Field Crops Research 132 (2012) 84–94

Contents lists available at SciVerse ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Conservation agriculture in dry areas of Morocco

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ARTICLE INFO

Article history:
Received 1 June 2011
Received in revised form 7 November 2011
Accepted 17 November 2011

Keywords:
Conservation agriculture
No-tillage
Dry areas
Soil quality
Carbon sequestration
Agricultural system
Policy

ABSTRACT

Moroccan agriculture is characterized by the co-existence of both modern and smallholder traditional agriculture. Both types of agriculture are under degradative processes due to mis-use of tillage implements, mis-management of crop residues and inappropriate links between grain and livestock productions. From the research conducted over the last three decades, the vast majority of beneficial tillage effects are transient. Conversely, the harmful effects of conventional tillage (CT) systems are long-lasting, if not permanent. The present paper aims at evaluating major achievements in conservation or no-tillage agriculture (CA or NT) research conducted in dry areas of Morocco and presenting important ways to implement these achievements within the Moroccan rural society. CA has been introduced in response to issues of soil conservation, drought mitigation and soil quality management. NT systems have resulted in reduced soil erosion, greater soil water conservation, improved soil quality and stable and higher crop yields. Changes in crop production practices due to shifting to NT or CA systems and retention of crop residues at or near the surface produced progressive qualitative and quantitative variations in soil organic matter. This can allow agriculture to contribute to country's efforts to reduce and control greenhouse gas emissions. These effects benefited both farmers and society in terms of higher returns and efficiencies. Under NT, benefits from improved agriculture's environmental performance must be added to remunerations of reducing costs of production and improving well-being of farmers. The other strong benefits that CA brings come from the opportunity for early sowing and savings in time, machinery and fuel. Even though, many agronomic, socio-economic and environmental benefits accrue from NT and increasing crop diversity; lack of incentives from the government and social factors encourage the continued use of CT systems. CA systems were sufficiently tested in research stations but found limited adoption in farm communities. The shift in the late nineties to more on-farm research did not result in the envisaged breakthroughs, mainly due to poor research-extension linkages and several social and technical barriers. Consequently, in order to realize durable agricultural growth, there is a huge challenge to out- and up-scale CA in Morocco through linkage of all stakeholders (farmers, developers, researchers, industrials and policy makers). This paper fulfills information gaps and presents a thorough discussion on constraints to CA adoption as well.

1. Introduction

1.1. Sustainable agricultural intensification in Morocco

Morocco's total area is of 71.08 million hectares (M ha), including 9.2 M ha of cultivated lands (13%), 5.8 M ha of forest (8%) and 24 M ha of rangelands (30%). Agricultural sector generates from 13% to 20% of gross domestic product (GDP) depending on harvest and 20% of the total export value of the country. It provides employment to near 44% of the work force.

Cereal production is the most significant agricultural resource. Wheat and barley are, and have been the most commonly grown dryland cereals and are of paramount importance in the national economy (Chebbi and El Mourid, 2005). Food legumes (i.e. fababean, chickpea and lentil), maize and oilseed crops represent important components of cropping systems. Perennials include olive, almond, fig, pistachio and fodder trees.

Dryland farming systems integrate crop and livestock production. Livestock accounts for 26–32% of the Agricultural GDP. It is dominated by sheep, with 16.3 M heads, 5.1 M goats, and 2.7 M heads of cattle (Boulanouar and Benlekhal, 2006). Due to its extensive nature, livestock production mainly relies upon grazing on communal lands, fallows and stubble (Ben Salem and Smith, 2008).

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doi:10.1016/j.fcr.2011.11.017

In a period of 50 years, cereal area varied from 4.5 to 5.3 M ha contributing to a 3.2-fold increase in cereal production (from 25 M quintals in 1961–1965 to more than 80 M quintals in 2008–2010), however crop yields are still low and stagnant even after adoption of fertilizers and appropriate crop cultivars.

The use of tillage implements like disks and hoes is intrinsic to Moroccan agriculture and extension services are still advertising it. Tillage research, which was initiated in 1970s, was mainly directed toward deep tillage combined with refining seedbeds. Moldboard plow as a primary tillage is still used for tilling depths down to 30–35 cm, followed by different hoe and disk harrow implements for seedbed preparation. On these traditional systems and previous to tillage operations, crop residues are removed, grazed or even burned. Off-set disks for both primary and secondary tillage operations are most common in large areas (53–61% of cultivated cereals). Chiseling and surface tillage with small hoe cultivators are now more common than 40 years ago and encouraged by extension services. This mis-use of tillage systems associated with overgrazing have induced alarming rates of soil organic matter decline, erosion and desertification (Dimanche, 1997).

Facing all these paradigms, the major objective brought by the newly launched Green Morocco Plan is sustainable production intensification for all types of farms and crops. The plan focuses on agricultural systems that are productive and remunerative which at the same time conserve and enhance the natural resource base and environment, and positively contribute to harnessing the environmental services. Among pertinent strategies of this plan is decreased cereal cultivated area by 22% while increasing cereal production by 44% at the 2020 horizon (Badraoui and Dahan, 2010). This plan recognizes the potential of no-tillage systems to intensify crop production systems in dry areas through sustainable precipitation use.

1.2. Climate and soils of Morocco's dry areas

Morocco is situated at the southern edge of the mid-latitude storm track. The country is lying within the influence zone of the Atlantic, the Mediterranean and the Sahara, together with very steep mountains. It is characterized by diverse but generally dry uncertain climate. Its mean features are low mean annual precipitation, high inter- and intra-annual rainfall variability and high rates of potential evapotranspiration (Chbouki et al., 1995). Most of the country is arid (90%) with aridity tending to increase with distance from the North. 95–98% of yearly rainfall is concentrated from October to April and this coincides with cereal production cycle. Precipitation is inversely related to the concurrent state of the North Atlantic Oscillation (Knippertz et al., 2003).

Owing to the high degree of aridity and variability of rainfall in most of the country, agriculture is particularly vulnerable to drought. Prolonged droughts were reported in 1979–1984; 1994–1995; 1998–1999 (Balaghi et al., 2006) and recently in 2006–2007. Consequently, the agricultural sector is highly sensitive to climate change and subjected to recurrent droughts (Dai et al., 2004; Esper et al., 2007). Touchan et al. (2011) projected more frequent and intense drought-like conditions. Another feature of rainfall is its high intensity, which produces flash-flood conditions.

The general aridity, in conjunction with factors related to topography, is also responsible for the widespread occurrence of soils with poor or no profile development (Regosols), dark cracking clays (Vertisols), and calcareous soils (Calcisols). These soils have poor physical and structural properties and are low in organic matter, which makes them vulnerable to water and wind erosion and compaction under heavy machinery use (Ryan et al., 2006).

2. Conservation agriculture: the evolving paradigms

2.1. Principles of conservation (no-tillage) agriculture

Conservation agriculture (CA) is an approach to managing agro-ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment (FAO, 2002). Dumanski et al. (2006) described CA as the integration of natural resources management with sustainable and economic agricultural production, providing beneficial ecosystems services such as (1) food and fiber and biofuels, and (2) less erosion, less pollution, clean water, fresh air, healthy soil, natural fertility, C sequestration, sustainability and higher production.

Parr et al. (1990) defined no-tillage (NT) system as a specialized type of CA consisting of one-pass planting and fertilizer operations during which the soil and surface residues are minimally disturbed. NT systems eliminate soil manipulation except at the time of combined seeding and fertilizer placement. Other terms used to describe this system include zero-tillage, slot-tillage and direct seeding systems. NT systems are composed of three dependent components: direct seeding without previous tillage operations or seedbed preparation; crop residue maintenance at or near the soil surface; and weed control mainly with herbicide application or with crop rotations. In this review, the term "no-tillage agriculture" is interchangeably used to replace the name "conservation agriculture" and to shift the focus away from the concept toward the system of soil management.

2.2. Machinery developments in no-till farming

Execution of no-tillage requires expensive machinery, mainly special drills, mulch traders and sprayers. Hence, the major constraint to adoption of NT systems in Morocco is the lack of planting equipments (El Gharas and Idrissi, 2006).

Research on NT systems was carried out using imported no-till disk drills (Bouzza, 1990; Kacemi, 1992; Mrabet, 1997). Dry seeding and deep placement of N and P fertilizers to promote plant vigor and root growth were the major drivers for developing appropriate local no-till drills for crops in Morocco (Bahri and Bansal, 1992; Dahane, 1992; Nousfi, 1993; Bahri et al., 1993).

Dry early seeding is important for guaranteeing crops maximum use of rainfall and early cover for better protection against intense rainfall and cold. Early seeding is also a prerequisite for high and stable yields due to earlier crop growth associated with the avoidance of late droughts and hot winds.

For fine textured soils, Bourarach et al. (1998) and El Gharras et al. (2004) recommended hoe type no-till drills for dry seeding winter cereals and several food legumes. However, no-till drills for row crops are not yet available and further research is needed for their development. For small scale farmers in mountainous areas, many animal-drawn planters are available in the market. These designs should be allowed for research and extension purposes in Morocco.

2.3. Defying the weed challenge

Under conventional agriculture, herbicide use in semiarid Morocco is still low (not exceeding 20% of cereal lands). Most weeds are considered forage for livestock. On the contrary, lack of tillage means rigorous use of herbicides in first years of NT adoption. Weed development is an important challenge under NT practices but does not pose insoluble problems (Avci et al., 2007). According to El-Brahli and Mrabet (2001), abandoning the plow induced a qualitative and quantitative change in the flora. Among important changes, there is an increase of specific annual (i.e. Bromus) and perennial weeds. Kacemi (1992) related decline in crop performances under NT to the use of inappropriate pre-seeding herbicides in controlling weeds. Nevertheless, El-Brahli and Mrabet (2001) were able to guaranty adequate control of weeds in several wheat based systems (i.e. continuous wheat, wheat-fallow, wheat-lentil, wheat-corn-fallow, and wheat-forage-fallow). Anderson (2007) reported that integrated weed management under CA may include the combination of applied soil herbicides, time of control, use of crop varieties with high competition against weeds, fallow management and weed biological characterization. Mrabet (2008) is considering adding to these strategies the analysis of weed seed bank.

If NT systems are considered as advancing techniques in Morocco, it is then important to note that there is a lack of data and knowledge in terms of herbicide fate in the environment (soil, air, water and vegetation). Weed resistance to herbicides can be a challenge to no-till farmers and there is no single solution.

2.4. Crop residues and livestock integration

In Morocco's pastoralist society, animal husbandry accounts for a major fraction of total farm income. Hence, the major issue is how to produce enough biomass to protect the soil and to maintain the efficiency of the NT systems, as competition for available biomass is frequently high due to grazing. The major threats to soil productivity and agricultural sustainability are stubble grazing and straw exportation. Traditionally, crop residue destinations include extraction, grazing, in situ burning, and incorporation, but rarely weathering and retention as mulch. The stubble is a de facto common pool resource due to a combination of high enforcement costs, traditions and norms, or both.

As stated by Ortiz et al. (2008), almost all advantages of the no-till system come from the permanent cover of the soil and only a few from not tilling the soil. Consequently, one serious difficulty for the establishment and adoption of NT systems is controlling stubble grazing to conserve sufficient mulch as soil cover (Magnan et al., 2011).

The quantities of crop residues that can be sustainably harvested without jeopardizing crop yields are influenced by crop rotation, tillage system and climate. In a study by Mrabet (2002a), no-tillage and deep tillage with disk plow performed equally well and subsurface tillage with an off-set disk produced the lowest yields. Up to 30% of straw produced under no-tillage can be removed for livestock feeding without putting at risk wheat crop performance.

In order to satisfy a better integration of livestock in NT cropping systems and avoid excessive grazing of stubble and flat residues, forage crops (barley, oat, and vetch) were incorporated as a second crop in wheat-fallow rotation. In terms of yields, wheat performed either equally or better in the 3-year rotation (wheat-forage-fallow) than in wheat-fallow at Sidi El Aydi, Chaouia (Mrabet and Bouzza, 1997). The 3-year rotation also helped improving soil organic matter level compared to other biennial rotations (Mrabet et al., 2001a).

3. Achievable NT impacts on crops and cropping systems

In last 3 decades, a significant number of studies dealt with the effects of NT systems on crop yields for different wheat rotations under rainfed conditions. Most available results comparing cereal yields under NT and conventional tillage systems in Morocco are presented in Table 1. Long-term experiments on tillage systems suggest that moldboard and disk plowing are not sustainable tillage systems of soil management, and that deep plowing and inversion operations for seedbed preparation should be eliminated (Bouzza, 1990). Results from these long-term trials have shown the following: (1) no-till system produces higher yields than conventional tillage systems; (2) crop rotation increases and stabilizes wheat yield more than continuous cropping; (3) no-till system plus crop rotation result in better energy conversion and balance than conventional tillage and continuous cropping; (4) no-till system combined with crop rotation is more lucrative and results in less risk as compared to conventional tillage and continuous cropping (Mrabet, 2008).

In a 9-year research experiment (starting in 1994), NT was compared with plowing and results revealed that NT wheat either out yielded or equaled CT wheat during the experimental period (Mrabet, 2011).

Kacemi et al. (1995) reported that NT system effect on wheat grain yield was found superior or equal to minimum tillage (V-blade Sweeps) for wheat-corn, wheat-lentil and wheat-chickpea cropping systems in two climatically contrasting sites (Sidi El Aydi with 358 mm and Jemaa Shaim with 270 mm).

In a single year experiment, Aboudrare (1992) found the same high wheat yielding under NT systems compared to CT systems in a slopping area receiving 450 mm near Meknes in Sais region. However, Chekli (1991) and Nebras (1992) concluded that reduced tillage system decreased wheat yields compared to CT systems in the same area due to weed and pest infestation. In his field study in Sais region, Boutahar (1992) did not find any differences in wheat yields between CT and NT systems.

When NT systems are used in favorable rainfed zones (>400 mm), it is very important to make the right choice of variety to prevent diseases. Due to residue cover, disease may cause problems in NT farming and screening for varieties with high disease tolerance for use in NT farming is required (Ramdani et al., 2010). In semiarid areas (<400 mm), special disease problems in NT have not been reported yet. In wheat, the greatest pest problem is Hessian fly (Lhaloui et al., 2006). The incidence of this insect can be reduced by early seeding and use of resistant varieties.

Other crops responded favorably to NT system, including lentil, chickpea and fababean (Kacemi, 1992), sunflower (Aboudrare et al., 2006), vetch-oat (El-Brahli et al., 1997) and barley (Mrabet and Bouzza, 1997), either by increasing or not negatively affecting yield in comparison with CT systems. Aboudrare et al. (2006) did not find significant impact of tillage systems (no-tillage; moldboard plow; chisel plow) on sunflower yield for the first 2 years of experimentation. However, conventional tillage systems based upon offset disk and para-plowing reduced sunflower yield in the second year. These authors reported that water use efficiency (WUE) of sunflower was similar among no-till, moldboard plow and chisel plow while lower for disk harrow and para-plow. These results suggest that there is no need for soil manipulation or perturbation in order to produce sunflower in Morocco.

From the middle of the nineties and especially from the beginning of the twenties, a new dissemination approach of NT systems was initiated by agricultural research institutions with the support of agriculture ministry and international organizations. These on-farm trials helped to experiment benefits from the NT system in various locations. In most of these trials, several crops (wheat, barley, chickpea, etc.) out-yielded under NT systems that under CT systems (El Gharras et al., 2010).

According to Avci et al. (2007), NT is well adapted to the dryland conditions of Central Anatolia if grass weeds are controlled by pre-emergence spraying of total herbicides. Good weed control in fallow with herbicides may gave higher yields under NT and at least a 50% cost saving (Avci, 2005). Poor weed control was also reported by Cakir et al. (2003) as a major reason for low wheat yield under NT in Turkey. Avci (2005) concluded that, in Turkish dryland agriculture, the following results were drawn from a 3-year research: (i) chemical fallow will be a good alternative to clean fallow and particularly provides savings in tillage cost; (ii) continuous wheat

Table 1
Regional assessment of wheat yield (Mg ha^{-1}) under no-tillage (NT) and conventional tillage (CT) systems in Morocco.

Region and Average annual rainfall (mm)	Soil type	Rotation	NT	CT	Years	References
Abda (270 mm)	Vertisol	Wheat-fallow	3.10	2.40	19	Mrabet (2008)
	Vertisol	Continuous wheat	1.60	1.60	19	
Chaouia (358 mm)	Mollisol	Continuous wheat	2.47	2.36	4	Mrabet (2000a)
	Vertisol	Wheat-fallow	3.70	2.60	10	Bouzza (1990)
	Vertisol	Continuous wheat	1.90	1.40	10	Mrabet (2000b)
	Mollisol	Different rotations	2.21	1.90	9	Mrabet (2011)
	Vertisol	Wheat-chickpea	1.87	0.76	3	Mrabet (2001)
	Rendzina	Wheat-chickpea	2.53	1.47	9	Mrabet (2010)
Zaers (410 mm)	Vertisol	Wheat-lentils	1.97	1.41	4	Mrabet and Moussadek (in press)
	Entisol	Wheat-lentils	2.99	2.72	4	
	Alfisol	Wheat-lentils	2.71	2.49	4	
Sais (438 mm)	Vertisol	Different rotations	2.55	2.49	4	Mrabet and Moussadek (in press)
	Alfisol	Different rotations	2.72	2.74	4	
Gharb (570 mm)	Vertisol	Continuous wheat	2.80	2.26	3	Razine and Raguin (2008)

increased the cheat grass infestation. No-tillage aggravated this problem. In spite of these drawbacks, no-tillage seemed economic and superior in terms of water conservation and erosion control.

In Tel Hadya (Syria), Pala et al. (2007) related wheat and chickpea NT yield advantages over CT to (i) higher moisture availability during early growth stages of both crops, (ii) increased infiltration, (iii) reduced evaporation and (iv) better development of deep root systems utilizing soil moisture in deeper horizons in late dry stages. Tunisian researchers are promoting NT systems in most agro-ecologies of their country (M'Hedhbi et al., 2003; Ben Moussa-Machraoui et al., 2010). As pointed out by Ben Moussa-Machraoui et al. (2010), the superior crop production effect of NT in comparison to CT is due to lower water evaporation from soil combined with enhanced soil water availability.

4. Changes in soil physical and environmental quality under NT

4.1. Scarce water storage and conservation

In low rainfall regions (200–300 mm) such as Abda and Ouardigha, long fallowing is traditionally practiced for water storage and conservation in soil profile. Experimental results showed that water storage efficiency in a Vertisol improved from 10% in weedy fallow and 18% in black fallow to 28% in chemical fallow. This increased water availability was reflected in higher wheat yields under NT systems (Bouzza, 1990) (Table 2). No-till crops become more tolerant to drought because of the better storage of water in the fallow or during the growing season, and this can be used either to increase crop yields, or if sufficient water is available, to increase cropping frequency (Bouzza, 1990). From this author, stored water in 1.2 m profile changed from 30 to 84 mm when shifting from disking to no-tillage.

In the surface soil layer (0–100 mm), water content is usually higher under no-tilled than in tilled soil. Evaporation of water from the soil is reduced with maintenance of mulch cover. Mrabet (1997) showed that time to reach wilting point in a Calcixeroll was proportional to residue cover under no-tillage. As reported by this author, NT with residue cover of 70–80% permitted higher time to reach wilting point than any applied tillage system.

4.2. Soil structure and aggregation

Soil porosity based on water-stable aggregates is of primary importance in joint consideration of soil productivity and soil erosion, because it moderates the movement of water, gases and roots within the soil. Aggregate stability near the surface (0–100 mm) in the zero-tilled soils was greater than in the plowed soils (Moussadek et al., 2011a; Lahlou and Mrabet, 2001; Mrabet et al., 2001a). The low compactibility and high aggregate stability under NT in soil near the surface was linked to the accumulation of organic material at the surface causing an increase in organic matter content. Further, in comparison to conventionally tilled soil, this organic matter under NT also contained a greater portion of particulate organic carbon, probably of microbial origin (Bessam and Mrabet, 2001, 2003b), and involved in stabilizing soil aggregates (Table 3).

4.3. Soil erosion and water infiltration

Erosion is the most important threat to food production and security in the country. The traditional tillage system based upon off-set disking caused runoff and soil loss under rainfall simulation and favored surface sealing (Dimanche and Hoogmoed, 2002).

Soil cover is the most important factor that influences water infiltration rate into the soil, thus reducing runoff and erosion as shown by Moussadek et al. (2011a) in Zaers region (Fig. 1) and Dimanche (1997) in Sais region (Table 4). A rainfall simulator was used on a Vertisol by Moussadek et al. (2011a) to compare water runoff and soil loss in a conventional tillage system and NT systems with crop residues removed (NT_0) and with 50% of crop residues

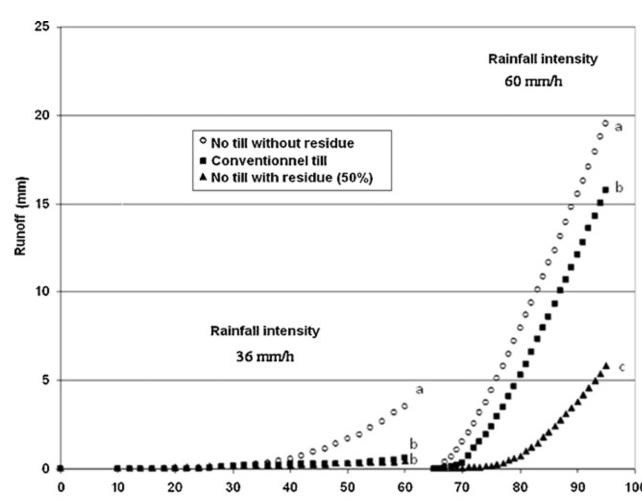

Fig. 1. Runoff loss as affected by tillage and NT residue removal under two rainfall intensities in Zaers region (Moussadek et al., 2011a).

Table 2
Valuing water from rainfall with no-tillage fallow (Bouzza, 1990).

	Fallow management	Storage efficiency (%)	Stored water[a] (mm)
Chemical/no-tillage fallow	Weeds controlled with herbicides only	28	84
Cultivated/black fallow	Weeds controlled with tillage implements, mainly disk harrows	18	54
Minimum/stubble mulch fallow	Co-control of weeds with herbicides and tillage, mainly sweeps	21	63
Weedy/pasture fallow	Uncontrolled weeds. Weeds used as forage	10	30

[a] In a 1.2 m soil profile.

Table 3
Effects of tillage systems on soil surface aggregation in two cereal regions of Morocco.

Region	Soil type	Horizon (mm)	Years	NT	CT	References
Zaers	Vertisol	0–100	4	0.97[a]	0.65	Moussadek et al. (2011a)
Chaouia	Mollisol	0–25	4	65[b]	48	Lahlou and Mrabet (2001)
	Mollisol	0–25	11	3.78[c]	3.21	Mrabet et al. (2001a)

[a] Mean weight diameter of aggregates (mm) according to Le Bissonnais (1996).
[b] % of 1–2 mm stable aggregates according to Kemper and Rosenau (1986).
[c] Mean weight diameter of aggregates (mm) according to Youker and McGuinness (1956).

Table 4
Percent of runoff volume and detachability under no-tillage and chisel plow as compared to disk plow at Ras Jerri (Meknes, Sais, Morocco) (Dimanche, 1997).

Tillage system	Rain intensity ($mm\,h^{-1}$)	θv = 25%		θv = 30%	
		50	80	50	80
Disk plow	Qr and De (%)	100	100	100	100
Chisel plow	Qr (%)	103	96.3	102.4	93.8
	De (%)	93.5	85.4	93.6	92.7
No-tillage	Qr (%)	52.9	66.2	49.2	69.7
	De (%)	28.9	38.9	30.0	49.4

θv = volumetric soil moisture, Qr = runoff volume: quantity of water generated as runoff, De = detachability (a term used to describe a soil's susceptibility to erosion).

returned to the soil surface (NT_{50}). From the plots in Fig. 1, showing two successive rainfall simulations of 36 and 60 $mm\,h^{-1}$, runoff rates were 3–4 times lower under NT_{50} compared to NT_0 and CT at the end of events. Moussadek et al. (2011a) reported a reduction of 50% in soil losses with NT_{50} compared to CT.

Table 4 shows that no-till treatment reduced runoff volume by 30–50% and sediment loss by 50–70% compared with disk plowing, for a sandy clay loam soil. In comparison with chisel plowing, no-till reduced runoff volume and sediment loss by 24–53% and 43–65%, respectively.

Rainfall infiltration is improved under NT system, which for heavy textured soils the amount of soil water available for plants increases (Bouzza, 1990) and for structurally weak soils, formation of crusts is eliminated with residue mulch. Hence, for most soils, infiltration properties are improved under NT system. These increased infiltration rates under NT are due to better aggregate stability and bioporosity. As shown for a Vertic Mollisol in Chaouia region (Fig. 2), water infiltration rates under well-managed NT are higher over extended periods than under CT systems. These results are in agreement with those found by Dimanche (1997) for Sais region on a clay soil.

4.4. Soil bulk density, pore size distribution and compaction

Soil compaction is a common problem in Morocco, especially with continuous use of tillage implements and livestock on degraded soils (Oussible et al., 1992). Compaction damages soil structure at the surface and below, resulting in quicker saturation of affected soil horizons and an increased runoff.

One of the most striking effects of NT systems is the increased density of topsoil in early years of experimentation at Sidi El Aydi (Chaouia) on a vertic Mollisol (Lahlou, 1999). Nonetheless, in the sixth year, the soil surface horizon (0–80 mm) under NT and CT had equal bulk density (Ait Cherki, 2000) (Table 5). In Table 5, bulk density values do not exceed critical levels for optimal plant growth after 6 years of NT (1.3–1.5 $Mg\,cm^3$) (Godwin, 1990; Dimanche, 1997).

At the same site, Lahlou et al. (2005) found that NT affected positively pore size distribution as compared to CT at the same experimental trial. Consequently, the overall soil structure in the topsoil was satisfactory for crop growth under NT and did not limit crop yields.

In a more humid region (Zaers), experimental investigations showed higher penetration resistance levels under NT compared to CT systems for a Vertisol, however, the root growth and development were not restricted (Fig. 3). Along the NT profile, soil strength did not exceed 2.5–3 MPa and hence the soil does not show restricted horizons to growth. Further research in these aspects is needed to accurately judge on soil behavior and compaction under NT vis-à-vis tillage history, climate variability and crop rotation.

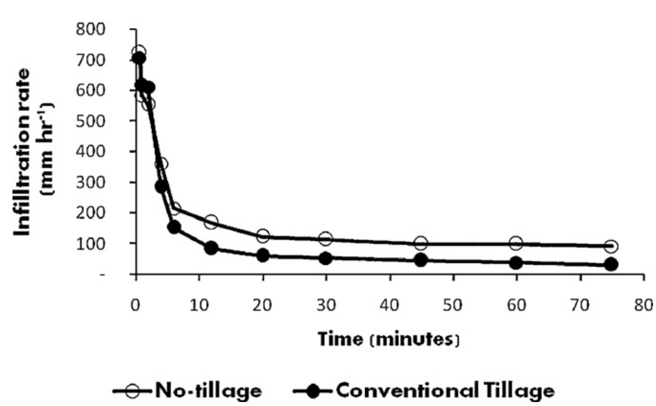

Fig. 2. Impact of tillage system on infiltration process in Sidi El Aydi clay soil. Conventional tillage = off-set disking (Mrabet, 2008).

Table 5
Tillage and time effects on dry soil bulk density (Mg m^3) (Lahlou, 1999; Ait Cherki, 2000).

	After 4 years		After 6 years	
	0–80 mm	80–160 mm	0–80 mm	80–160 mm
No-tillage	1.56a	1.54a	1.26a	1.29b
Conventional tillage	1.45b	1.54a	1.23a	1.32a
Average	1.51	1.54	1.25	1.31

Within the same column, values followed by the same letter are not different using LSD test at 5%.

5. NT impacts on soil chemical quality and carbon sequestration

5.1. Carbon emission abatements with no-tillage systems

According to Lal (2004), all operations involving mechanical soil disturbance for seedbed preparation affect directly and indirectly soil CO_2 emissions. Moussadek et al. (2011b) found that no-till systems reduce the unnecessarily rapid oxidation of organic matter to CO_2 which is induced by tillage (Fig. 4). CT systems resulted in rapid oxidation to, respectively, and loss to the atmosphere. The CO_2 flux was 4.94, 3.95, 2.1 and 0.73 g m^2 per hour at initiation of tillage, respectively, for chisel, disk plow, stubble plow and NT. At 96 h, these fluxes were 1.81, 1.60, 1.30 and 0.80 g m^2 per hour as shown in Fig. 4. Reicosky and Saxton (2006) reported that NT reduces CO_2 loss to 50 g C per m^2 from the loss of 250 g C per m^2 under moldboard plowing in 19 days after tillage. In NE Spain, soil CO_2 emissions just after tillage were 40% higher under conventional tillage than under no-tillage as the CO_2 accumulated on soil pores was released to the atmosphere after the tillage event (Alvaro-Fuentes et al., 2004, 2008).

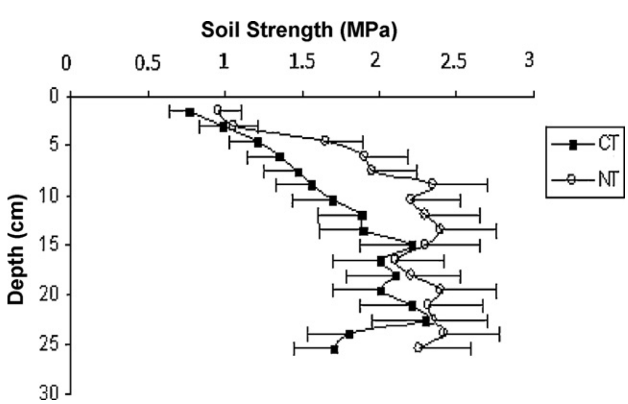

Fig. 3. Soil strength profiles comparing conventional tillage (CT) and no-tillage (NT) at wheat emergence (Vertisol-Zaers) (Mrabet, 2008).

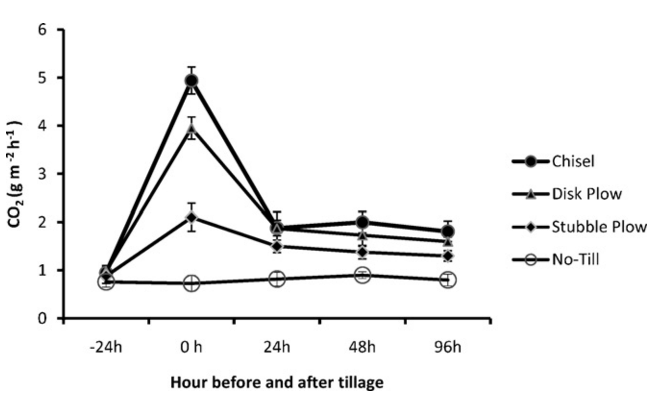

Fig. 4. Soil CO_2 flux associated with primary fall tillage as compared to no-tillage (NT) systems (Moussadek et al., 2011b).

From the study by Uri et al. (1999), expanded across a wide area, NT has potential to slow and even reverse rate of emissions of CO_2 and other greenhouse gases by agriculture sector. With NT, reduced use of tractors and other powered farm equipment results in lesser emissions of exhaust gases. No-tillage is about eight times more efficient in fuel consumption than CT (El Gharras et al., 2004; Table 6). In studies by Bourarach (1989) and Chekli (1991), machinery and fuel costs tend to be lower in no-till systems, with CT systems requiring 3.2 times more fuel.

5.2. NT as a prime strategy for carbon sequestration

Worldwide, the literature abounds in references to soil organic matter (SOM) under contrasting tillage and cropping systems. However, SOM research is recent in south-Mediterranean countries.

NT impacts soil organic carbon (SOC) stock in two ways: (i) by reducing disturbance which favors the formation of soil aggregates and protects SOC encapsulated inside these stable aggregates from rapid oxidation (Six et al., 2000); and (ii) by modifying the local edaphic environment: bulk density, pore size distribution, temperature, water and air regime that might restrict SOM biodegradation (Kay and VandenBygaart, 2002). Paustian et al. (1998) summarized the rate of accumulation of SOC stock under NT at 300–800 kg C ha^{-1} $year^{-1}$.

The stratification of soil properties is an important effect of NT (Mrabet, 2002b) that could potentially be used as an indicator of soil quality (Franzluebbers, 2002). Maintenance of residue mulch at the (or near) the surface under NT increases the ability of soil to sequester CO_2 (Table 7) in two contrasting regions in terms of rainfall amount and pattern. In a clay soil at (0–200 m) horizon, Mrabet et al. (2001a) found, following 11 years of NT, that SOC increased by 13.6%. Increased organic matter also improves nutrient (Mrabet et al., 2001b) and water holding capacity of the soil (Mrabet et al., 2003) (Table 8). Mrabet (2008) did not find any SOC depletion at lower depths with NT compared to CT but rather a build-up at surface horizon with NT. López-Garrido et al. (2011) showed that for long-term NT use, nutrients and SOC measurements with depths are needed to demonstrate the effect of conservation tillage on C sequestration and nutrient distribution and build-up in Mediterranean environment.

5.3. Particulate organic matter

Particulate organic matter (POM) or light fraction (LF) is generally considered one of the primary indicators of soil quality, both for agriculture and for environmental functions (Leifeld and Kogel-Knabner, 2005). SOM fractions with turnover times of years to decades, such as POM or LF, often respond more rapidly to NT-induced changes in the SOC pool than more stabilized, mineral-associated fractions with longer turnover times (Six et al., 1998; Bessam and Mrabet, 2003b). POM and aggregation are both related to crop nutrient acquisition, N leaching and organic matter dynamic (Tan et al., 2007). In aggregated soils, POM is thought to be predictive of N mineralization potential (Yakovchenko et al., 1998).

Table 6
Energy, time and power use by different tillage systems in Morocco (El Gharras et al., 2004).

Tillage systems	Power (Horse power/m)	Time (h/ha)	Fuel use (L/h)	Number of passes
Conventional tillage system	100–140	6.5–8.5	31–45	4
1. Deep disking	50–70	3–4	10–15	
2. Stubble plow	20–30	2–2.5	10–12	
3. Seedbed preparation	15–25	1–1.5	6–8	
4. Seeding	15	0.5	5	
Simplified tillage system	50–70	3.5–5	21–25	3
1. Stubble plow	20–30	2–3	10–12	
2. Seedbed preparation	15–25	1–1.5	6–8	
3. Seeding	15	0.5	5	
Traditional tillage system	30–40	2–2.5	11–13	2
1. Off-set disking	15–25	1–1.5	5–8	
2. Seeding	15	0.5	5	
No-tillage: seeding with no-till drill	25–35	0.6–1	5–7	1

Table 7
Impact of tillage system on soil organic carbon (g/100 g) in surface horizon of two soils from agricultural regions of Chaouia and Zaers.

Region	Soil type	Horizon (mm)	Years	NT	CT	References
Zaers	Vertisol	0–70	4	2.05	1.47	Moussadek et al. (2011a)
Chaouia	Mollisol	0–25	5	1.73	1.66	Bessam and Mrabet (2003a)

Table 8
Impact of tillage system on soil organic carbon and nitrogen (Mg ha^{-1}) in 0–200 mm (Mrabet et al., 2001a).

Tillage system	Organic carbon	Total nitrogen
No-tillage	37.28a (13.6%)	3.52a
Conventional tillage	33.92b (3.3%)	3.28b
Average	35.58	3.35

Numbers in parenthesis are increases in SOC after 11 years.
Within the same column, values followed by the same letter are not different using LSD test at 5%.

As shown in Table 9, NT improves the quality of organic matter by increasing the level of POM at the soil surface over time. Mrabet et al. (2001a) confirmed these results after 11 years of NT and CT.

Mrabet et al. (2003) expressed that POM contents are proportional to residue level under NT system. Retaining an increased residue cover by NT enhanced SOM content and quality (Ibno-Namr, 2005) and improved soil structure and aggregation (Lahlou and Mrabet, 2001).

5.4. Total and particulate N

Differential accumulation of SOM implies changes in concentration and distribution of N, either total or particulate. After 11 years of experimentation at Sidi El Aydi, NT recorded significantly higher N than conventional off-set disking, particularly at the surface (0–70 mm) (Mrabet et al., 2001a). For these authors, NT effect on particulate – N was confined to (0–25 mm), however, for other depths differences are slight among tillage practices. After 7 years, Tab (2003) found in the same site and under continuous wheat rotation that NT sequesters more N than various conventional and reduced tillage systems. The disk plow is the system which performed the worst by reducing content of the soil N in all depths. However, this author found modest differences in wheat yields between NT and conventional tillage systems with respect to N application level in a clay calcareous soil. Over time, availability of nutrients can be improved by returning crop residues to soils through adoption of NT (Mrabet et al., 2001b; Salinas-Garcia et al., 2002).

No-tillage is intrinsically linked to residue management, i.e. full, partial or stubble-only retention. N content of the soil surface (0–50 mm) increased linearly with increased crop residue maintained on the surface (Ibno-Namr and Mrabet, 2004; Ibno-Namr, 2005). Total N at the seeding zone (0–7 cm) was much higher under NT than CT (Mrabet et al., 2001a) but similar N levels were found below this depth. There is a stratification of N at the surface without depletion in the deeper root zone.

Bessam and Mrabet (2001, 2003b) reported that N in POM was higher under NT than CT in the seed zone from 4 to 13 years of experimentation (Fig. 5). However, the effect of these tillage systems was not significant in lower depths (50–100 and 100–200 mm).

Particulate N is much influenced by residue management than total N as expressed by Ibno-Namr (2005) and is a much better differential index of soil biochemical quality. Differential increase in N content, greater C/N and a relative increase in particulate organic N fraction near the surface suggest changes with rates of N mineralization and hence in the content of available N (Doran et al., 1998). However, the higher water content in the surface of no-tilled soil (Mrabet, 1997) may influence the downward displacement of soluble N.

Under no-tillage, crop fertilization should not be taken as an addition of nutrients to crops. It should be understood as the time-interactions among soil chemical and biological properties, soil structure, organic matter dynamic and nutrient cycling. Fertilizer

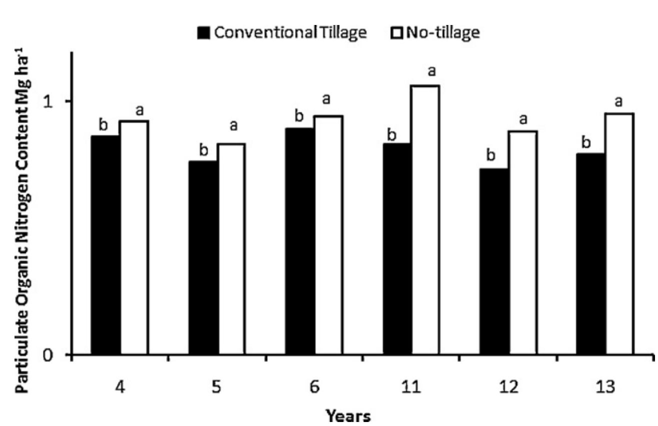

Fig. 5. Time effect on surface (0–50 mm) particulate N content of a Mollisol under tillage systems at Sidi El Aydi experiment station (Bessam and Mrabet, 2003b). For each date, values followed by same letters are not different (LSD, 5%).

Table 9
Carbon content in particulate organic matter (Mg ha^{-1}) as affected by contrasting tillage histories in semiarid Morocco (Bessam and Mrabet, 2003b).

Time (years)	Horizon (mm)					
	0–50		50–100		100–200	
	NT	CT	NT	CT	NT	CT
5	10.62a	9.75b	9.45a	9.32a	17.23a	16.81a
13	11.88a	8.94b	8.53a	9.07a	14.80b	16.28a

In each raw and for each horizon, values followed by same letter are not significantly different at $p = 0.05$ using LSD test; NT = no-tillage and CT = conventional tillage with disk harrows.

Table 10
Soil extractable-P, exchangeable K and pH under no- and conventional tillage applied for 11 years (Mrabet et al., 2001b).

Depth (mm)	No-tillage	Conventional tillage	Difference
Extractable-P (mg/kg)			
0–25	29.9a	18.0b	11.9
25–70	19.3a	16.5b	2.8
70–200	8.7b	10.9a	−2.2
Exchangeable K (mg/kg)			
0–25	476.4a	284.1b	192.3
25–70	291.7a	256.9b	34.8
70–200	148.6b	177.9a	−29.3
pH water			
0–25	7.8b	8.0a	−0.2
25–70	8.1a	8.0a	0.1
70–200	8.2a	8.2a	0

Means followed by the same letters in the row do not differ by LSD test at $p = 0.05$.

requirements of crops grown under CA have received relatively little attention (Mrabet et al., 2001b; Tab, 2003). It is hypothesized that in short term more N would be applied in order to compensate for any suboptimal physical or biological conditions resulting from such systems. On the other hand, over the long-term, requirements may decline as a result of organic matter accumulation and mineralization (Lupwayi et al., 2006). Thus, optimum fertilization is more critical with NT, and soil analysis is necessary before applying fertilizer. Split N application may increase efficiency, and precise banding to separate fertilizer from residues can reduce N immobilization.

5.5. Phosphorus and potassium concentration and distribution

No-till management causes surface enrichment with low mobility nutrients such as P and K (Bravo et al., 2006), from both crop residues and P fertilizers (Table 10). P and K were probably higher in the surface of NT soil due to higher SOM and to the fact that these systems maintained surface-applied P (Mrabet et al., 2001b; Ibno-Namr, 2005). Progressive mineralization of organic matter was the most important source of these nutrients in this soil under NT. The probable advantage of direct drilling is the formation of a thin surface layer rich in accumulated phyto-available P (Bravo et al., 2006) which can thus meet plant P requirements at the early growth stages. However, there is a decline in P and K content with depth below the seed zone under NT which requires deep P (and K) banding to avoid any risk of crop deficiency. Similar results were found by López-Garrido et al. (2011) for a sandy clay loam soil (Xerofluvent) near Seville (Spain) after 4 years of experiment.

5.6. Cations, pH and cation exchange capacity

There is a slight acidification of the soil at the surface under NT, which may increase nutrient availability to crops (Table 10). The absence of soil mixing following fertilizer application generally results in higher soil acidity, of at least at the soil surface, while pH of lower soil layers may change very little.

Table 11
Influence of tillage system on cation exchange capacity (CEC) and exchangeable cations (mequiv./100 g) at the seed zone (0–50 mm) of Sidi El Aydi soil (Chaouia, Morocco) (Mrabet, 2008).

Tillage system	CEC	Ca+	Mg+	Na+	K+
No-tillage	48.5a	62.8a	6.85b	0.36a	1.64a
Conventional tillage	48.6a	63.5a	9.29a	0.41a	1.09b
Average	48.5	63.2	8.07	0.38	1.36

In the same column, values followed by same letter are not different (LSD, 5%).

The cation exchange capacity (CEC) and base saturation are usually adequate in experimental station's soils. The Sidi el Aydi soil had a CEC of 50 mequiv./100 g at initiation of the experiment (Mrabet et al., 2001a). Results in Table 11 show that tillage system did not significantly affect CEC and exchangeable cations (Na and Ca). However, NT has accumulated more potassium and depleted the soil surface in its Mg pool. Under CT, possible loss of CEC with decreasing organic matter may represent an issue in the long-term, especially if there is some link with aggregate stability and dispersitivity.

6. Socio-economic benefits with NT shifting

Moroccan farmers face rising input prices, particularly for fuel, chemicals, fertilizers and machinery, and constant, or even declining, prices for the commodities they produce. To be economically attractive for farmers, no-tillage agriculture must be perceived to provide a net economic benefit in terms of lower production costs, higher crop yields, higher net returns, lower business risks or some combination of these (Magnan et al., 2011). Farmer's long-term economic viability relies on long-term productivity; NT permits greater stability in yields (Mrabet, 2011). No-tillage has enabled to reduce cost of wheat production and increase yields over CT by facilitating timeliness in planting, i.e. 1–2 weeks earlier planting (Bouzza, 1990). Early planting is also associated with reduced seeding rates and better management of crops in terms of weed control and fertilizer use. NT systems are more energy efficient (reduced fuel usage) than CT systems (Bourarach, 1989). These efficiencies normally lead to an increase in farmer's incomes.

Environmental benefits with NT, erosion reduction and CO_2 emission mitigation, combined with higher net returns by NT systems should contribute to a sharp increase in CA acceptance by government officers. According to Baker et al. (2006), the only developed technology that reduces both erosion and costs while improving simultaneously crop and soil productivity is NT system. This rational use of soil and water stands out as the best immediate solution to satisfy food requirements over the next decades of Moroccan population (Badraoui and Dahan, 2010).

NT systems allow poverty reduction due to lower costs and higher incomes. NT can reduce drudgery and permit releases of labor for other economic and social needs (more spare time). Bourarach (1989) stated that the main reason for farmers to shift to no-tillage agriculture could be lower costs of labor and fuel.

7. Further research needs

- Soil organic matter and erosion research and modeling under CA systems (NT with residue management options) are still scarce and should be prioritized.
- Special research should be conducted on soil biological aspects and on rhizosphere environment under contrasting soils and crops and with a special emphasize on optimizing fertilizer management under CA.
- Research on plant nutrition and fertilization recommendations should be given priority in order to guaranty durable production, this in relation with residue management.
- An in-depth understanding and modeling of crop behavior, physiology and adaptation to drought stress and other limiting abiotic factors are of high concern.
- Weed and disease research is lacking under conditions of CA. Major efforts should be made to get profound understanding of weed, disease and insect responses to NT soil and microclimate conditions. Development of integrated weed, disease or pest control strategies is of paramount importance.
- Because herbicides cannot be completely eliminated from no-tillage crop management, degradation pathways, adsorption–desorption and transport processes of herbicides remain important research areas.
- New research directions for experimenting or designing no-till drills for row crops such as corn, sunflower, fababean, sorghum and many others are needed.
- Cover crops species should be experimented in research stations to seek possible advantages and uses under CA in dry and irrigated cropping systems.
- Crop variety development should be carried out for NT systems in order to account for best advantages from genetic and agronomic performances of the crop.
- The ability of CA systems to provide better economic performance and reduce production risks and to improve energy use efficiency is not yet adequately documented. There is a great need to develop CA economical and risk analysis at farmer, community and country scales. The trade-off between crop residue uses: livestock, soil quality, energy and environment should be deeply studied at these scales.
- There is a need to carry an analysis of factors affecting adoption and acceptance of no-tillage agriculture, particularly factors related to farmer and farm household individualities, farm biophysical features and farm financial and management characteristics.
- Irrigation research should be conducted on soils and crops under CA in order to improve water productivity.

8. Conclusions

Efforts have been carried out over the past 3 decades to define and develop NT systems as management strategies which are resource conserving, non-exploitative and yield enhancing and which minimize and/or reduce adverse environmental impacts. This paper was an assessment of the comprehensive inventory of the existing knowledge on sustainable no-tillage agriculture in Morocco. The summary from the available data showed that with adoption of no-tillage (conservation agriculture principles) farmers can re-build the harmony between soils and crops and escape adverse effects of climate (droughts). Moreover, to transform CA research onto information and skills for farmers' use and to expand no-tillage agriculture frontiers, there is a need to build up a network of scientists, manufacturers, industrials, innovative farmers and opinion developers. These stakeholders should arrive to mutually acceptable goals from using or applying NT principles in order to satisfy food and environmental needs of the population. Farmer‘s participation in research and extension programs needs strong attention for increasing the desirability and adoptability of NT technology.

Acknowledgements

The authors gratefully acknowledge the help received from many colleagues, friends, students and farmers in the preparation of this paper. Authors acknowledge the high quality evaluation of the manuscript by the two anonymous reviewers.

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