO (2012) Soil organic carbon accumulation and greenhouse gas emission reductions from conservation agriculture: a literature review. Integr Crop Manag 16:89

FAO (2014) FAOSTAT database. FAO, Rome, Italy. http://www.fao.org/faostat. Accessed 10 Feb 2014

Farrar JF (1996) Sinks, integral parts of a whole plant. J Exp Bot 47:1273–1279

Ferguson HJ, McPherson RM (1985) Abundance and diversity of adult carabidae in 4 soybean cropping systems in Virginia. J Entomol Sci 20:163–171

Ferreras LA, Costa JL, García FO, Pecorari C (2000) Effect of no-tillage on some soil physical properties of a structural degraded Petrocalcic Paleudoll of the southern “Pampa” of Argentina. Soil Till Res 54:31–39

Filho CC, Lourenco A, Guimaraes MDF, Fonseca ICB (2002) Aggregate stability under different soil management systems in a red latosol in the state of Parana, Brazil. Soil Till Res 65:45–51

Flessa H, Beese F (2000) Laboratory estimates of trace gas emissions following surface application and injection of cattle slurry. J Environ Qual 29:262–268

Folgarait PJ (1998) Ant biodiversity and its relationship to ecosystem functioning: a review. Biodivers Conserv 7:1221–1244

Fontaine S (2007) Stability of organic carbon in deep soil layers controlled by fresh carbon supply. Nature 450:277–280

Fontaine S, Bardoux G, Abbadie L, Mariotti A (2004) Carbon input to soil may decrease soil carbon content. Ecol Lett 7:314–320

Francis GS, Knight TL (1993) Long-term effects of conventional and no-tillage on selected soil properties and crop yields in Canterbury, New Zealand. Soil Till Res 26:193–210

Franzaring J, Högy P, Fangmeier A (2008) Effects of free-air CO_2 enrichment on the growth of summer oilseed rape (Brassica napus cv. Campino). Agric Ecosyst Environ 128:127–134

Franzluebbers AJ, Hons FM (1996) Soil-profile distribution of primary and secondary plantavailable nutrients under conventional and no tillage. Soil Till Res 39:229–239

Franzluebbers AJ, Hons FM, Zuberer DA (1995a) Tillage and crop effects on seasonal soil carbon and nitrogen dynamics. Soil Sci Soc Am J 59:1618–1624

Franzluebbers K, Weaver RW, Juo ASR, Franzluebbers AJ (1995b) Mineralization of carbon and nitrogen from cowpea leaves decomposing in soils with different levels of microbial biomass. Biol Fertil Soils 19:100–102

Franzluebbers AJ, Haney RL, Hons FM, Zuberer DA (1999) Assessing biological soil quality with chloroform fumigation-incubation: why subtract a control? Can J Soil Sci 79:521–528

Frey SD, Elliott ET, Paustian K (1999) Bacterial and fungal abundance and biomass inconventional and no-tillage agroecosystems along two climatic gradients. Soil Biol Biochem 31:573–585

Friebe B, Henke W (1991) Bodentiere und deren Strohabbauleistungen bei reduzierter Bodenbearbeitung. Z. f. Kulturtechnik und Landentwicklung 32:121–126

Frielinghaus M (2002) Soil erosion and pesticide translocation control. In: Pimental D (ed) Encyclopedia of pest management. CRC, New York, pp 777–780

Gál A, Vyn TJ, Michéli E, Kladivko EJ, Mcfee WW (2007) Soil carbon and nitrogen accumulation with long-term no-till versus moldboard plowing overestimated with tilled-zone sampling depths. Soil Till Res 96:42–51

Galloway JN, Townsend AR, Erisman JW, Bekunda M, Cai ZC, Freney JR, Martinelli LA, Seitzinger SP, Sutton MA (2008) Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. Science 320:889–892

Gerard BM, Hay RKM (1979) The effect on earthworms of plowing, tined cultivation, direct drilling and nitrogen in a barley monoculture system. J Agr Sci 93:147–155

Giannakopoulos C, Le Sager P, Bindi M, Moriondo M, Kostopoulou A, Goodess CM (2009) Climatic changes and associated impacts in the Mediterranean resulting from a 2 °C global warming. Glob Planet Change 68:209–224

Gicheru PT (1994) Effects of residue mulch and tillage on soil-moisture conservation. Soil Technol 7:209–220

Goddard T, Haugen-Kozyra K, Ridge A (2009) Conservation agriculture protocols for green house gas offsets in a working carbon market. Paper presented at the IV World Congress on Conservation Agriculture, 3–7 February 2009, New Delhi, India

Gómez JA, Giraldez JV, Fereres E (2005) Water erosion in olive orchards in Andalusia (Southern Spain): a review. Geophys Res Abst 7

Gotwald WH (1986) The beneficial economic role of ants. In: Vinson SB (ed) Economic impact and control of social insects. Praeger, New York, pp 290–313

Govaerts B, Sayre KD, Lichter K, Dendooven L, Deckers J (2007) Influence of permanent raised bed planting and residue management on physical and chemical soil quality in rain fed maize/wheat systems. Plant Soil 291:39–54

Grandy AS, Robertson GP, Thelen KD (2006) Do productivity and environmental trade-offs ustify periodically cultivating no-till cropping systems? Agron J 98:1377–1383

Greb BW (1966) Effect of surface-applied wheat straw on soil water losses by solar distillation. Soil Sci Soc Am Proc 30:786

Gregorich EG, Drur CF, Baldock JA (2001) Changes in soil carbon under long-term maize in monoculture and legume-based rotation. Can J Soil Sci 81:21–31

Gregorich EG, Rochette P, VandenBygaart AJ, Angers D (2005) Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. Soil Till Res 81:53–72

Guggenberger G, Frey SD, Six J, Paustian K, Elliott ET (1999) Bacterial and fungal cellwall residues in conventional and no-tillage agroecosystems. Soil Sci Soc Am J 63:1188–1198

Haines PJ, Uren NC (1990) Effectsof conservation tillage farming on soil microbial biomass, organic matter and earthworm population, in north-eastern Victoria. Aust J Exp Agric 30:365–371

Hansen S, Maehlum JE, Bakken LR (1993) N_2O and CH_4 fluxes in soil influenced by fertilization and tractor traffic. Soil Biol Biochem 25:621–630

Hansen EM, Munkholm LJ, Melander B, Olesen JE (2010) Can non-inversion tillage and straw retainment reduce N leaching in cereal-based crop rotations? Soil Till Res 109:1–8

Harper D (1992) Eutrophication of fresh waters. Chapman & Hall, Saffolk, p 327

Harper LA (2005) Ammonia: measurement issues. In: Hatfield JL, Baker JM, Viney MK (eds) Micrometeorology in agricultural systems, Agronomy Monograph, vol 47. ASA, Madison, pp 345–379

Harrison PA, Butterfield R, Downing TE (1995) Climate change and agriculture in Europe: assessment of impacts and adaptations. Research Report No. 9, Environmental Change Unit, University of Oxford, pp 330–388

Hatfield JL, Sauer TJ, Prueger JH (2001) Managing soils to achieve greater water use efficiency: a review. Agric J 93:271–280

Havlin JL, Kissel DE, Maddux LD, Claassen MM, Long JH (1990) Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Sci Soc Am J 54:448–452

Hernanz JL, Lopez R, Navarrete L, Sanchez-Giron V (2002) Long-term effects of tillage systems and rotations on soil structural stability and organic carbon stratification in semiarid central Spain. Soil Till Res 66:129–141

Hernanz L, Sánchez-Girón V, Navarrete L (2009) Soil carbon sequestration and stratification in a cereal/leguminous crop rotation with three tillage systems in semiarid conditions. Agric Ecosyst Environ 133:114–122

Herrero EV, Mitchell JP, Lanini WT, Temple SR, Miyao EM, Morse RD, Campiglia E (2001) Soil properties change in no-till tomato production. Calif Agric 55:30–34

Holland JM, Reynolds CJM (2003) The impact of soil cultivation on arthropod (Coleoptera and Araneae) emergence on arable land. Pedobiologia 47:181–191

Holt JA, Robertson LN, Radford BJ (1993) Effects of tillage and stubble residue treatments on termite activity in 2 central Queensland vertosols. Aust J Soil Res 31:311–317

Horáček J, Ledvina R, Raus A (2001) The content of quality of organic matter in cambisol in a long-term no tillage system. Rostlinná Výroba 47:205–210

House GJ, Stinner BR (1983) Arthropods in no-tillage soybean agroecosystems—community composition and ecosystem interactions. Environ Manag 7:23–28

House GJ, Parmelee RW (1985) Comparison of soil arthropods and earthworms from conventional and no-tillage agroecosystems. Soil Till Res 5:351–360

Hu ZH, Ling H, Chen ST, Shen SH, Zhang H, Sun YY (2013) Soil respiration, nitrification, and denitrification in a wheat farmland soil under different managements. Commun Soil Sci Plant Anal 44:3092–3102

Huijsmans JFM, Hol JMG, Vermeulen GD (2003) Effect of application method, manure characteristics, weather and filed conditions on ammonia volatilization from manure applied to arable land. Atmos Environ 37:3669–3680

Hulme M, Osborn TJ, Johns TC (1998) Precipitation sensitivity to global warming: comparisons of observations with HadCM2 simulations. Geophys Res Lett 25:3379–3382

Hussain A, Mulholland BJ, Black CR, Taylor IB, Roberts JA (1999a) Novel approaches for examining the effects of differential soil compaction on xylem sap ABA concentration, stomatal conductance and growth in barley (*Hordeum vulgare* L.). Plant Cell Environ 22(11):1377–1388

Hussain I, Olson KR, Ebelhar SA (1999b) Long-term tillage effects on soil chemical properties and organic matter fractions. Soil Sci Soc Am J 63:1335–1341

Hütsch BW (1998) Tillage and land use effects on methane oxidation rates and their vertical profiles in soil. Biol Fertil Soils 27:284–292

Hütsch BW (2001) Methane oxidation, nitrification, and counts of methanotrophic bacteria in soils from a long-term fertilization experiment (“Ewiger Roggenbau”at Halle). J Plant Nutr Soil Sci 164:21–28

Hütsch BW, Webster CP, Powlson DS (1993) Long term effects of nitrogen fertilization on methane oxidation in soil of the broadbalk wheat experiment. Soil Biol Biochem 25:1307–1315

IPCC (2001) Climate Change 2001: The Scientific Basis. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 881

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University , Cambridge, p 996

IPCC (2013) Climate Change 2013: The Physical Science Basis 2013

Jagtap V, Bhargava S, Streb P, Feierabend J (1998) Comparative effect of water, heat and light stresses on photosynthetic reactions in Sorghum bicolor (L.) Moench. J Exp Bot 49:1715–1721

Jarecki MK, Lal R (2003) Crop management for soil carbon sequestration. Crit Rev Plant Sci 22:471–502

Jiang Y, Huang B (2001) Drought and heat stress injury to two cool season turfgrasses in relation to antioxidant metabolism and lipid peroxidation. Crop Sci 41:436–442

Johnson AM, Hoyt GD (1999) Changes to the soil environment under conservation tillage. HortTechnology 9:380–393

Kassam A, Friedrich T, Shaxson F, Pretty J (2009) The spread of conservation agriculture: justification, sustainability and uptake. Int J Agric Sustainabil 7:292–320

Kassam A, Basch G, Friedrich T, Shaxson F, Goddard T, Amado T, Crabtree B, Hongwen L, Mello I, Pisante M, Mkomwa S (2013) Soil management is more than what and how crops are grown. In: Lal R, Stewart BA (eds) Principles of sustainable soil management in agroecosystems. Series: advances in soil sciences. CRC, Boca Raton, pp 338–387, ISBN: 978-1-4665-1346–4

Kay BD (1990) Rates of change of soil structure under different cropping systems. Adv Soil Sci 12:1–52

Kimball BA, Kobayashi K, Bindi M (2002) Responses of agricultural crops to free-air CO_2 enrichment. Advn Agron 77:293–368

Kirkby MJ, Jones RJA, Irvine B, Gobin A, Govers G, Cerdan O, Van Rompaey AJJ, Le Bissonnais Y, Daroussin J, King D, Montanarella L, Grimm M, Vieillefont V, Puigdefabregas J, Boer M, Kosmas C, Yassoglou N, Tsara M, Mantel S, Van Lynden G (2004) Pan-European soil erosion risk assessment: the PESERA Map, Version 1 October 2003. Explanation of special publication

Ispra 2004 No73 (S.P.I.04.73). European Soil Bureau Research Report No. 16, EUR 21176, 18 pp. and I map in ISO B1 format. Office for Official Publications of the European Communities, Luxembourg

Kladivko EJ (2001) Tillage systems and soil ecology. Soil Till Res 61:61–76

Kladivko EJ, Akhouri NM, Weesies G (1997) Earthworm populations and species distributions under no-till and conventional tillage in Indiana and Illinois. Soil Biol Biochem 29:613–615

Klein T, Holzkamper A, Calanca P, Seppelt R, Fuhrer J (2013) Adapting agricultural land management to climate change: a regional multi-objective optimization approach. Landscape Ecol 28:2029–2047

Knowles TA, Singh B (2003) Carbon storage in cotton soils of northern New South Wales. Aust J Soil Res 41:889–903

Kuzyakov Y, Friedel JK, Stahr K (2000) Review of mechanisms and quantification of priming effects. Soil Biol Biochem 32:1485–1498

Laflen JM, Roose EJ (1998) Methodologies for assessment of soil degradation due to water erosion. In: Lal etal (eds) Methods for assessment of soil degradation: advances in soil science. CRC, Boca Raton, pp 31–55

Lafond GP, Walley F, Schoenau J, May WE, Holzapfel CB, McKell J, Halford J (2008) Long-term vs. short-term conservation tillage: 28-43. In: Proceedings of the 20th annual meeting and conference of the Saskatchewan Soil Conservation Association, Regina, Saskatchewan, 12–13 February

Lal R, Follett RF, Stewart BA, Kimble JM (2007) Soil carbon sequestration to mitigate climate change and advance food security. Soil Sci 172(12):943–956

Lampurlanés J, Cantero-Martınez C (2006) Hydraulic conductivity, residue cover and soil surface roughness under different tillage systems in semiarid conditions. Soil Till Res 5:13–26

Le Mer J, Roger P (2001) Production, oxidation, emission and consumption of methane by soils: a review. Eur J Soil Biol 37:25–50

Lessard R, Rochette P, Topp GC, Pattey E, Desjardins RL (1994) Methane and carbon dioxide fluxes from poorly drained adjacent cultivated and forest sites. Can J Soil Sci 74:139–146

Levy PE, Burden A, Cooper MDA, Dinsmore KJ, Drewer J, Evans C, Fowler D, Gaiawyn J, Gray A, Jones SK, Jones T, McNamara NP, Mills R, Ostle N, Sheppard LJ, Skiba U, Sowerby A, Ward SE, Zielinskli P (2012) Methane emissions from soils: synthesis and analysis of a large UK data set. Glob Change Biol 18:1657–1669

Li HW, Gao HW, Wu HD, Li WY, Wang XY, He J (2007) Effects of 15 years of conservation tillage on soil structure and productivity of wheat cultivation in northern China. Aust J Soil Res 45:344–350

Linn DM, Doran JW (1984) Aerobic and anaerobic microbial populations in no-till and plowed soils. Soil Sci Soc Am J 48:794–799

Lobb D, Lindstrom MJ (1999) Tillage translocation and tillage erosion. Poster Presentation at Manitoba Soil Science Society Meeting Winnipeg, Manitoba, vol 75, pp 211–218, 1–2 February 1999

Lobb D, Kachanoski RG, Miller MH (1995) Tillage translocation and tillage erosion on shoulder slope landscape positions measured using 137Cs as a tracer. Can J Soil Sci 75:211–218

Lobell DB, Field CB (2007) Global scale climate-crop yield relationships and the impacts of recent warming. Environ Res Lett 2

López MV, Arrue JL (2005) Soil tillage and wind erosion in fallow lands of Central Aragaon, Spain: an overview. In: Faz A, Ortiz R, Mermut AR (eds) Sustainable use management of soils: arid semiarid regions Advances in Geo Ecology, vol 36. Catena, Reiskirchen, 93–102

Lopez MV, Gracia R, Arrue JL (2001) An evaluation of wind erosion hazards in fallow lands of semiarid Aragon (NE Spain). J Soil Water Conserv 56:212–219

López-Bellido RJ, Fontán JM, López-Bellido FJ, López-Bellido L (2010) Carbon sequestration by tillage, rotation, and nitrogen fertilization in a mediterranean vertisol. Agron J 102:310–318

Lopez-Fando C, Pardo MT (2001) The impact of tillage systems and crop rotations on carbon sequestration in calcic luvisol of central Spain. I World Congress on Conservation Agriculture. Madrid, 1–5 October

López-Fando C, Dorado J, Pardo MT (2007) Effects of zone-tillage in rotation with no-tillage on soil properties and crop yields in a semiarid soil from central Spain. Soil Till Res 95:266–276

Lupwayi NZ, Monreal MA, Clayton GW, Grant CA, Johnston AM, Rice WA (2001) Soil microbial biomass and diversity respond to tillage and sulphur fertilizers. Can J Soil Sci 81:577–589

Magdoff F, Weil RR (2004) Soil organic matter management strategies. In: Magdoff F, Weil RR (eds) Soil organic matter in sustainable agriculture. CRC, New York, pp 45–65

Mando A, Miedema R (1997) Termite-induced change in soil structure after mulching degraded (crusted) soil in the Sahel. Appl Soil Ecol 6:241–249

Marasas ME, Sarandon SJ, Cicchino AC (2001) Changes in soil arthropod functional group in a wheat crop under conventional and no tillage systems in Argentina. Appl Soil Ecol 18:61–68

Mele PM, Carter MR (1999) Impact of crop management factors in conservation tillage farming on earthworm density, age structure and species abundance in south-eastern Australia. Soil Till Res 50:1–10

Mitchell CC, Arriaga FJ, Entry JA, Novak JL, Goodman WR, Reeves DW, Runge MW, Traxler GJ (1996) The Old Rotation, 1896–1996 100 Years of Sustainable Cropping Research. Alabama Agricultural Experiment Station, Auburn, AL.z<1

Miyazawa K, Tsuji H, Yamagata M, Nakano H, Nakamoto T (2002) The effects of cropping systems and fallow managements on microarthropod populations. Plant Prod Sci 5:257–265

Mojeremane W, Rees RM, Mencuccini M (2011) The effects of site preparation practices on carbon dioxide methane and nitrous oxide fluxes from a peaty gley soil. Forestry 19:1–15

Montzka SA, Dlugokencky EJ, Butler JH (2011) Non-CO_2 greenhouse gases and climate change. Nature 476:43–50

Moreno F, Murillo JM, Pelegrín F, Girón IF (2006) Long-term impact of conservation tillage on stratification ratio of soil organic carbon and loss of total and active $CaCO_3$. Soil Till Res 85:86–93

Moretto AS, Distel RA, Didone NG (2001) Decomposition and nutrient dynamic of leaf litter and roots from palatable and unpalatable grasses in a semiarid grassland. Appl Soil Ecol 18:31–37

Moriondo M, Bindi M, Kundzewicz ZW, Szwed M, Chorynski A, Matczak P et al (2010) Impact and adaptation opportunities for European agriculture in response to climatic change and variability. Mitig Adapt Strateg Glob Change 15:657–679

Mrabet R (2008) No-tillage systems for sustainable dryland agriculture in Morocco. Institut National de la Recherche Agronomique, Tangier

Mrabet R, Saber N, El-Brahli A, Lahlou S, Bessam F (2001) Total particulate organic matter and structural stability of a calcixeroll soil under different wheat rotations and tillage systems in a semiarid area of Morocco. Soil Till Res 57:225–235

Mudge F, Adger WN (1995) Methane fluxes from artificial wetlands: a global appraisal. Environ Manag 19:39–55

Mupangwa W, Twomlow S, Walker S, Hove L (2007) Effect of minimum tillage and mulching on maize (Zea mays L.) yield and water content of clayey and sandy soils. Phys Chem Earth 32:1127–1134

Nesbit SP, Breitenbeck GA (1992) A laboratory study of factors influencing methane uptake by soils. Agric Ecosyst Environ 41:39–54

Neue HU (1997) Fluxes of methane from rice fields and potential for mitigation. Soil Use Manag 13:258–267

Newcombe CP, Macdonald DD (1991) Effects of suspended sediments on aquatic ecosystems. N Am J Fisheries Manag 11(1):72–82

Nisbet MC (2009) Communicating climate change: why frames matter for public engagement. Environ Sci Policy Sustain Develop 51(2):12–23

Nkem JN, de Bruyn LAL, Grant CD, Hulugalle NR (2000) The impact of ant bioturbation and foraging activities on surrounding soil properties. Pedobiologia 44:609–621

Nouchi I, Hosono T, Aoki K, Minami K (2010) Seasonal variation in methane flux from rice paddies associated with methane concentration in soil water, rice biomass and temperature, and its modeling. Plant Soil 161:195–208

Novak SM, Fiorelli JL (2010) Greenhouse gases and ammonia emission from organic mixed crop—dairy systems: a critical review of mitigation options. Agron Sustain Dev 30:215–236

Nuutinen V (1992) Earthworm community response to tillage and residue management on different soil types in Southern Finland. Soil Till Res 23:221–239

OECD (2009) The organisation for economic co-operation and development (OECD) annual report. OECD Publ., Paris

OECD (2011) Fostering productivity and competitiveness in agriculture. OECD, Paris

Olesen JE, Trnka M, Kersebaum KC, Skjelvåg AO, Seguin B, Peltonen-Sainio P et al (2011) Impacts and adaptation of European crop production systems to climate change. Eur J Agron 34:96–112

Olesen JE, Børgensen CD, Elsgaard L, Palosuo T, Rötter R, Skjelvåg AO (2012) Changes in time of sowing, flowering and maturity of cereals in Europe under climate change. Food Addit Contam A 29(10):1527–1542

Owens LB, Malone RW, Hothem DL, Starr GC, Lal R (2002) Sediment carbon concentration and transport from small watersheds under various conservation tillage. Soil Till Res 67:65–73

Palm C, Blanco-Canqui H, De Clerck F, Gatere L, Grace P (2013) Conservation agriculture and ecosystem services: an overview. Agric Ecosyst Environ 187:87–105

Papendick RI, Lindstro MJ, Cochran VL (1973) Soil mulch effects on seedbed temperature and water during fallow in Eastern Washington. Soil Sci Soc Am J 37:307–314

Parmesan C (2006) Ecological and evolutionary responses to recent climate change. Annu Rev Ecol Evol Syst 37:637–669

Pelster DE, Chantigny MH, Rochette P, Angers DA, Laganière J, Zebarth B, Goyer C (2013) L̓apport de résidus de culture au sol modifie les émissions de protoxyde d̓azote induites par les cycles gel-dégel. Can J Soil Sci 93:415–425

Peltonen-Sainio P, Jauhiainen L, Hakala K, Ojanen H (2009) Climate change and prolongation of growing season: changes in regional potential for field crop production in Finland. Agric Food Sci 18:171–190

Perego A, Basile A, Bonfante A, De Mascellis R, Terribile F, Brenna S, Acutis M (2012) Nitrate leaching under maize cropping systems in Po Valley (Italy). Agric Ecosyst Environ 47:57–65

Phillips FA, Leuning R, Baigent R, Kelly KB, Denmead OT (2007) Nitrous oxide flux measurements from an intensively managed irrigated pasture using micrometeorological techniques. Agric For Meteorol 143:92–105

Pinheiro EFM, Pereira MG, Anjos LHC (2004) Aggregate distribution and soil organic matter under different tillage systems for vegetable crops in a Red Latosol from Brazil. Soil Till Res 77:79–84

Pisante M (2002) Tecniche agronomiche conservative per la riduzione dei processi di degradazione del suolo. Atti convegno nazionale "Desertificazione: la nuova emergenza del bacino del mediterraneo", Catania-Caltagirone-Palermo, 22–25 maggio 2001, pp 3–9

Pisante M, Corsi S, Amir K, Friedrich T (2010) The challenge of agricultural sustainability for Asia and Europe. Transit Stud Rev 17(4):662–667. doi:10.1007/s11300-010-0181-z

Pisante M, Stagnari F, Grant C (2012) Agricultural innovations for sustainable crop production intensification. Ital J Agron 7(4):300–311

Prasad PVV, Boote KJ, Allen LH (2006a) Adverse high temperature effects on pollen viability, seed-set, grain yield and harvest index of grain sorghum [Sorghum bicolor (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperatures. Agric For Meteorol 139:237–251

Prasad PVV, Boote KJ, Allen LH, Sheehy JE, Thomas JMG (2006b) Species, ecotype and cultivar differences in spikelet fertility and harvest index of rice in response to high temperature stress. Field Crops Res 95:398–411

Prasad PVV, Staggenborg SA (2008) Impacts of drought and/or heat stress on physiological, developmental, growth, and yield processes of crop plants. In: Ajuha LR, Reddy VR, Saseendran SA, Yu Q (eds) Response of crops to limited water: understanding and modeling water stress effects on plant growth processes. American Society of Agronomy, Madison, pp 301–356

Puget P, Chenu C, Balesdent J (1995) Total and young organic matter distributions in aggregates of silty cultivated soils. Eur J Soil Sci 46:449–459

Qaderi MM, Reid DM (2005) Growth and physiological responses of canola (*Brassica napus*) to UV-B and CO_2 under controlled environment conditions. Physiol Plant 125:247–259

Quine TA, Walling DE (1993) Use of caesium—137 measurements to investigate relationships between erosion rates and topography. In: Thomas DSG, Allison RJ (eds) Landscape sensitivity. Wiley, Chichester, pp 31–48

Rao KPC, Steenhuis TS, Cogle AL, Srinivasan ST, Yule DF, Smith GD (1998) Rainfall infiltration and runoff from an Alfisol in semiarid tropical India. I. No-till systems. Soil Till Res 48:51–59

Raper RL, Reeves DW, Schwab EB, Burmester CH (2000) Reducing soil compaction of Tennessee Valley soils in conservation tillage systems. J Cotton Sci 4(2):84–90

Rasmussen KJ (1999) Impact of ploughless soil tillage on yield and soil quality: a Scandinavian review. Soil Till Res 53:3–14

Reeleder RD, Miller JJ, Coelho BRB, Roy RC (2006) Impacts of tillage, cover crop, and nitrogen on populations of earthworms, microarthropods, and soil fungi in a cultivated fragile soil. Appl Soil Ecol 33:243–257

Regina K, Alakukku L (2010) Greenhouse gas fluxes in varying soil types under conventional and no-tillage practices. Soil Till Res 109:144–152

Reicosky DC (1997) Tillage-induced CO_2 emissions from soil. Nutr Cycl Agroesyst 49:273–285

Reicosky DC (1998) Effect of Tillage on the release of CO_2. Paper presented to the Symposium "Conservation Tillage: can it assist in mitigating the Greenhouse Gas Problem?". The University of Queensland

Reicosky DC, Lindstrom MJ (1993) Fall tillage methods: effect on short-term carbon dioxide flux from soil. Agron J 85-6:1237–1243

Reicosky DC, Lindstrom MJ (1995) Impact of fall tillage and short-term carbon dioxide flux. In: Lal R, Kimble J, Levine E, Stewart B (eds) Soil Global Change. Lewis , Chelsea, pp 177–187

Reicosky DC, Lindstrom MJ, Schumacher TE, Lobb D, Malo DD (2005) Tillage-induced CO_2 loss across an eroded landscape. Soil Till Res 81(2):183–194

Rhoton FE, Shipitalo MJ, Lindbo DL (2002) Runoff and soil loss from midwestern and southeastern US silt loam soils as affected by tillage practice and soil organic matter content. Soil Till Res 66:1–11

Riley HCF, Bleken MA, Abrahamsen S, Bergjord AK, Bakken AK (2005) Effects of alternative tillage systems on soil quality and yield of spring cereals on silty clay loam and sandy loam soils in the cool, wet climate of central Norway. Soil Till Res 80:79–93

Rizhsky LH, Liang H, Shuman J, Shulaev V, Davletova S, Mittler R (2004) When defense pathways collide: the response of Arabidopsis to a combination of drought and heat stress. Plant Physiol 134:1683–1696

Robertson LN, Kettle BA, Simpson GB (1994) The influence of tillage practices on soil macrofauna in a semiarid agroecosystem in Northeastern Australia. Agric Ecosyst Environ 48:149–156

Robertson GP, Bruulsema TW, Gehl RJ, Kanter D, Mauzerall DL, Rotz CA, Williams CO (2012) Nitrogen-climate interactions in US agriculture. Biogeochemistry 114:41–70

Robinson CA, Cruse RM, Ghaffarzadeh M (1996) Cropping system and nitrogen effects on Mollisol organic carbon. Soil Sci Soc Am J 60:264–269

Rochette P (2008) No-till only increases N_2O emissions in poorly-aerated soils. Soil Till Res 101:97–100

Rochette P, Janzen HH (2005) Towards a revised coefficient for estimating N_2O emissions from legumes. Nutr Cycl Agroecosyst 73:171–179

Rochette P, Angers DA, Chantigny MH, Bertrand N (2008) N_2O emissions respond differently to no-till in a loam and a heavy clay soil. Soil Sci Soc Am J 72:1363–1369

Röhrig R, Langmaack M, Schrader S, Larink O (1998) Tillage systems and soil compaction: their impact on abundance and vertical distribution of Enchytraeidae. Soil Till Res 46:117–127

Roth CH, Meyer B, Frede HG, Derpsch R (1988) Effect of mulch rates and tillage systems on infiltrability and other soil physical-properties of an oxisol in Parana, Brazil. Soil Till Res 11:81–91

Rötter RP, Palosuo T, Pirttioja NK, Dubrovski M, Salo T, Fronzek S, Aikasalo R, Trnka M, Ristolainen A, Carter TR (2011) What would happen to barley production in Finland if global warming exceeded 4°C? A model-based assessment. Eur J Agron 35:205–214

Rovira AD, Smettem KRJ, Lee KE (1987) Effect of rotation and conservation tillage on earthworms in a red-brown earth under wheat. Aust J Agric Res 38:829–834

Sauer TJ, Hatfield JL, Prueger JH (1996) Corn residue age and placement effects on evaporation and soil thermal regime. Soil Sci Soc Am J 60:1558–1564

Sauer TJ, Hatfield JL, Prueger JH (1997) Over-winter changes in radiant energy exchange of a corn residue-covered surface. Agric Forest Meteorol 85:279–287

Schütz H, Holzapfel-Pschorn A, Conrad R, Rennenberg H, Seiler W (1989) A three years continuous record on the influence of daytime, season and fertilizer treatment on methane emission rates from an Italian rice paddy field. J Geophys Res 94:16405–16416

Seghers D, Top EM, Reheul D, Bulcke R, Boeckx P, Verstraete W, Siciliano SD (2003) Long-term effects of mineral versus organic fertilizers on activity and structure of the methanotrophic community in agricultural soils. Environ Microbiol 5:867–877

Seinfeld JH, Pandis SN (2006) Atmospheric chemistry and physics: from air pollution to climate change. Wiley, New York, pp 1–1203

Sidiras N, Pavan MA (1985) Influencia do sistema de manejo do solo no seu nivel de fertilidade. Rev Bras Cienc Solo 9:244–254

Sisti CPJ, dos Santos HP, Kohhann R, Alves BJR, Urquiaga S, Boddey RM (2004) Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. Soil Till Res 76:39–58

Six J, Elliot ET, Paustian K, Doran JW (1998) Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci Soc Am J 62:1367–1377

Six J, Ogle SM, Breidt FJ, Conant RT, Mosier AR, Paustian K (2004) The potential to mitigate global warming no-tillage management is only realized when practiced in the long run. Global Change Biol 10:155–160

Skjøth CA, Geels C (2013) The effect of climate and climate change on ammonia emissions in Europe. Atmos Chem Phys 13:117–128

Smith P, Olesen JE (2010) Synergies between the mitigation of, and adaptation to, climate change in agriculture. J Agric Sci 148:543–552

Smith P, Powlson DS, Glendenning MJ, Smith JU (1998) Preliminary estimates of the potential for carbon mitigation in European soils through no-till farming. Global Change Biol 4:679–685

Smith P, Goulding KW, Smith KA, Powlson DS, Smith JU, Falloon P, Coleman K (2001) Enhancing the carbon sink in European agricultural soils: including trace gas fluxes in estimates of carbon mitigation potential. Nutr Cycl Agroecosyst 60:237–252

Soane BD, Ball BC, Arvidsson J, Basch G, Moreno F, Roger-Estrade J (2012) No-till in northern, western and south-western Europe: a review of problems and opportunities for crop production and the environment. Soil Till Res 118:66–87

Sommer SG, Hutchings NJ (2001) Ammonia emission from field applied manure and its reduction—invited paper. Eur J Agron 15:1–15

Sommer SG, Schjoerring JK, Denmead OT (2004) Ammonia emission from mineral fertilizers and fertilized crops. Adv Agron 82:558–622

Soussana JF, Lüscher A (2007) Temperate grasslands and the global atmospheric change: a review. Grass Forage Sci 62:127–134

Southworth J, Randolph JC, Habeck M, Doering OC, Pfeifer RA, Rao DG et al (2000) Consequences of future climate change and changing climate variability on maize yields in the midwestern United States. Agric Ecosyst Environ 82:139–158

Spedding TA, Hamel C, Mehuys GR, Madramootoo CA (2004) Soil microbial dynamics in maize-growing soil under different tillage and residue management systems. Soil Biol Biochem 36:499–512

Springett JA (1992) Distribution of lumbricid earthworms in New Zealand. Soil Biol Biochem 24:1377–1381

Stagnari F, Ramazzotti S, Pisante M (2009) Conservation agriculture: a different approach for crop production through sustainable soil and water management: a review. Agronomy for sustainable development. In: Lichtfouse E (ed) Organic farming, pest control and remediation of soil pollutants, sustainable agriculture reviews 1. Springer, New York, pp 55–83. doi:10.1007/978-1-4020-9654-9

Stahl PD, Parkin TB, Christensen M (1999) Fungal presence in paired cultivated and uncultivated soils in central Iowa, USA. Biol Fertil Soils 29:92–97

Steiner JL (1989) Tillage and surface residue effects on evaporation from soils. Soil Sci Soc Am J 53:911–916

Stinner BR, House GJ (1990) Arthropods and other invertebrates in conservation-tillage agriculture. Annu Rev Entomol 35:299–318

Stockfisch N, Forstreuter T, Ehlers W (1999) Ploughing effects on soil organic matter after twenty years of conservation tillage in Lower Saxony, Germany. Soil Till Res 52:91–101

Stuart M, Gooddy D, Bloomfield J, Williams A (2011) A review of the impact of climate change on future nitrate concentrations in groundwater of the UK. Sci Total Environ 409(15):2859–2873

Sudhishri S, Dass A, Lenka NK (2008) Efficacy of vegetative barriers for rehabilitation of degraded hill slopes in eastern India. Soil Till Res 99:98–107

Supit I, Van Diepen CA, De Wit AJW, Kabat P, Baruth B, Ludwig F (2010) Recent changes in the climatic yield potential of various crops in. Europe Agric Syst 103:683–694

Sutton M (2006) Scope and overview of the UNECE Expert Workshop on Ammonia. C. E. H. Clean Air, December, Edinburgh, pp 1–8

Tebrügge F (2001) No-tillage visions-protection of soil, water and climate and influence on management and farm income. Garcia-Torres L Benites J Martınez-Vilela A (eds) Conservation agriculture-a worldwide challenge World Congress on Conservation Agriculture 1:303–316

Tebrügge F (2000) No-tillage visions—protection of soil, water and climate. Justus-Liebig University, Giessen

Tebrügge F, During RA (1999) Reducing tillage intensity—a review of results from a long-term study in Germany. Soil Till Res 53:15–28

Terman GL (1979) Volatilization of nitrogen as ammonia from surface applied fertilizers, organic amendments and crop residues. Agron J 31:189–223

Thierfelder E, Amézquita C, Stahr K (2005) Effects of intensifying organic manuring and tillage practices on penetration resistance and infiltration rate. Soil Till Res 82(2):211–226

Tolk JA, Howell TA, Evett SR (1999) Effect of mulch, irrigation, and soil type on water use and yield of maize. Soil Till Res 50:137–147

Tubiello FN, Amthor JS, Boote KJ, Donatelli M, Easterling W, Fischer G et al (2007) Crop response to elevated CO_2 and world food supply. A comment on 'Food for Thought… ' by Long et al. Science 312, 1918–1921. Eur J Agron 26:215–233

Unger PW (1991) Organic-matter, nutrient, and ph distribution in no-tillage and conventional-tillage semiarid soils. Agric J 83:186–189

Unger PW, Parker JJ (1976) Evaporation reduction from soil with wheat, sorghum, and cotton residues. Soil Sci Soc Am J 40:938–942

Uri ND, Atwood JD, Sanabria J (1998) The environmental benefits and costs of conservation tillage. Sci Total Environ 216:13–32

Ussiri DAN, Lal R, Jarecki MK (2009) Nitrous oxide and methane emissions from long-term tillage under a continuous corn cropping system in Ohio. Soil Till Res 104:247–255

Van derMJ, Van Faassen HG, Vertregt N, Bussink W, Den Boer DJ (1989) Ammonia emissions from arable and grassland soils. In: Hansen JA, Hendricksen K (eds) Nitrogen in organic wastes applied to soil. Academic, Waltham, pp 185–201

Van DBosscheA, De Bolle S, De Neve S, Hofman G (2009) Effect of tillage intensity on N mineralization of different crop residues in a temperate climate. Soil Till Res 103:316–324

Van denHRN, Bakker SE, Jetten MSM, Hefting MM (2011) Decreased N_2O reduction by low soil pH causes high N_2O emissions in a riparian ecosystem. Geobiology 9:294–300

Van Groenigen JW, Oenema O, Van Groenigen KJ, Velthof G, Van Kessel C (2011) Best nitrogen management practices to decrease greenhouse gas emissions. Better Crops 95(2):16–17

Van Kessel C, Farrell RE, Roskoski JP (1994) Recycling of the naturally-occurring 15 N in an established stand of Leucaena leucocephala. Soil Biol Biochem 26:757–762

Van Kessel C, Venterea R, Ix JS, Adviento-Borbe MA, Linquist B, van Groenige KJ (2013) Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: a meta-analysis. Global Change Biol 19:33–44

Van den Bygaart AJ, Yang XM, Kay BD, Aspinall JD (2002) Variability in carbon sequestration potential in no-till soil landscapes of southern Ontario. Soil Till Res 65(2):231–241

Van den Bygaart AJ, Gregorich EG, Angers DA (2003) Influence of agricultural management on soil organic carbon: a compendium and assessment of Canadian studies. Can J Soil Sci 83:363–380

Venterea RT, Dolan MS, Ochsner TE (2010) Urea decreases nitrous oxide emissions compared with anhydrous ammonia in a Minnesota corn cropping system. Soil Sci Soc Am J 74:407–418

Wanniarachchi SD, Voroney RP, Vyn TJ, Beyaert RP, MacKenzie AF (1999) Tillage effects on the dynamics of total and corn-residue-derived soil organic matter in two southern Ontario soils. Can J Soil Sci 79:473–480

Wardle DA (1995) Impacts of disturbance on detritus food webs in agro-ecosystems of contrasting tillage and weed management practices. In: Begon M, Fitter AH (eds) Advances in ecological research. Academic, New York, pp 105–185

Wassmann R, Wang MX, Shangguan XJ, Xie XL, Shen RX, Wang YS, Papen H, Rennenberg H, Seiler W (1993) First records of a field experiment on fertilizer effects on methane emission from rice fields in Hunan-province (PR China). Geophys Res Lett 20:2071–2074

Webb J, Pain B, Bittman S, Morgan J (2010) The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response-A review. Agric Ecosyst Environ 137:39–46

West TO, Post WM (2002) Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci Soc Am J 66(6):1930–1946

Wheeler TR, Ellis RH, Hadley P, Morison JIL, Batts GR, Daymond AJ (1996) Assessing the effects of climate change on field crop production. Aspects Appl Biol 45:49–54

Whitbread AM, Lefroy RDB, Blair GJ (1998) A survey of the impact of cropping on soil physical and chemical properties in north-western New South Wales. Aust J Soil Res 36:669–681

Wuebbles DJ, Hayhoe K (2002) Atmospheric methane and global change. Earth Sci Rev 57:177–221

Wuest SB (2001) Earthworm, infiltration, and tillage relationships in a dryland pea-wheat rotation. Appl Soil Ecol 18:187–192

Wyss E, Glasstetter M (1992) Tillage treatments and earthworm distribution in a swiss experimental corn field. Soil Biol Biochem 24:1635–1639

Xu H, Cai ZC, Tsuruta H (2003) Soil moisture between rice-growing seasons affects methane emission, production, and oxidation. Soil Sci Soc Am J 67:1147–1157

Xu L, Penner JE (2012) Global simulations of nitrate and ammonium aerosols and their radiative effects. Atmos Chem Phys 12:9479–9504

Yang SS, Chang HL (2001) Methane emission from paddy fields in Taiwan. Biol Fertil Soils 33:157–165

Yang XM, Kay BD (2001) Impacts of tillage practices on total, loose- and occluded-particulate, and humified organic carbon fractions in soils within a field in southern Ontario. Can J Soil Sci 81:149–156

Yano T, Aydin M, Haraguchi T (2007) Impact of climate change on irrigation demand and crop growth in a Mediterranean environment of Turkey. Sensors 7:2297–2315

Zavattaro L, Monaco S, Sacco D, Grignani C (2012) Options to reduce N loss from maize in intensive cropping systems. Agric Ecosyst Environ 147:24–35

Zhao M, Running SW (2010) Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science 329:940–943

Zunino M (1991) Food relocation behaviour: a multivalent strategy of Coleoptera. In: Zunino M, Bellés X, Blas M (eds) Advances in coleopterology. AEC, Barcelona, pp 297–313

Chapter 23
Farmer Adoption of Conservation Agriculture: A Review and Update

Duncan Knowler

Abstract Conservation agriculture (CA) reduces soil productivity loss by introducing various practices that minimize changes to soil composition and structure. Adoption of CA remains a challenge despite reasonable economic evidence for its desirability from an on-farm perspective in most regions and, even more so, from a social perspective (with perhaps the exception of Africa). Although on-farm profitability for CA varies, it is not likely to be the key barrier to adoption. Instead, it is argued here that other factors play a critical role in determining the successful dissemination of CA practices among farmers but that these will vary from site to site. This chapter explores the issues involved in the adoption of CA, first by reviewing existing research on economic profitability and other factors thought to influence adoption and, second, by considering what new directions this research is taking, or could take, in order to better understand on-farm adoption behaviour. It is argued that the addition of further empirical studies using advanced methods and new perspectives to assess sustainable farming methods could increase our understanding of the adoption and diffusion of new farming technologies such as CA. Using better approaches to model individual decisions regarding CA adoption is one area to improve our understanding of adoption. Though social, institutional and network (social capital) factors are extremely important, they are not addressed in detail here as the methods are quite different. Although the issues and approaches related to the study of agricultural technology adoption discussed in this chapter are in the context of promoting CA, they have a much broader relevance for the study of other sustainable farming technologies.

Keywords Economics · Tillage · Sustainable agriculture · Technology dispersal · Africa

---

D. Knowler (✉)
School of Resource and Environmental Management,
Simon Fraser University, Burnaby, British Columbia, Canada
e-mail: djk@sfu.ca

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4_23

23.1 Introduction

Conservation agriculture (CA) reduces soil productivity loss by introducing various practices that minimize changes to soil composition and structure (ECAF 2001). CA maintains permanent or semi-permanent organic soil cover with a growing crop or mulch that physically protects the soil from the elements and feeds soil biota. Zero-tillage with direct seeding is perhaps the best example of CA, since it avoids the disturbance caused by mechanical tillage. A varied crop rotation is also important to avoid disease and pest problems. Some examples of CA techniques include: (i) direct sowing/direct drilling/no-tillage, where the soil remains undisturbed from harvest to planting except for nutrient injection; (ii) ridge-till, where the soil remains undisturbed but planting takes place in a seedbed prepared on ridges; (iii) mulch till/reduced tillage/minimum tillage, where the soil is disturbed prior to planting; and (iv) cover crops, where appropriate species are sown between successive annual crops to prevent soil erosion and to control weeds.

This chapter explores the issues involved in the adoption of CA, first by reviewing the literature which examines economic profitability and other factors thought to influence adoption and, second, by considering new directions that this research is taking, or could take, in order to better understand on-farm adoption behaviour. Using better approaches to model individual decisions regarding CA adoption is one area to improve our understanding of adoption. However, social, institutional and network (social capital) factors are increasingly important for adoption research but are not addressed in detail here as the methods are quite different. For an overview of some of these approaches within the broader context of natural resources management, see Moore and Cisse (2005). For an example of a method to measure social capital empirically that can be used in statistical modelling, see Wood et al. (2008).

The past several decades have seen rapid advances in the technologies associated with minimum or no-tillage agriculture and their adaptation for nearly all farm sizes, soil and crop types and climate zones. To date, CA has been implemented on approximately 125 million ha worldwide (Kassam et al. 2012), but adoption remains slow in some regions (e.g. Africa). As such, there is considerable interest in promoting further CA adoption around the world. To effectively do so, it must first be demonstrated that, for society as a whole, adoption of the new technology generates net benefits (however defined). While few studies have addressed this broader social welfare aspect of agricultural technologies such as CA, it is often assumed that the net benefits are positive. Table 23.1 shows the spatial incidence of benefits from adopting CA.

Table 23.1 suggests that there may be substantial benefit beyond the farm itself for which the farmer may not be compensated. That is, differences appear to exist between privately appropriable benefits and national or global economic benefits stemming from an expansion of the area under CA. In agriculture sectors around the world, government policy has long sought to address such divides in an effort to boost collective benefits. This situation would appear to similarly invite the promotion of CA by government, international and non-government agencies; however,

Table 23.1 The distribution of benefits and costs associated with conservation agriculture across different spatial scales (*check mark* indicates presence of benefit or cost). (Source: Knowler and Bradshaw 2007)

Benefits and costs	Incidence at various scales		
	Farm	Regional/national	Global
Benefits			
Reduction in on-farm costs: savings in time, labour and mechanized machinery	✓		
Increase in soil fertility and moisture retention, resulting in long-term yield increase, decreasing yield variations and greater food security	✓	✓	✓
Stabilization of soil and protection from erosion leading to reduced downstream sedimentation		✓	
Reduction in toxic contamination of surface water and groundwater		✓	
More regular river flows, reduced flooding and the re-emergence of dried wells		✓	
Recharge of aquifers as a result of better infiltration		✓	
Reduction in air pollution resulting from soil tillage machinery		✓	✓
Reduction of CO_2 emissions to the atmosphere (carbon sequestration)			✓
Conservation of terrestrial and soil-based biodiversity			✓
Costs			
Purchase of specialized planting equipment	✓		
Short-term pest problems due to the change in crop management	✓		
Acquisition of new management skills	✓		
Application of additional herbicides	✓	✓	
Formation and operation of farmers' groups	✓	✓	
High perceived risk to farmers because of technological uncertainty	✓	✓	
Development of appropriate technical packages and training programmes		✓	

questions exist around the effectiveness of particular policy approaches and whether CA is sufficiently attractive to farmers and to society in some regions to warrant aggressive government intervention (Giller et al. 2009). These questions are not easily answered; technology adoption at the smallholder level is complex, as demonstrated in Fig. 23.1.

In Fig. 23.1, smallholders make choices about technology and resource use under the constraints imposed by their household and on-farm resources, as well as higher level factors at local to global scales. Information about new technologies and financial conditions is a precursor to changes in farm practices. All these factors affect net returns, risks and other pecuniary elements that drive the decision-making process which are then subject to a variety of feedbacks that further complicate the decision process.

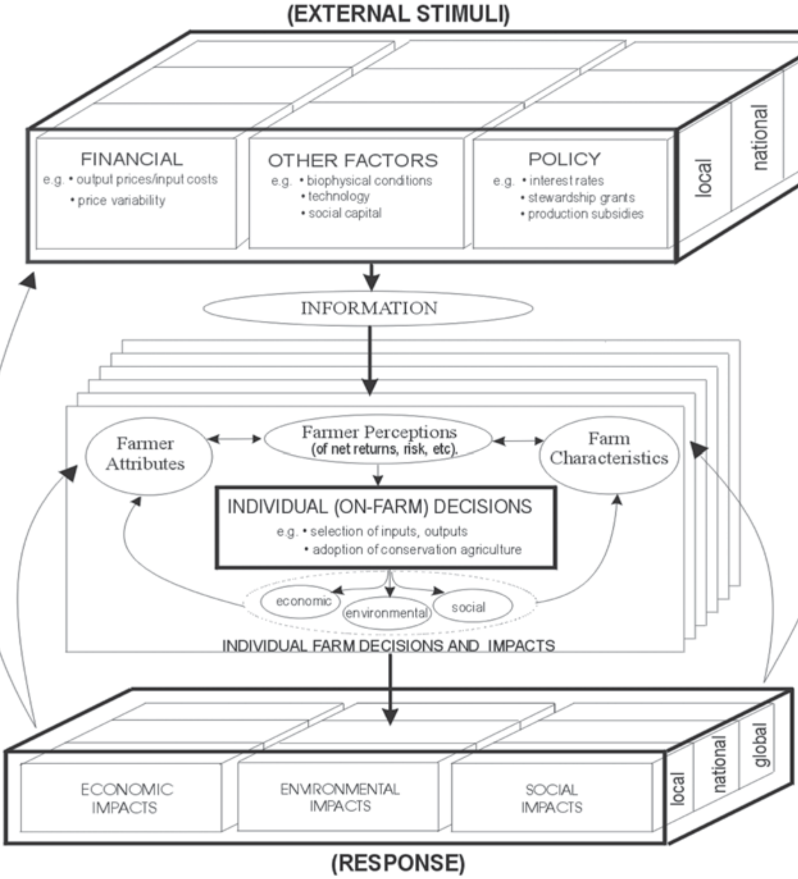


Fig. 23.1 A conceptual framework for studying the adoption of conservation agriculture. (Source: FAO 2001)

In the following sections, financial and other factors that play upon the adoption of CA and similar technologies by smallholders are reviewed within the context of Fig. 23.1. Is farm profitability likely to improve when adopting CA? If not, what factors help explain when it is or is not profitable? While financial profitability may be necessary, it is not a sufficient condition for adoption, as many studies have shown. More recent research has employed increasingly sophisticated statistical tools to analyze the myriad influences on adoption. Some of this new research is discussed here (other new directions include social learning, network analysis and social capital, but these are not covered in detail). In particular, the traditional statistical approach to modelling adoption decisions at the farm level needs upgrading to account for a variety of influences not always properly considered in farm-level adoption studies. We can reasonably ask: What new approaches for modelling the adoption of sustainable agricultural technology, and specifically CA, at the farm level are most promising? The chapter concludes with an assessment of the current state of and some possible future directions for CA adoption research.

23.2 Farmer Adoption of Conservation Agriculture

In the following section, farmer adoption of CA is considered from two distinct perspectives. First, the role of financial profitability is analyzed in terms of whether CA technologies are likely to be viable and under what conditions. Second, other factors potentially influencing adoption are assessed.

23.2.1 Financial Considerations in Adopting Conservation Agriculture

Crosson (1981) and numerous subsequent financial analyses of conservation tillage have shown that typically it produces higher farm-level net returns than conventional tillage. Much of this advantage stems from reduced costs for machinery, fuel and labour, combined with unchanged or improved yields over time. Beyond conservation tillage, numerous soil-conserving practices typically produce net financial benefits for adopters, but certainly not all. An important question is whether CA is more likely to be profitable than other soil and water conservation technologies. To help answer this question, a meta-analysis was carried out of farm-level financial analyses from sub-Saharan Africa and Latin America/Caribbean undertaken during the 1990s. This was a period when soil and water conservation was promoted aggressively by various multi-lateral banks and agencies. Table 23.2 presents data collected from 12 different studies, each of which included up to two dozen individual technology analyses. These analyses examined the on-farm, financial profitability of a given technology and reported this as a discounted net present value (NPV), benefit–cost ratio (BCR) or internal rate of return (IRR). The number of technology analyses demonstrating positive profitability (e.g. $NPV>0$) varied from study to study. To derive some insight as to the relative financial attractiveness of CA technologies versus other conservation technologies, a regression analysis was carried out on the data contained in the studies.

Each study used standard cost–benefit methodology and decision criteria to assess profitability (Hanley and Barbier 2009). Of the 130 individual technology analyses indicated in Table 23.2, 95 were suitable for the regression procedure in terms of providing complete information for all the variables of interest. For the dependent variable, technology analyses were partitioned according to the NPV criteria ($NPV>0$ or <0) to give a binary variable coded as 0 or 1, enabling use of the binomial probit procedure. Each of the 95 technologies was then coded according to the World Overview of Conservation Approaches and Technologies (WOCAT) classification system for conservation technologies (WOCAT 2004) which recognizes four classes of technology:

(i) Agronomic (cover crops, mulching, conservation tillage, etc.)
(ii) Vegetative (grass strips, *Vetivera* spp., etc.)
(iii) Structural (drains, terraces, check dams, etc.)
(iv) Management (not used)

Table 23.2 Description of 130 conservation technology financial analyses contained in 12 economic studies from which 95 technology analyses were used in the regression analysis

Study	Location	No. of technology analyses	Percentage with NPV>0 (%)	Ex ante or Ex post
Barbier (1992)	Africa	6	100.0	Ex post
Current and Scherr (1995)	C. America/ Caribbean	34	79.4	Ex post
Ehui et al. (1990)	Africa	3	100.0	Ex ante
Ellis-Jones et al. (1995)	C. America/ Caribbean	11	27.3	Ex ante
FAO/IC (1991)	Africa	11	27.3	Ex ante
Giger et al. (1999)	Africa	27	51.9	Ex post
Kuyvenhoven et al. (1998	Africa	1	100.0	Ex ante
Lutz et al. (1994)	C. America/ Caribbean	11	63.6	Ex ante
Mwanza and Place (1995)	Africa	1	100.0	Ex ante
Williams (1997)	Africa	2	100.0	Ex post
World Bank (1990)	Africa	10	90.0	Ex ante
World Bank (1992)	Africa	13	53.8	Ex ante

FAO Food and Agriculture Organization, *IC* investment center

While not a perfect correspondence, the agronomic class essentially represents what is referred to as CA, as these technologies are associated with annual crops and are repeated each growing season or in a rotational sequence. In contrast, vegetative technologies are of longer duration and often lead to a changed slope profile through use of perennial grasses, shrubs or trees to construct grass strips, hedge barriers or windbreaks. All technology variables were coded as dummy variables, so that each study analysis technology was coded ‘1’ for the relevant technology class and ‘0’ for other technology class variables. The management technology class was not used and the structural technology variable was left out of the estimated regression relationship to avoid the dummy variable trap.

In addition to the type of technology used as an independent variable, several other independent variables were included in the regression analysis; the discount rate was considered since benefit–cost analysis outcomes can depend on this parameter and the project life used in the technology analysis was considered for the same reason. Several additional steps were included to test for possible biases. First, we added a dummy variable to indicate whether a study had been conducted ex ante or ex post, since conceivably this might affect the outcome of the analysis. Second, after preliminary model runs, studies from Africa showed a systematic influence not apparent in studies conducted elsewhere, so an additional dummy variable was used to indicate an African study site. Finally, as the data consisted of a larger set of technology analyses (95) spread across only 12 individual studies, it was important to test for a researcher or study bias influencing the individual technology outcomes. As a result, a random effects model was employed to test for such an effect. In the end, the estimated binary probit model took the following form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \epsilon, \tag{23.1}$$

Table 23.3 Results of binary probit regression analysis where dependent variable is based on whether analysis demonstrates $NPV > 0$ ($Y = 1$) or $NPV < 0$ ($Y = 0$), $n = 95$

Variables	Model 1		Model 2	
	Parameters	Marginal effects[a]	Parameters	Marginal effects[a]
Constant (β_0)	3.126[b]	1.111[b]	4.243[c]	1.510[c]
	(2.18)	(2.29)	(4.15)	(4.42)
Agronomic dummy (β_1)	1.431c	0.392c	1.355c	0.378c
	(3.20)	(4.45)	(3.22)	(4.43)
Vegetative dummy (β_2)	0.977b	0.318c	0.826b	0.274c
	(2.48)	(2.82)	(2.39)	(2.65)
Africa dummy (β_3)	−1.084	−0.360b	−1.486c	−0.476c
	(−1.91)	(−2.13)	(−3.49)	(−4.19)
Discount rate (β_4)	−0.181c	−0.064c	−0.205c	−0.073c
	(−3.35)	(−3.40)	(−4.24)	(−4.35)
Project life (β_5)	0.016	0.0058	–	–
	(1.02)	(1.01)		
Ex post dummy (β_6)	0.222	0.079	–	–
	(0.67)	(0.67)		
Prediction accuracy (%)	75.8		76.8	

[a] Marginal effect for dummy variable is $P(1-P)0$ (Greene 1993)

[b] 5 % level of significance

[c] 1 % level of significance

where

Y	Index measure of technology profitability (binary-dependent variable)
X_1	Dummy for an agronomic technology
X_2	Dummy for a vegetative technology
X_3	Dummy for an African study location
X_4	Measures the discount rate used
X_5	Measures the project life used in the technology analysis
X_6	Dummy for an ex ante versus ex post analysis
ϵ	The error term

Two models were estimated using LIMDEP 7.0 and the results are shown in Table 23.3. As part of the analysis, various statistical tests for bias were carried out. For example, random effects modelling did not reveal a systematic study-by-study influence related to authorship, nor was there any statistical significance associated with whether the studies were carried out ex ante or ex post. Project life did not significantly influence the results. Only the test for a regional or geographic bias turned up a significant influence, in the case of Africa. All other coefficients for the explanatory variables were significant at the 1 % level or, at worst, the 5 % level of significance (Table 23.3). Since the coefficients for project life and ex ante/ex post variables were not significant at the 5 % level, the ensuring discussion focuses on the results for Model 2, which excludes these two variables.

The analysis reveals that for the sub-Saharan African and Latin American/Caribbean regions, financial analyses of various farm-level conservation practices produce a positive NPV in most cases (Table 23.2). However, the regression analysis showed that technology clearly makes a systematic difference with agronomic technologies (CA) most likely to produce a positive NPV, followed by vegetative technologies, which in turn are preferred to structural technologies (Table 23.3). As a measure of this increased attractiveness associated with CA technologies, the marginal effects indicate that shifting from a structural to a vegetative technology increases the probability of a positive NPV by 0.274, and moving from a vegetative to an agronomic technology increases this probability a further 0.104–0.374. Geographic location matters too, since African studies are markedly less likely to be profitable when all else is equal. As a measure of this negative influence, shifting from a Latin American or Caribbean to an African site reduces the probability of viability by −0.48. More recent research has raised concerns about the economic attractiveness of CA-specific smallholder conditions in Africa (Giller et al. 2009). The results reported here appear to reinforce that concern. However, the debate around this point continues to stir controversy and is yet to be resolved.

23.2.2 Other Considerations in Adopting Conservation Agriculture

Can we draw final conclusions about technology from economic studies alone? Probably not, since other factors are sure to be important. If true, then even if the practices associated with CA are profitable, their diffusion among farmers need not occur automatically. In other words, there is a need to identify factors beyond just farm-level profitability that explain adoption of CA. For example, if many farmers in a locale face similar conditions of profitability, why do some adopt new technologies and others not? There is a long and rich tradition of research that seeks to explain farmers' adoption of particular agricultural innovations (Feder et al. 1985). Researchers typically select a number of potential independent variables for inclusion in their analysis based on prior theorizing and test, usually via logistic (logit) or probit regression, which variables correlate with adoption. Variables typically used in such analyses and their explanatory power were reviewed by Knowler and Bradshaw (2007) and a summary of their findings is presented below.

Farmer awareness or perception of soil problems frequently is correlated positively with the adoption of soil conservation practices like no-till. More generally, assessments of the presence of conservation attitudes among farmers adopting CA have revealed both positive and insignificant correlations. For example, the education level of a farm operator commonly correlates positively with the adoption of CA practices; however, some analyses have found education to be an insignificant factor, or even negatively correlated with adoption. The farmer's age has been assessed often but it is difficult to link to the adoption of CA, as with assessments of 'experience' that reveal both positive and insignificant correlations.

Assessments of the adoption of conservation tillage and similar soil conserving practices have often included the biophysical characteristics of the farm itself. For example, owners of larger operations may be more willing to invest in new technologies such as direct seed drills. However, empirical studies demonstrate mixed results so that the overall impact of farm size on adoption is inconclusive, despite casual empirical evidence from individual countries such as the USA or, perhaps, Brazil. With respect to rainfall, similar mixed results have been observed. Some studies have found that the presence of soil erosion and other soil problems on a farm correlate positively with conservation tillage adoption. Related to this finding, various studies have shown that farm operations located within regions of steep slopes and erodible soils have a greater tendency to adopt soil conservation practices, but not always. Indeed, farmer awareness of, and concern for, soil erosion is probably the more critical factor affecting adoption.

Land tenure, farm income/profitability and labour supply have garnered some attention in studies of CA adoption. With respect to tenure, conventional wisdom suggests that owned land is better maintained by farmers than leased land. While some empirical results have supported this hypothesis, other studies have not. With respect to wealth, it is regularly hypothesized that the adoption of CA, or indeed any new technology, requires sufficient financial well-being, especially if new equipment is required. Many analyses that have investigated the role of income and farm profitability on adoption have revealed a positive influence. Complicating this picture is the presence of off-farm activities/income which can have a mixed effect on adoption.

Without knowledge of the practices associated with CA via some information or communication channel, adoption is improbable. Indeed, studies of innovation adoption and diffusion have long recognized information as a key variable, and its availability has been correlated with adoption. Information becomes especially important as the degree of complexity of the conservation technology increases (Nowak 1987). Government extension programmes can do much to provide such information on CA and thereby influence farmers' decisions. However, social factors may be even more important in the dissemination of information about technology (Pierce 1996).

For example, Lynne (1995) argued that farmer decision making reflects a compromise between private and social interests. Producers often identify this latter interest as 'the right thing to do', at least in those places where stewardship is part of the cultural norm. More generally, it has been recognized that individual actions related to the environment may reflect a society's social capital (Pretty and Ward 2001). In the broadest sense, social capital refers to the interconnectedness among individuals in society and considers relationships as a type of asset. Attributes such as 'kinship', 'connectedness to others', and related social capital characteristics have been argued to influence positively the adoption of conservation technology (Moore et al. in press). Similarly, some analyses have identified membership in producer organizations and other social networks as a positive influence on adoption. Investigations in the role of social capital and networks in conservation technology adoption are increasing but more needs to be done. More recent analyses of the adoption of broadly defined best management practices emphasizes the role of agency and local networks of farmers or watershed groups (Baumgart-Getz et al. 2012).

Since the preceding and cursory review suggests a varied and fuzzy picture regarding non-financial influences on adoption behaviour, a more systematic analysis can reveal more useful insights. Knowler and Bradshaw (2007) reviewed 31 CA technology adoption analyses, culled from 23 larger studies, to see if a systematic pattern existed among the explanatory variables used with respect to sign and significance of estimated coefficients. Most studies used the standard adopt-/no adopt-dependent variable approach involving a binary probit or logistic (logit) regression procedure. The researchers considered approximately 170 independent regression variables having significant estimated coefficients and grouped these variables as:

(i) farmer and farm household characteristics
(ii) farm biophysical characteristics
(iii) farm financial and management characteristics
(iv) external factors

The researchers found that few, if any, variables universally explained adoption behaviour. Knowler and Bradshaw conclude by stating: 'it is … possible that we researchers have reached a limit in terms of contributing to a refined understanding of the reasons for conservation agriculture adoption' (p. 44). Such a finding suggests that other avenues need to be explored to reach a better understanding of why some farmers adopt CA and other do not. For example, should we focus on developing better site-specific models or have we simply omitted important social and collective action variables with strong explanatory power? A further concern is with the modelling techniques themselves: perhaps these are simply not up to the task. This question and some suggestions on how to address such a problem are discussed in the next section.

23.3 Problems and New Approaches in Studying Adoption of Conservation Agriculture

Several key issues arise in reviewing the way in which adoption behaviour is studied, including whether empirical studies use the most appropriate statistical methods. For example, how do we incorporate the constraints that farmers face in managing their operations? That is, should we be considering the objective function as farm net returns but recognize that these are maximized subject to a variety of constraints? Should we be interested in ex ante analysis, ex post analysis or both, when studying adoption? Most adoption studies are undertaken ex post after a sufficient time lapse to allow for the accumulation of behavioural data. But how useful is this for project planning? Analysis of the prospects for adoption will be more useful if available before a project is implemented to aid with design. A related but separate point is that many empirical analysts are unable to wait long enough for good quality data to accumulate (say, 10 years minimum), so that even many ex post studies may lack a degree of rigor.

Additionally, what about the time dimension? Most adoption studies are cross-sectional and consider only a single point in time, whereas adoption is in reality a dynamic process. Clearly, the results of static cross-sectional analyses will depend critically on where the technology dispersal process is situated along the typical *S*-curve, usually assumed to represent the dynamics of adoption (see Fig. 23.2), at the time the study is undertaken.

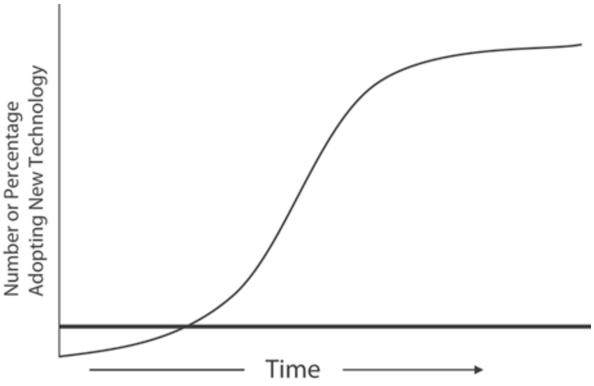


Fig. 23.2 Standard *S*-curve representing adoption of an agricultural innovation over time

Moreover, how do we explain the intensity of CA adopted on a given farm? While most studies only assess adoption versus non-adoption, there may be greater insights from knowing how much of the farmer's limited land base has been devoted to CA. Obviously, this can be complex in itself, as farmers may adopt initially on a small area for experimental purposes and then expand the area if satisfied with performance; other farmers may vary the land area under CA over time, adding another dimension to the problem.

Finally, when the farmer faces a set of technology choices, how should we model the adoption of a given technology? In other words, rather than a simple binary decision between adopt or not adopt, the decision problem facing the farmer more realistically may involve selecting from several options or 'packages' among which not to adopt is just one of these multiple alternatives.

Recent adoption analyses address some of the problems cited above but not all of them and, certainly, not all together within a single study. However, in most cases, adequate statistical methods are available. In the examples discussed below, a variety of these potential methods is introduced and, where possible, case studies are discussed in an attempt to demonstrate the usefulness of the methods.

Example 1: Trade-off Analysis

Knowler (2005) examined methods to incorporate non-financial constraints in assessing prospects for the adoption of sustainable farming technologies (including CA). He found that simple trade-off analyses can reveal important information about technology characteristics that may influence adoption by allowing the analyst to eliminate dominated or inferior technology choices when financial profitability is compared to the sorts of constraints discussed above. In the remainder of this section, a summary of this work is presented, involving a case study that was carried out as project planning work in Ghana under the Food and Agricultural Organization (FAO)/World Bank Cooperative Programme. The purpose was to assess the viability of a range of soil and water conservation measures, including some CA techniques, at the farm level. See Knowler (2005) for details.

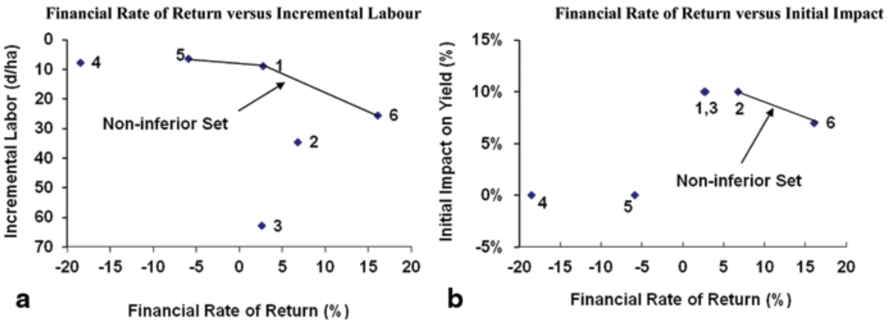


Fig. 23.3 Trade-off curve analyses for land management technologies in Ghana. **a** Financial rate of return versus incremental labour. **b** Financial rate of return versus initial impact. Note: Data labels correspond to: *technology 1*—mulching, *technology 2*—ridging, *technology 3*—stone lines, *technology 4*—strip cropping with groundnut, *technology 5*—strip cropping with cowpea and *technology 6*—bunding with Vetivera grass. (Source: Knowler 2005)

While farmers may perceive a soil degradation problem and know of profitable technologies that address the problem, numerous factors may conspire to inhibit their adoption. The benefits of some technologies may be perceived as more distant and riskier than the benefits of alternatives. Some technologies involve the timing of labour and capital inputs that are inconvenient or have high associated opportunity costs because of seasonal cropping or off-farm income generation demands. Other conservation investments are lumpy and require substantial outlays that may be beyond most households, while still others may involve highly specialized and difficult to obtain inputs. As discussed above, such factors help to explain why the adoption of new technologies might be less than predicted by net returns analysis alone.

The above considerations were incorporated into the screening of potential land management technologies using trade-off analysis. In the case study, six conservation technologies were assessed using criteria that reflected differing smallholder objectives, one of which was financial profitability. For illustration purposes, the following two criteria are assessed against financial profitability using trade-off curve analysis:

(i) incremental labour demand, which makes allowance for limits on the availability of household labour to undertake new tasks at peak periods in the cropping calendar
(ii) initial impact of the technology in terms of meeting subsistence food needs, which takes into account any immediate boost in yield, as well as land removed from production to accommodate the technology

Trade-off curves were used to assess the trade-offs between the above criteria and financial profitability for all six soil and water conservation technologies (Fig. 23.3). This quantitative technique allows the analyst to eliminate dominated or inferior choices. To illustrate, consider any two technologies showing equivalent scores on one of the criteria but differing scores on another. The technology with the higher score in the latter case obviously dominates. Repeating this exercise for all possible comparisons leads to the so-called non-inferior or non-dominated set, as illustrated in the two figures. This smaller choice set can then be subjected to further screening.

Figure 23.3a shows the trade-off between the incremental labour required when adopting one of the technologies and its estimated financial rate of return, with preferred technologies situated further up and to the right in the figure. Three of the technologies are clearly dominated (technology 2—ridging, technology 3—stone lines and technology 4—strip cropping with groundnut). Three technologies are not dominated, although technology 5 (strip cropping with cowpea) has a low rate of return and only marginally lower labour demand than technology 1 (mulching), so that many households may be willing to accept the additional labour demanded by the latter. The trade-off between financial gain and labour demand is more substantial when comparing technologies 5 and 6 (bunding with *Vetivera* grass). A similar pattern emerges when the trade-off is between financial gain and the initial impact on subsistence crop production (Fig. 23.3b). Overall, technology 6 provides the most attractive financial returns, but a significant increase in labour demand and an initial loss of crop production is the price paid for these higher financial returns. Its attractiveness to individual households, therefore, will depend on household-specific circumstances.

While in this case, the trade-off analysis appears to identify a preferred technology, this may not always be the case. If not, then planners are faced with the challenge of explicitly or implicitly weighting the different criteria, i.e. are incremental labour requirements more important than yield impacts, when assessing trade-offs against financial rates of return? While such weightings can be formal, as in standard scoring and weighting schemes used in traditional multi-criteria analysis, this may not be the preferred approach. Individual farmers are likely to make their own assessment of the trade-offs among competing conservation technologies, taking into consideration their own particular situations. However, using the simple trade-off technique described here may help planners to improve their project designs. In fact, some researchers are employing similar techniques in designing CA projects in Africa, such as pair-wise ranking and propensity score matching (PSM) methods (Bashaasha and Sikuku, personal communication).

Example 2: Discrete Choice Experiments

The discrete choice experiment (DCE) is a stated preference technique that has been used extensively in applied decision making and market research and more recently in environmental assessment (Adamowicz et al. 1998). In a DCE, the researcher can incorporate multiple policy dimensions simultaneously, instead of simply evaluating one change at a time. As a result, a DCE is an ex ante technique that can jointly address the constraints issue and many other issues raised by ex post analyses regarding planning and design of CA projects (e.g. timing) but much earlier at the programme planning stage.

Attribute	Conservation Technology Choice #1	Conservation Technology Choice #2	Status Quo
 PROFITS	\$50/ha/yr	\$25/ha/yr	\$100/ha/yr
 LABOR	+20 days/yr	+5 days/yr	none
 CROP AREA	-10% of crop area	none	none
 INVESTMENT	\$100	\$50	none

Fig. 23.4 Sample choice set for a hypothetical study of trade-offs in adopting conservation technologies

In a DCE, a respondent is presented with a series of hypothetical choice sets, each consisting of two or more alternative scenarios and indicating his/her preference, assuming these are the only alternatives available (for a hypothetical example, see Fig. 23.4). Each alternative is described in terms of attributes that can take multiple values. By aggregating the responses from all the respondents, it is possible to derive part-worth utility functions for each attribute. In our case, the attributes should include factors that influence the choice of farming technology at the farm level, i.e. conventional farming, CA methods or perhaps other conservation technologies. These attributes might include the impact of technology choice on expected profits, on labour use, on cropped area or the upfront investment costs of the technology. It is always best to gather information about what factors are important in technology choice from the stakeholders themselves via rapid rural appraisal (RRA), pilot testing or participatory techniques.

In a DCE, product profiles are constructed from various levels of decision-influencing factors (attributes) and presented to respondents who are then asked to choose the profile they prefer (see Fig. 23.4). Researchers then estimate the part-worth utility for each attribute level (Louviere et al. 2000). Formally, DCE analysis makes use of random utility theory which proceeds from the assumption that the utility from selecting a technology can be decomposed into a deterministic and stochastic component as follows (Adamowicz et al. 1998; McFadden 1974):

$$U_{ij} = V_{ij} + \varepsilon_{ij}, \tag{23.2}$$

where V_{ij} is the observable indirect utility function for consumer *i* and alternative *j* and ε_{ij} is the stochastic component that cannot be observed. If alternative *j* refers to a specific conservation technology, then a farmer will choose conservation technology *j* over another alternative *k* if $U_{ij} > U_{ik}$ for all $j \neq k$.

Furthermore, we can use this information to describe the probability that a respondent will choose alternative *j* as:

$$Prob\{j\, is\, chosen\} = Prob\{V_{ij} + \varepsilon_{ij} \geq V_{ik} + \varepsilon_{ik}; for\, all\, k \in C_i\}, \tag{23.3}$$

where C_i is the choice set with all technologies available to respondent *i*. Making the usual assumptions about the random error term ε_{ij}, the probability of alternative *j* being chosen may be formulated using the multinomial logit (MNL) model (Adamowicz et al. 1998):

$$Prob\{j\, is\, chosen\} = e^{v_{ij}} / \sum_k e^{v_{ik}}; for\, all\, k \in C_i. \tag{23.4}$$

If V_{ij} is assumed to be linear in parameters, its functional form may be expressed as:

$$V_{ij} = \beta_1 x_{ij1} + \beta_2 x_{ij2} + \ldots + \beta_n x_{ijn}, \tag{23.5}$$

where x_{ijn} is the *n*th attribute value for alternative *j* for consumer *i* and β_n represents the coefficient of the *n*th attribute value to be estimated.

Practically, the implementation of a DCE involves carrying out a farm household survey. Farmers are presented various choice sets (cards) and select a preferred package combination from each set. Figure 23.4 presents a hypothetical choice card that might be used in such an exercise, including visual portrayals of the different attributes to help with comprehension. Various analyses can be carried out using the MNL model results in terms of building understanding of the factors likely to influence the extent and reasons for adopting a technology such as CA. Furthermore, it is possible to use the estimated model to create a decision support system (DSS) to forecast ‘market share’, which is the predicted adoption of individual technology packages. An extension is the use of latent class analysis (or the random parameters logit model) to examine sample heterogeneity by modelling the response behaviour of subgroups or like-minded ‘classes’ within the sample (Train 2009).

As an example, Duke et al. (2012) used hypothetical scenarios in a DCE to analyze potential adoption of no-till and several other technologies in Delaware where these various technologies were included as components in varying contract packages presented to farmers. While the expected welfare benefits from acceptance of contracts including technologies other than no-till were positive and significant, this was not the case for no-till viewed in isolation. Instead, farmers appeared not to expect a significant welfare gain from adopting no-till. This result was expressed in a low willingness to pay for including no-till in a contract, US$ 3.39 versus US$ 29.59 for including increased riparian buffer areas in the contract. The authors conclude that: ‘any management contract that included no-till cropping would not be expected to increase, or decrease, welfare among the residents in the area’ (p. 101). Of course, this is not the result promoters of CA would like to hear but surely it is helpful to know this ahead of implementing a programme rather than years later.

Other applications of DCEs used to analyze land management problems include Blazy et al. (2011) who examined the adoption of agro-ecological innovations aimed at reducing pesticide use in banana production in the French West Indies. Additionally, members of the US Department of Agriculture (USDA)-funded Sustainable Agriculture and Natural Resource Management (SANREM) programme team working in Ecuador and Uganda have been using DCEs to assess CA adoption, which should produce welcome additions to the literature on ex ante analysis of the prospects for adoption at the project planning and implementation stage (Norton, personal communication).

Example 3: Duration Analysis

Recall that most adoption research concentrates on analysing adopters versus non-adopters at a single point in time. There is little consideration of the timing of the decision to adopt. Yet, presumably this can be as important to understand as the decision whether to adopt at all. We can frame this problem instead as being time dependent. Suppose that farmers have available to them a new farming technology that offers potential net benefits and that they can adopt at any time. Such an approach falls under the heading of models of duration. Duration models are used to analyze dependent variables that are lengths of time (Keifer 1988). These models use the idea of conditional probabilities to estimate a hazard rate *h,* or the probability that an observation will move from one state to another at time *t,* given that it has not changed states up to time *t*. For our purposes, the hazard rate measures the timing of adoption assuming the farmer has not yet adopted. Formally, this can be described as follows:

$$h = \lim_{\Delta t \to 0} \left\{ \Pr(\text{farmer adopts in } [t,\ t + \Delta t] \middle| \text{ farmer has not adopted by } t) / \Delta t \right\} \tag{23.6}$$

The hazard rate, *h,* may not be constant and instead it may be a function of time, or a hazard function, $h(t)$, which describes how the probability of adopting a technology such as CA changes over time. The hazard rate can also be a function of covariates in addition to changing over time (e.g. farm and farmer characteristics).

To estimate such models, we begin by defining a cumulative distribution function $\mathrm{F}(t)$:

$$\mathrm{F}(t) = \int_0^t f(t)\mathrm{d}t, \tag{23.7}$$

where $\mathrm{F}(t)$ expresses the cumulative level of adoption of the technology up to the present or, in other words, the time path of diffusion (Fuglie and Kascak 2001). In addition, $f(t)$ is the associated probability density function for $\mathrm{F}(t)$. Related to $\mathrm{F}(t)$ is the survivor function, referring here to the proportion of the farm population that has not yet adopted and expressed simply as $\mathrm{S}(t) = 1 - \mathrm{F}(t)$. Following Fuglie and Kascak (2001), we can assume a specific functional form for the survival function

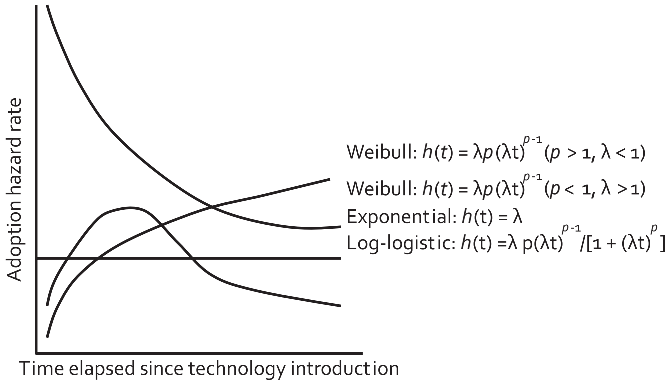


Fig. 23.5 Some probability distributions for the hazard rate *h*(*t*) describing adoption of a new conservation technology. (Source: Keifer 1988)

such as the log-logistic distribution function, which is commonly assumed for agricultural technology diffusion and expressed as:

$$\mathrm{S}(t) = \frac{1}{1+(\lambda t)^{p}}, \tag{23.8}$$

where λ and *p* are parameters of the distribution to be estimated. The associated hazard function can be derived from this survival function as:

$$h(t) = \frac{-\mathrm{d}\ln S(t)}{\mathrm{d}t} = \frac{f(t)}{S(t)} = \frac{\lambda p(\lambda t)^{p-1}}{1+(\lambda t)^{p}}. \tag{23.9}$$

Standard econometric techniques can be used to estimate λ and *p* and this information can be used to plot the diffusion path of the technology. While the logistic distribution is a sensible and common choice to describe the technology dispersal process, various other distributions can be used so that the researcher can use his/her judgment to select the most appropriate one (see Fig. 23.5 for some possible alternative distributions). To model not only timing of adoption but also the adopt/no adopt decision, a split-population duration model is used. Data collection is more demanding than conventional adopt/no-adopt models with no duration element since the timing of adoption for each respondent is needed.

Several studies have modelled technology adoption using duration analysis, including adoption of elements of CA. For example, Fuglie and Kascak (2001) used duration analysis to study conservation tillage adoption in the USA. Their modelling made use of a national sample of US farms to estimate the long-term trends in adoption and diffusion of three technologies: conservation tillage, integrated pest management (IPM) and soil fertilizer testing. All of these technologies are concerned with reducing the externalities from agriculture. Their duration modelling results show that diffusion has been quite slow for these technologies and has been characterized by long lags in adoption, the latter due to differences in land quality, farm size, farmer education and various regional factors. A second study used duration analysis to examine the influence of various factors on the adoption and spread of fertilizer and herbicide on smallholder farms in Ethiopia prior to 1996 (Dadi et al. 2004). Results suggest that economic incentives were the most important determinant of the timing of adoption, along with whether animal traction was being used on the farm. Other farm and farmer characteristics had little, if any, effect on the timing of adoption. Adoption of herbicides proved to be slower than adoption of fertilizer.

Example 4: Some Other Methods
Several other shortcomings of the standard adoption modelling approach were cited earlier. For example, most adoption models consider only the 'adopt/no adopt' alternatives and ignore how much area is converted to CA. Clearly, whether a small experimental parcel is converted or there is large-scale conversion across an entire farm has substantial implications for understanding the adoption and diffusion process for CA and other technologies. Double-hurdle regression models invoke a two-step nested procedure and can be used to estimate first the probability of adopting and then the area converted to CA (Greene 1993). Gebremedhin and Swinton (2003, p. 75) make some useful observations about this approach in the context of adoption of conservation technologies:

> The decisions of whether to adopt and how much to adopt can be made jointly or separately. When the decisions are joint, the Tobit model is appropriate for analysing the factors affecting the joint decision. This assumption has been the norm in previous research into the determinants of the intensity of soil conservation investments. However, adoption and intensity of use decisions are not necessarily made jointly. The decision to adopt may precede the decision on the intensity of use, and the factors affecting each decision may be different, as assumed in the present case. In this case, it is more suitable to apply a 'double hurdle' model in which a probit regression on adoption (using all observations) is followed by a truncated regression on the non-zero observations.

The authors go on to study the decision to adopt soil conservation technology (stone terraces) and consider a large set of influences (e.g. market access, physical factors, land tenure, etc.) that they test with respect to the decision to adopt the technology as well as the intensity of adoption. The study's results support the case for modelling these two processes separately as the authors found that the factors influencing adoption versus intensity were not the same. Double-hurdle modelling approaches applied more specifically to CA practices are beginning to appear in conference papers and in the published literature with increasing frequency. A recent example is Ngoma et al. (2013), who use pooled cross-sectional household data from Zambia to assess influences on farmer decisions to use minimum tillage and the amount of land cultivated using minimum tillage. Results suggest that age of the household head, landholding size, incidences of flood and droughts in the previous season influence the probability of farmers using minimum tillage and the amount of land they cultivate under minimum tillage.

In addition, most adoption models consider a single technology that is either adopted or not, ignoring cases where farmers have choices. For example, CA is usually described as consisting of three practices: reduced or no-tillage, mulching of crop residues and rotations that typically involve legumes. Farmers may choose to adopt any combination of these three practices. Understanding this decision is obviously of interest but it is a more complex undertaking than simply assessing the adopt/no adopt decision. As a solution, an MNL model can be used when the dependent variable is a set of non-ordered options and the farmer's choice from these can be regressed against a set of explanatory variables.

An early application and widely cited example of using a multinomial modelling approach to analyze CA decision is Wu and Babcock (1998). In this study, the authors examined the choice problem involving conservation tillage, rotations and soil N testing on cornfields in Central Nebraska. The options available to farmers included seven separate combinations or packages involving these three individual practices (an eighth option had too few observations). The authors considered the role of various independent variables in explaining the choice of crop management package, including farmer experience, education, crop insurance, irrigated land (or not), land ownership and physical attributes such as proximity to a stream and slope. While slope consistently played a positive and significant role in explaining the adoption of various packages, some variables (e.g. crop insurance, farm size and irrigated land) demonstrated a varying negative or positive influence on the adoption of different packages. Clearly, analysing the adoption of a single farming practice in isolation would not have provided a correct assessment of what determines adoption, instead this is a joint adoption decision involving several conservation practices but conditioned on the specific mix in question.

23.4 Summary and Directions for Future Research

Adoption of CA is still a challenge despite a reasonable economic case for its desirability from an on-farm viewpoint in most regions and, even more so, from a social perspective (with perhaps the exception of Africa). Although on-farm profitability for CA varies, it is not likely to be the key barrier to adoption. Instead, it has been argued here that other factors play a critical role in determining the successful dissemination of CA practices among farmers but the appropriate practices to assess and the factors influencing their adoption will vary from site to site. We need to recognize that farm households are heterogeneous but that intra-household differences are important too. Farm site conditions vary and farmers typically face many constraints, both physical and socioeconomic. Social and network aspects (social capital?) add a more recently identified influence to the fold and need special techniques to be incorporated into adoption studies. But which factors matter the most? It is the job of adoption analyses to sort out the possible answers to this question.

As a result, assessing adoption from either an ex ante or ex post perspective must rely on careful locational studies that make use of advanced statistical methods to ensure that greater site-specific realities are captured in the analysis. Better and more appropriate statistical methods are increasingly available to analyze these barriers to adoption at the study level. Some of these methods are being used now in more advanced studies of CA adoption, as discussed earlier. But the addition of further empirical studies using advanced methods and new perspectives in assessing sustainable farming methods could increase our understanding of the adoption and diffusion of new farming technologies such as CA even more. [1]

As the development and promotion of CA and related practices advance, there will be opportunities for additional adoption research in key areas. For example, research related to the social and network aspect of adoption is still in its infancy, as is the use of more advanced statistical techniques (e.g. instrumental variable methods). Promoting greater use of ex ante study approaches, such as discrete choice modelling, will enhance the planning and management usefulness of adoption studies. However, we need to keep the following comment concerning advanced methods from Doss (2006, p. 209) in mind:

> Using new methodologies or econometric techniques cannot resolve the problems if the data are fundamentally inappropriate to the question being asked, or if the questions are not the appropriate ones.

While the issues and approaches related to the study of agricultural technology adoption discussed in this chapter were in the context of promoting CA they, obviously, have much broader relevance for the study of other sustainable farming technologies.

References

Adamowicz W, Boxall P, Williams M, Louviere J (1998) Stated preference approaches for measuring passive use values: choice experiments and contingent valuation. Am J Agric Econ 80(1):64–75

Andersson JA, D’Souza S (2014) From adoption claims to understanding farmers and contexts: a literature review of conservation agriculture (CA) adoption among smallholder farmers in southern Africa. Agric Ecosyst Environ 187(1):116–132

Barbier EB (1992) Rehabilitating gum Arabic systems in Sudan: economic and environmental implications. Environ Resour Econ 2:341–358

Baumgart-Getz A, Prokopy LS, Floress K (2012) Why farmers adopt best management practice in the United States: a meta-analysis of the adoption literature. J Environ Manag 96:17–25

Blazy J-M, Carpentier A, Thomas A (2011) The willingness to adopt agro-ecological innovations: application of choice modelling to Caribbean banana planters. Ecol Econ 72:140–150

Crosson P (1981) Conservation tillage and conventional tillage: a comparative assessment. Soil Conservation Society of America, Ankeny

Current D, Scherr S (1995) Farmer costs and benefits from agroforestry and farm forestry projects in Central America and the Caribbean: implications for policy. Agrofor Syst 30:87–103

---

[1] Evidence that indeed this is happening include soon-to-be published papers concerned with farm-level economics and adoption of CA from Andersson and D’Souza (2014) and Pannell et al. (2014).

Dadi L, Burton M, Ozanne A (2004) Duration analysis of technology adoption in Ethiopian agriculture. J Agric Econ 55(1):613–631

Doss C (2006) Analyzing technology adoption using micro studies: limitations, challenges, and opportunities for improvement. Agric Econ 34:207–219

Duke JM, Borchers AM, Johnston RJ, Absetz SA (2012) Sustainable agricultural management contracts: using choice experiments to estimate the benefits of land preservation and conservation practices. Ecol Econ 74:95–103

ECAF (2001) Conservation agriculture in Europe. http://www.ecaf.org/English/First.htm. Accessed 24 April 2013.

Ehui SK, Kang BT, Spencer DS (1990) Economic analysis of soil erosion effects in alley cropping, no-till and bush fallow systems in south western Nigeria. Agric Syst 34:349–368

Ellis-Jones J, Sims B (1995) An appraisal of soil conservation technologies on hillside farms in Honduras, Mexica and Nicaragua. Proj Apprais 10(2):125–134

FAO (2001) The economics of conservation agriculture. Land and Water Development Division, Rome

FAO/IC (1991) Ghana land resource management study, World Bank/FAO investment centre cooperative program. FAO, Rome

Feder G, Just R, Zilberman D (1985) Adoption of agricultural innovations in developing countries: a survey. Econ Dev Cult Change 33(2):255–298

Fuglie KO, Kascak CA (2001) Adoption and diffusion of natural-resource-conserving agricultural technology. Appl Econ Perspect Policy 23(2):386–403

Gebremedhin B, Swinton SM (2003) Investment in soil conservation in northern Ethiopia: the role of land tenure security and public programs. Agric Econ 29:69–84

Giger M, Liniger HP, Critchley W (1999) Use of direct incentives and the profitability of soil and water conservation in Eastern and Southern Africa. In: Sanders D, Huszars P, Sombatpanit S, Enters T (eds) Incentives for soil conservation—from theory to practice. World Association of soil and water conservation/Oxford & IBH Publishing, New Delhi

Giller KE, Witter E, Corbeels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: the heretics view. Field Crops Res 114:23–34

Greene W (1993) Econometric analysis. Prentice-Hall, Englewood Cliffs

Hanley N, Barbier EB (2009) Pricing nature—cost–benefit analysis and environmental policy. Edward Elgar, London

Kassam A, Friedrich T, Derpsch R, Lahmar R, Mrabet R, Basch G, González-Sánchezg EJ, Serraj R (2012) Conservation agriculture in the dry Mediterranean climate. Field Crops Res 132:7–17

Keifer NM (1988) Economic duration data and hazard functions. J Econ Lit 26:646–679

Knowler D (2005) Short cut techniques to incorporate environmental considerations into project appraisal: an exploration using case studies. J Environ Plan Manag 48(5):747–770

Knowler D, Bradshaw B (2007) Farmer's adoption of conservation agriculture: a review and synthesis of recent research. Food Policy 32:25–48

Kuyvenhoven A, Becht J, Ruben R (1998) Financial and economic evaluation of phosphate rock use to enhance soil fertility in West Africa: is there a role for government?. In: Wossink G, van Kooten C, Peters G (eds) Economics of agro-chemicals: an international overview of use patterns, technical and institutional determinants, policies and perspectives. Ashgate, Aldershot

Louviere J, Hensher D, Swait J (2000) Stated choice methods: analysis and applications. Cambridge University Press, New York

Lutz E, Pagiola S, Reiche C (1994) The costs and benefits of soil conservation: the farmers' viewpoint. World Bank Res Obs 9(2):273–295

Lynne G (1995) Modifying the neo-classical approach to technology adoption with behavioural science models. J Agric Appl Econ 27(1):67–80

McFadden D (1974) Conditional logit analysis of qualitative choice behavior. In: Zarembka P (ed) Frontiers in econometrics. Academic, New York, pp 105–142

Moore K, Cisse S (2005) Social capital and improved NRM. In: Moore KM (ed) Conflict, social capital and managing natural resources. CAB International, Oxford, pp 229–246

Moore K, Myers J, Clements C (in press) Small farmer choice and decision making for sustainable soil management. In: Lal R, Stewart BA (eds) Soil management of smallholder agriculture. Taylor and Francis, New York

Mwanza S, Place F (1995) Cost-benefit analysis of improved fallows in Eastern Zambia. ICRAF, Nairobi

Ngoma H, Mulenga BP, Jayne TS (2013) Determinants and extent of use of minimum tillage practices among Zambian smallholder crop farmers from 2008 to 2012. Presented at the 4th international conference of the African Association of Agricultural Economists, Hammamet, 22–25 September 2013, Tunisia

Nowak PJ (1987) The adoption of agricultural conservation technologies: economic and diffusion explanations. Rural Sociol 52(2):208–220

Pannell DJ, Llewellyn RS, Corbeels M (2014) The farm-level economics of conservation agriculture for resource-poor farmers. Agric Ecosyst Environ 187(1):52–64

Pierce J (1996) The conservation challenge in sustaining rural environments. J Rural Stud 12(3):215–229

Pretty J, Ward H (2001) Social capital and the environment. World Dev 29(2):209–227

Train KE (2009) Discrete choice methods with simulation. Cambridge University Press, Cambridge

Williams TO (1997) Problems and prospects in the utilization of animal traction in semi-arid West Africa: evidence from Niger. Soil Tillage Res 42:295–311

WOCAT (2004) World Overview of Conservation Approaches and Technologies (WOCAT) CD ROM. Land and water digital media series Nr.9a, Land and water division, FAO, Rome

Wood J, Knowler D, Gurung O (2008) Assessing the prospects for community-based wildlife management: the Himalayan musk deer (*Moschos chrysogaster*) in Nepal. Hum Dimens Wildlife 13:1–15

World Bank (1990) Burkina Faso—economic issues in renewable natural resource management. Agricultural Operations, Sahelian Department, Africa Region. World Bank, Washington

World Bank (1992) Federal republic of Nigeria land resource management-technology, policy and implementation. Report no. 10694-UNI, Western Africa Department, Agricultural Operations Division. World Bank, Washington

Wu J, Babcock BA (1998) The choice of tillage, rotation, and soil testing practices: economic and environmental implications. Am J Agric Econ 80:494–511

Index

M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture,*
DOI 10.1007/978-3-319-11620-4