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Nature's laws of declining soil productivity and Conservation Agriculture

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ABSTRACT

Soils are critical for agriculture and natural ecosystems and need protection, and adherence to nature's principles. The objective of this work is to understand how nature manages resources and describe management of the 'living soil' and its soil productivity and use nature's laws as guidelines for the management. These guidelines provide the foundation of modern Conservation Agriculture (CA) systems characterised by three principles: continuous no or minimum soil disturbance, permanent biomass soil cover, and biodiversity in crop rotations, all of which form the basis for the protection against degradation and for sustaining productivity. Historically, soil tillage was considered a necessary component of agriculture, but it is the root cause of soil degradation. Tillage-based agriculture with bare soils and poor cropping diversity violates nature's laws of soil productivity. Reasons for soil tillage are primarily for short-term convenience of farm management. The negative impacts of tillage on soil health and function may appear inconsequential. However, their cumulative effects over time result in major soil degradation and loss in productivity. Tillage in any form and intensity destroys soil biological, physical, chemical, and hydrological properties. Mechanical tillage is not experienced in natural ecosystems. In CA systems, natural conditions are emulated offering similar productivity, economic and environmental benefits to both large and small landowners globally. In 2018/19, CA was practiced on more than 205 million hectares across more than 100 countries. The impacts of climate change and tillage on food production and environmental degradation require the application of nature-based solutions as Conservation Agriculture.

Introduction

Life on earth has been sustained over the past 3.8 billion years through a set of life-supporting natural processes and their ecological relationships. These processes and relationships constitute the life supporting operating systems that underpin the delivery of several categories of ecosystem services (MEA, 2005). In nature, these laws govern the properties of the "living soil" and the associated carbon (C), water and nutrient cycling such that when violated results in loss of soil health and function and decrease in soil productivity. It is therefore important that these negative impacts must be understood when managing soils in agricultural production. The term 'nature's laws' is applied to describe phenomena and processes that operate in a consistent and predictable manner based on certain governing conditions (Wilson, 2008; Carroll, 2020). In the case of agricultural soils, based on the global scientific evidence over serval decades now, the negative impact and consequences of tillage agriculture on soil productivity and function are so drastic and predictable that we have decided to use the term nature's laws of degrading soil productivity in this paper. Some of these laws that impact agricultural soil productivity were identified by Derpsch et al. (2006). They concluded the inevitable negative effects of soil tillage on soil organic matter, erosion, structure, temperature, humidity, infiltration of water, flora and fauna (soil biology), and water and nutrient retention. These effects result in chemical, physical, hydrological, and

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biological degradation of the soil and in environmental degradation and loss of ecosystem services from agricultural landscapes. With more than 95 % of global food produced originating from land-based production systems, this soil and landscape degradation in agriculture contributes to global warming, decrease in soil productivity and crop yields, and in food insecurity.

Meeting the twin challenges of sustaining food production and reducing or avoiding environmental damage will require careful attention to the world's soils and nature's laws that govern their agricultural productivity. Soils are a critical component of terrestrial ecosystems, mitigating climate extremes, and serving as a fundamental constituent for sustaining all life on Earth. Carbon dioxide (CO_2) emissions that comprise about 80 % of the contribution to global warming of current greenhouse gas emissions (Lashof and Ahuja, 1990), elevates the importance of C cycling and its management in our ecosystems, especially agriculture.

Globally, traditional and modern tillage-based agriculture and monoculture practices in organic and non-organic production systems have resulted in a gradual degradation of soils and productivity that may ultimately jeopardize food security. Meeting the food and agriculture needs of a growing population (United Nations, 2014) whilst eliminating lasting impacts on the environment (Foley et al., 2011) will require the sustainable intensification of agriculture (Tilman et al., 2011; Garnett et al., 2013). Conservation Agriculture (CA) has been highlighted as a key path toward achieving this urgent food security for the global population (Kassam, 2020a, 2020b, 2022). Accordingly, CA systems and practices are evolving worldwide as an excellent example of the way agriculture can cooperate with nature's laws to provide food on a sustainable basis (Hobbs et al., 2008; Kassam et al., 2009, 2020, 2022; Erenstein et al., 2012; Kassam and Friedrich, 2012; Corsi et al., 2012; Pretty and Bharucha, 2014; Kassam, 2022).

As a society, producers and consumers of food and agricultural products need to take ownership of the anthropogenic impact agriculture is having on the environment, including climate change. Conservation programmes need to be integrated into agriculture and linked to C management. The many attributes of C cycling are critically important in transforming agricultural land management into effective CA systems for improved management of agroecosystems and their services to society (Mitchell et al., 2019; Kassam, 2020a, 2020b; Kassam, 2022; Kassam et al., 2020, 2022; Reicosky and Janzen, 2019; Friedrich, 2020; Reicosky, 2020; Reicosky and Kassam, 2021). CA integrates system concepts based on the application of three key principles: (1) continuous no or minimum soil disturbance (no-tillage); (2) permanent crop biomass cover on the soil surface; and (3) maximum crop biodiversity with diverse crop rotations, and/or sequences, and/or associations including cover crop mixes. These key practices work with location-specific complementary practices of integrated crop, soil, nutrient, pest, water, and farm power management to help optimize the overall land use and farming systems. Enhanced C management enables interactive synergies between the biological, physical, hydrological, and chemical properties and processes with multiple economic and environmental benefits. Thus, with the increased frequencies and intensities of climate extremes and their impacts on food security, the negative impacts of intensive tillage on soil organic C and crop productivity must be addressed globally as a matter of urgency (Reeves, 1977, 1997; Lal et al., 2007; Montgomery, 2007a, 2007b; Reicosky and Lindstrom, 1993; Reicosky, 2015; Reusser et al., 2015; Banwart et al., 2015, 2019; Janzen, 2015; Haddaway et al., 2017; Jackson et al., 2017; Chenu et al., 2019).

The objective of this article is to: (a) describe the history of tillage agriculture and the inevitable negative consequences; (b) identify a set of nature's laws of agricultural soil productivity; and (c) elaborate on how these laws operate in CA as a basis of C centric management for sustaining and regenerating soil and crop productivity and landscape-mediated ecosystem functions and services. Given the large scope of the article, the information provided is relevant to all stakeholders responsible for sustainable agriculture production and land management. They include farmers, supply chain service providers and manufacturers, education, research and extension community, policy makers and politicians, and those in the fields of natural resources, environment, food security, climate change, and agriculture and rural development.

History of tillage agriculture

Sustainability of farming has been a concern for decades, but little progress has been made. Particularly farming as done in the moderate climate of northern Europe has long been considered as being sustainable. Until the first part of the 20th century most of the environmental parameters of agricultural landscapes, being of particular concern today, appeared seemly stable, namely biodiversity, environmental pollution, and organic matter content of soils. Farming was characterized by integrated crop-livestock farms with a high percentage of pasture and fodder crops including legumes in the crop rotations. Operations were done with draft animals or low horsepower tractors, allowing relatively low working speeds and shallow tillage operations. However, from the end of WWII, farming began to change, relying increasingly on agrochemicals and intensive tillage, and less diversified cropping systems.

Farmers around the world have relied on tillage for >10,000 years (Lal et al., 2007; Montgomery, 2007a, 2007b; Reusser et al., 2015; Reicosky, 2015). Reasons justifying the need for tillage have been increasing over the years with emphasis on loosening the soil for easier planting, crop biomass incorporation and weed control.

As conventional tillage-based agriculture intensified, more specific reasons evolved and are summarized in Table 1. Many of the reasons seem logical from a crop production perspective, but they appear to be primarily aimed at meeting a short-term need for crop establishment with perceived operational convenience, with little regard to consequences in terms of soil degradation, loss of environmental quality, and poor plant nutrient management. More so, they often try to remedy conditions in the soil which have been created by the negative impacts of tillage operations in the first place.

Although the tillage approach to crop production has short-term benefits, it also has serious problems and long-term consequences, notably the resulting loss of soil to erosion and other forms of degradation. According to Pimentel et al. (1995), about 430 million ha—almost one-third of the global arable land area—has been lost to soil erosion. Efforts to control human-induced land degradation and soil erosion have been building on the ruins of the past tillage and monoculture concepts (Lal et al., 2007). Both Diamond (2005) and Montgomery (2007a) agree: agricultural sustainability—particularly the conservation of soils—is critical to our long-term survival.

Our agricultural heritage and origin of soil degradation was a

Table 1
Reasons given for tillage. Source: Personal Communication: Lyle Carter, USDA-ARS Shafter, CA plus a few additions.

1. To plant a seed/seedling	13. For pest control
2. To remove a crust	14. For recreation
3. To reduce compaction	15. To refine seed bed
4. For water infiltration	16. For salinity control
5. To remove vegetation & weed control	17. The feeling of power and dominion
6. For rain capture	18. For aeration
7. To incorporate vegetation	19. To mix soil layers
8. To dry & warm the surface soil	20. For the satisfaction of doing "good work"
9. To control irrigation	21. To control soil temperature
10. To incorporate nutrients & amendments	22. To pierce impermeable layer
11. Pride in a clean field & straight furrows	23. To hear the tractor roar working at capacity
12. To reduce erosion	24. To undo compaction from previous tillage

fundamental factor in the rise and fall of ancient civilizations (Montgomery, 2007a; Herrera and Garcia-Bertrand, 2018). Initial human settlements were in geographical regions with high soil productivity used primarily for agriculture: food, fibre production, and shelter. However, a typical pattern in many societies was that the regional soil productivity diminished after years of use. Scholars have found evidence of soil degradation by erosion, nutrient depletion, and salinization as devastating factors among different cultures (Montgomery, 2007a; Plieninger, 2008).

In North America, the US Dust Bowl in the Great Plains was a prolonged and massive series of wind erosion events that occurred during severe drought years in the 1930s (Lal et al., 2007). The Dust Bowl created a controversy about the usefulness of the "mouldboard plough" as a tool for seedbed preparation. Then in 1942, Edward Faulkner published a book titled "Plowman's Folly" (Faulkner, 1942a & Faulkner, 1942b) which raised the then radical concept of farming without ploughing or "tillage" as the solution to wind and water erosion. Faulkner stated: *"No one has ever advanced a scientific reason for plowing"* and his vision of farming without the plough was initially advanced through the efforts of visionary mechanical engineers and agronomists in the public sector, however, it was slow to be implemented. After the WWI, agriculture began to be industrialized starting in North America and after WWII in Europe. This involved the intensification of soil mechanical disturbance through ploughs and other tillage implements to prepare seed bed and control weeds and the intensification of chemical application for crop nutrition and protection against weeds, insect pests and diseases. In Europe also the industrialization of agriculture led to similar consequences, ultimately also leading to yield ceilings below agroecological potentials, high input costs and environmental degradation (Brisson et al., 2010).

When this kind of agriculture was exported to other climatic zones in the tropics and sub-tropics in times of colonization, it proved to be unsustainable as the ploughed soil started to degrade and erode quickly. As industrialization advanced, agriculture was mechanized, replacing draft animals by tractors which allowed higher working speeds and deeper ploughing depths. Forage areas were reduced, crop rotations shortened. The 'Green Revolution' technologies with modern inputs as synthetic fertilizers, pesticides and high yielding crop varieties allowed to compensate for the soil degradation and loss of productivity. However, today it becomes obvious that these technologies have led agriculture into a dead end: yields in tropical climates with severe soil degradation problems are declining, farming is becoming increasingly risky and uneconomic, and landscapes are desertifying. Even in Europe and the Americas, where intensive tillage agriculture is practiced, yields are stagnating, factor productivities are decreasing, and soil erosion and environmental problems are increasing as a result of climate change with more extreme weather events against which the degraded agricultural soils cannot resist anymore.

Nature's fragile "Living soils"

The "living soil" is full of bacteria, fungi, algae, protozoa, nematodes, and many other fragile creatures affected by intensive tillage and reflects a fundamental shift in care for our soils. Soil is a dynamic, living resource with many micro-, meso-, and macro-biota that are essential to the sustainable production of food and non-edible products and to the maintenance of global biogeochemical C, water and nutrient cycling and ecosystem functioning. Tillage is an "apocalyptic event" for the soil organisms causing mortality in addition to all the C, nutrient and water lost. All forms of tillage disturb all soil biology and ecological functions and can be considered as a "broadband biocide". In general, larger organisms of the megafauna (organisms $>$ 2 mm, earthworms, and large invertebrates) and fungi are damaged more by intensive tillage than smaller organisms of the meso- and microfauna and microflora (Ball and Robertson, 1994; Barnes and Ellis, 1979; Black and Okwakol, 1997; Folgarait, 1998; Chan, 2001). This may also be a reason for a shift in the ground beetle population due to a change in the tillage regime, as the prey of some species of ground beetles appear more or less frequently after tillage. Physical interference with the soil by ploughing results in larger organisms of higher trophic levels being disadvantaged, while small organisms of lower trophic levels are less affected or may even benefit to a small extent (Wardle, 1995).

Soil macrofauna are important in soil fertility dynamics as their burrowing activities aid in improvement of soil aeration and water infiltration. Earthworms affected by tillage practices have been documented in review by Rasmussen (1999). A six-year study by Anderson (1987) revealed a significantly higher earthworm population in no-till soil than in ploughed soil as Briones and Schmidt (2017) found using a global meta- analysis. Kemper et al. (2011) reported that less intense tillage increased the activities of surface-feeding earthworms. Due to disruption of fungi mycelia by tillage, Cookson et al. (2008) observed a decreased fungal biomass and increased bacterial biomass with increasing tillage disturbance. They also reported alteration in the composition and substrate utilization of the microbial community with distinct substrate utilization in no-till soil. Six et al. (2006), indicate that most tilled agricultural soils are dominated by bacterial activity. They found a quantitative and qualitative increase in soil organic matter (SOM) is generally observed in agricultural systems favouring a fungal dominated community suggesting the need for minimum soil disturbance to optimize fungal activity. Muller et al. (2022) reviewed the effect of soil tillage on ground beetles (carabids) investigated in many experimental studies. However, there is currently no clear and differentiated picture of how ground beetles are affected by tillage operations in direct and indirect ways showing that the effects of intensive tillage on ground beetles—especially the use of mouldboard ploughing—are variable. The high variability of carabid responses to tillage is also likely a consequence of various modifying factors such as cover cropping, rotations, and variations in weed control associated with tillage.

Conservation as a modifier of agriculture in CA systems appeals to a wide range of farmers because it preserves and protects the natural resources in a regenerative manner, with greater yields and yield stability as well as higher factor productivity—thus better and more reliable income (Kassam, 2019, 2020a). Conservation incorporates a biologically dynamic ecological foundation in production systems such that the natural resource base and its agricultural potential and ecosystem functions are conserved, enhanced, and maintained at the optimum level. This means that all three interlinked CA practices work together to provide a sustainable ecological and biological foundation (Kassam, 2020a). Combined with complementary good agricultural practices dealing with integrated soil, crop, nutrient, water, pest and energy management, CA systems offer an optimal performance involving maximum efficiency, adaptability and resilience (and profitability and stability), and maximum economic output with minimum production inputs (FAO, 2016; Kassam et al., 2013; Kassam, 2020a).

Negative effects of soil tillage

Generally, the negative side effects of ploughing or tilling the soil are not often discussed in research papers. The degrading effects when tilling the soil have not earned the attention they deserve, keeping in mind that there are more living organisms in a handful of undisturbed soil than the number of humans on earth. Some of the main negative effects (without claiming the list to be complete) are summarized as follows in Table 2.

While many of these negative impacts of tillage may seem small and inconsequential, the cumulative effects of small changes over time can evolve into major soil degradation that limits productivity and production efficiency, requiring additional production inputs. Soil lost or degraded in any type of erosion is difficult to restore or regenerate within a generation or two. Ignoring the long-term negative environmental effects of tillage leads to economic losses at the farm and landscape level that threaten the food production system. The unintended

Table 2
Negative consequences of tillage agriculture in 6 impact areas.

1. Carbon capture and storage	2. Hydrological	3. Ecological
• leads to soil organic matter (C) losses • soil C is oxidized to form CO_2 • decreased C leads to biodiversity loss • cuts and chops plant biomass for better incorporation maximizing biomass-soil contact and decomposition • mixes soil and surface plant biomass to increase decomposition rate • constant and continual soil disturbance decreases overall soil C content, fertility and quality • depletes C required for microbial activity and soil structure formation	• destroys water stable aggregates and soil structure • rainfall causes surface sealing which impedes infiltration, causing runoff and soil erosion • water that does not infiltrate into the soil is lost to the growing crop • bare soil leads to water, wind and tillage erosion • each tillage operation reduces soil water equivalent ~ 15 to 20 mm of rain • bare soil water evaporation leads to high losses of plant-available water	• most unnatural and intrusive operation in the "living soil" with no parallel in nature • disturbs all ecological functions • negatively affects soil animals and insects living in and on the soil surface • destroys soil insects, arthropods, bacteria and fungi • alters the fungi to bacteria ratio • destroys previous crop root and earthworm bio-pores for deep water storage • destroys earthworms and their habitat and that of other soil meso- and macrofauna • destroys the habitats of ground-nesting birds • some ecological impacts take > 100 years to recover from a single tillage event (Isbel et al., 2019).
4. Physical	5. Climate	6. Input Costs
• causes compaction and tillage pan requiring more tillage • sediment load in water from soil erosion cause damages to water treatment plants • erosion causes the siltation of creeks, rivers, lakes, dams, asphalt roads ditches, and harbours • most soil degradation is caused by physical and mechanical disturbance	• tillage-induced CO_2 is a major GHG emission • contributes to global warming and climate change • leads to warmer soil temperatures and evaporation losses • high intensity rain events lead to more flooding and associated damage	• largest fossil fuel consuming operation • most time-consuming farm operation • operation with the highest power demand in size and number of tractors • highest wear and tear requiring more equipment repair • requires more costly and degrading chemicals • leads to negative economic and environmental consequences

consequences also lead to negative social and livelihood consequences that threaten our food security. If for instance in an economic study the negative externalities are not considered, it will invalidate the study and its conclusions. The true cost of any type of complex environmental degradation is very challenging to quantify from an economic perspective. For example, tillage-induced soil erosion is a serious threat to global sustainability, endangering global food security, driving desertification and biodiversity loss, and degrading other vital ecosystem services, all with major challenges in developing effective metrics and quantifying financial costs (Pimentel et al., 1995; Montgomery, 2007a; Nkonya et al., 2016).

Some may think that our position is too harsh against the plough and other tillage tools, but this is not the case. The plough has had its place in time and in history and without it certainly millions of people would have needed to go to bed hungry and others would have been killed or would have been close to starvation (Lal et al., 2007; Montgomery, 2007a & b; Reusser et al., 2015). As a matter of fact, the history of the plough and soil tillage is a fascinating story that is accessible to anyone because of the information we can find on the internet. However, it had its glorious times in moderately cool humid and sub-humid temperate climates with integrated diversified farming systems at an animal traction level of mechanization. In warm semi-arid climates as in the middle east already the very early wooden 'ard' type tillage implements resulted in permanent desertification of landscapes long before the arrival of modern tillage-based green revolution agriculture and climate change. Tillage can also be compared to the use of fossil fuel – it was necessary for some time for human development, but it always degraded the environment and as sustainable alternatives become available it should be discontinued.

Tillage and soil degradation

The use of tillage tools and implements in agriculture combined with maintaining bare soil surface with no explicit measures to protect and conserve soil biology have been responsible for the steady decline in soil quality and function. It has also led to a loss of overall soil fertility although this decline has been masked by the ever-increasing application of fertilizers**.** Bauer and Black (1994) showed that soil degradation is closely correlated with the duration of soil used in tillage farming (Fig. 1). Tillage causes a disruption of all soil attributes, of all the biological and ecological processes that occur in soils under natural conditions as an integral part of the ecosystem functions, and of natural food webs. The disruption involves breaking nature's laws through the break-up of soil physical structure and the oxidation of soil organic matter, leading to a loss in function and resilience as well as living space for soil micro, *meso* and macrofauna. Further, in tillage farming, bare and unprotected soils are exposed to erosive rainfall, high wind speed and direct solar radiation. This leads to many negative consequences for soil health which are dealt with in more detail in the following sections. Additionally, tillage causes a greater loss of soil C into the atmosphere in the form of greenhouse gas CO_2 emissions that contribute to climate extremes. Instead of C being stored/captured in the soil to improve its productivity, tillage promotes and exacerbates greenhouse gas emissions which contribute to global warming and climate change (Kern and Johnson, 1993a, 1993b; Reicosky, 2015; Reicosky and Lindstrom, 1993, 1995; Ellert and Janzen, 1999; Rochette and Angers, 1999).

The key problem in tillage agriculture is the steady decline in soil fertility and productivity which is closely correlated with the duration of soil use (Fig. 1). The reason for lower resilience is found primarily in the occurrence of the loss of soil organic matter, soil biota and biophysical structure leading to decreased water infiltration, increased water runoff and soil erosion, and soil water evaporation, all together leading to extensive land degradation. Beyond soil impoverishment, there is a major transfer of nutrients and pesticides to watercourses, reservoirs, and ultimately to the seas.

Fertility loss leads to increased needs for synthetic fertilizer resulting often in unbalanced and unhealthy plant nutrition. The disruption of soil food webs leads to a loss of natural control of pests and diseases. Both effects result in increased necessity for the use of pesticides, which then further destroy the natural control mechanisms, resulting in a vicious circle of increased use of agrochemicals.

It must be kept in mind that soil tillage is an unnatural, intrusive, and incorrect soil treatment. It consumes high amount of fossil fuel, labour, and time, and increases the capital and maintenance cost of farm machinery and equipment. Soil tillage has three basic detrimental effects: (a) elimination of crop biomass soil cover, fragmenting and incorporating them into the disturbed soil layer; (b) pulverization/disaggregation of the topsoil; and (c) increased biological decomposition of crop biomass and decreased soil organic matter level. These effects are now recognized as the 'root' cause of soil degradation and erosion, and loss of soil and landscape-mediated environmental functions in agricultural land. These functions are many and include water, nutrient and C cycling, C storage, water retention and groundwater recharge, streamflow regulation, provisioning of good quality water, and habitat for soil microorganisms and soil inhabiting mesofauna as well as ground-nesting

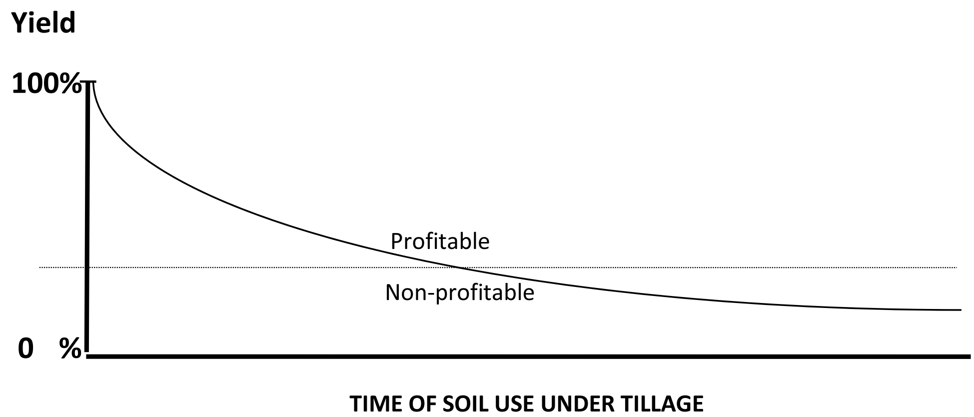

Fig. 1. An illustration of yield Losses due to soil degradation through time in tillage agriculture (Bauer and Black, 1994).

wildlife. Generally, to sustain crop production and profit in tillage farming, particularly in medium and large-scale farms, excessive amounts of mineral fertilizers and pesticides are applied in poorly diversified cropping systems causing environmental and water pollution, loss of biodiversity and biological productivity, and enhanced greenhouse gas emissions.

Carbon and water are intimately linked in all aspects of C and water cycling in agricultural production systems. "Soil organic carbon (SOC) is the most often reported attribute from long-term studies and is chosen as the most important indicator of soil quality and agronomic sustainability because of its impact on other physical, chemical, and biological indicators of soil" (Reeves, 1977, 1997; Reicosky, 2015; Chenu et al., 2019; Wiesmeier et al., 2019; Reicosky and Kassam, 2021; Reicosky et al., 2021). Natures laws of declining soil productivity due to tillage disturbance are based on this fundamental fact. These laws must be taken into consideration when engaging in agricultural production systems involving crops, animals, and trees (Derpsch and Moriya,1998; Derpsch et al., 2006). Disregarding these laws promotes soil degradation and loss of biological and ecological productivity of soils, landscapes, and ecosystems, jeopardizing our food security.

Many soil functions in agricultural ecosystems relate to C management, C cycling and C energy flow through the soil–plant–atmosphere system (Kuzyakov and Cheng, 2004; Janzen, 2015). Warkentin (2001) discussed how alteration of soils by tillage changes the sustainability of soil functions. Soil tillage presents an enigma in thinking about soil sustainability in ecosystems. This is because sustainable soil functions when viewed from a 'natural perspective' depend on minimum soil disturbance and soil C for optimum results. Tillage releases CO_2 from rapid oxidation of SOM and mixes soil and crop biomass (Reicosky and Lindstrom, 1993, 1995; Reicosky, 1997; Reicosky, 2002; Ellert and Janzen, 1999; Rochette and Angers, 1999; Jackson et al., 2003). In this way, tillage is a "double negative", rapidly releasing CO_2 from both the soil and the fossil fuel consumed in the tillage operation. Decreasing tillage-induced greenhouse gas emissions requires minimum soil disturbance and enhanced C input through biomass production including cover crops to increase C storage (Reicosky et al., 2021).

> "Land, then, is not merely soil; it is a fountain of energy flowing through a circuit of soils, plants, and animals […] like a slowly augmented revolving fund of life." (Leopold, 1949).

The flow of energy to power our "living biological systems" revolves around the biological C cycle. Carbon is energy flowing into and out of the soil through plant exudates and the deposition of plant biomass used for the creation and maintenance of the biological activity (Kuzyakov and Cheng, 2004; Janzen, 2015; Reicosky and Janzen, 2019). The biological community uses that energy for the creation and maintenance of the soil structure creating enhanced hydrological properties. Williams and Plante (2018) proposed a bioenergetic framework for the quantitative assessment of soil organic matter changes. Wacha et al. (2022) described an analogous concept of soil energetics as a framework to better understand changes in soil function and C dynamics. They expanded the framework that quantifies the net energy flows within a soil control volume using energetic components including mechanical, biogeochemical, and hydrological processes. Their integrated analysis indicated over half of the energetics in the soil comes from the in-season deposition of root exudates through growing plants, supporting the soil health principle requiring a living plant as long as biologically possible. Management practices, especially intensive tillage, impact energy fluxes through tillage type and intensity enabling raindrop-induced erosion events. They applied system analysis to three different tillage management practices to assess energy balances. They found that seasonal net energy balances for a conventional till, no-till, and grassland system were negative, neutral, and positive, respectively (Wacha et al., 2022), suggesting that tillage not only physically destroys soil structure, but it also has a major impact on C energy flow and cycling resulting in the net soil C loss to the atmosphere (Reicosky and Lindstrom, 1993; Ellert and Janzen, 1999; Rochette and Angers, 1999; Dold et al., 2016). These works reinforce the negative impacts of tillage on the biological processes in soils and the need for further recognition and acceptance of nature's laws.

Plant C is transient with continuous movement through the soil food biological web, meaning that plant C is constantly changing as SOM is decomposed and is transformed into new organisms or converted into different compounds (Janzen, 2015; Kane, 2015: Reicosky and Janzen, 2019; Wiesmeier et al., 2019). Evidence is slowly accumulating on the benefits of no or minimum soil disturbance (i.e., no-tillage in practice for crop establishment and weeding) enhancing C accumulation and all the associated synergistic benefits (Allison, 1973; Lal, 2009, 2014; Chenu et al., 2019). There is a widely acknowledged consensus among researchers, regardless of their philosophical orientations or past experience, that this long-term retention of OM in soils, and its effect on the resilience of soil architecture (e.g., Chenu et al., 2019; Wiesmeier et al., 2019; Vogel et al., 2022), are essential to guarantee that soils will be able, in spite of climate change, to continue fulfilling the key functions on which humanity depends (Reicosky et al., 2011, 2021; Baveye et al., 2018).

We are slowly understanding the ecological implications of intensive tillage on both the water and C cycles. Isbell et al. (2019) found that after 91 years of tillage, formerly ploughed fields still had only three quarters of the plant diversity and half of the plant productivity observed in a nearby remnant ecosystem that had never been ploughed. These findings are supported by the review of Reeves (1977, 1997) who concluded that long-term tillage studies are in their infancy and these findings shed new light on the implications of "long-term" tillage research conducted for about 30 years, since the advent of conservation tillage techniques, and only in developed countries in temperate regions. In most tillage research, paired tillage data sets > 20 years are considered long-term, often required for NT to show significantly more C storage than conventional tillage-based agriculture (Cusser et al., 2020). Dick et al. (1986a, 1986b) discussed difficulties associated with accurately quantifying changes in soil C stocks emphasize the importance of following well-conceived sampling and analytical strategies, and the need for carefully evaluating earlier measurements to ensure they are not inadvertently biased by sampling methods. Their data demonstrated both a tillage and a soil type effect on the changing soil C content summarized in Fig. 2.

The initial soil C content was lower in the well-drained soil and showed reasonable trends likely reflecting better aeration relative to the poorly drained soil, even though both sites were tile drained. The well-drained soil showed a slightly higher increase in soil C than the poorly drained soil, which was more erratic. At the end of the measurement period, the well-drained NT soil had 18 g kg^{-1} more C than the ploughed soil, whereas in the poorly drained soil, NT had about 16 g kg^{-1} more C than the ploughed soil. Other soil type differences such as clay mineral type, pH, salinity, etc., may have contributed to the soil differences. Reeves (1977, 1997) reviewed the long-term SOC changes in continuous cropping studies. Other long-term studies showing NT enables more C storage than tilled soils include Ismail et al., 1994; Wiesmeier et al., 2015; Nunes et al., 2018; Daigh et al., 2018; Wiesmeier et al., 2019. Nouri et al. (2019) found long-term (34 years) incorporation of cover crops in NT cropping system significantly improved the infiltration rate, and field-saturated hydraulic conductivity and increased the mean weight diameter of aggregates by promoting the macro-aggregation and enhanced water storage.

Nature's laws of degrading soil productivity

Conventional thinking is that most human beings have limited moral obligation for the care of soil resources. Soil conservationists, understanding the nature of "living soil", provide a contrasting perspective that humans do indeed have an ethical responsibility caring for the natural resources and the environment for food security. Humanity must learn to love and appreciate our planet and work within nature's laws. There are four very distinct spheres that make up the planet: the atmosphere, biosphere, geosphere, and hydrosphere, but all are interconnected. Within these four spheres, we have different ecosystems that include biotic factors (all types of organisms) as well as abiotic factors (physical and chemical in the environment) working together as a unit with common characteristics. There are many different types of ecosystems on our planet as an interacting group of living organisms in a "living soil," including humans, that operate in conjunction with non-living environmental components. Living organisms and abiotic components are closely connected through C energy flows and the nutrient cycling (Kuzyakov and Cheng, 2004; Janzen, 2015; Reicosky and Janzen, 2019; Wacha et al., 2022). In addition to agriculture, we have all types of terrestrial ecosystems. The planet as our home providing our ecosystem services requires agriculture to maintain food security with minimum impact on the natural resources and the environment. There is growing concern about agricultural tillage and environmental degradation as evidenced in a few selected research articles (Briones and Schmidt, 2017; Haddaway et al., 2017; Jackson et al., 2003; Nouri et al., 2019; Wardak et al., 2022; Wardle, 1995). Viewing and understanding our existence on the planet with finite resources, requires consideration of all ecosystems and how they can be managed appropriately with emphasis on minimizing soil disturbance and integrating conservation and agriculture (Kassam, 2019).

Sustainable soil management at the production system level is defined as a set of soil biological and ecological processes that do not degrade soil productivity irreversibly but regenerates and enhances it, with the aim of maintaining the desired regenerated levels of soil and land productivity and functions over time, with minimum environmental impact (Reeves, 1977, 1997). Only within these boundaries can agriculture be managed as an ecologically multifunctional and sustainable system for the society and the planet. CA has slowly evolved over several decades as such a sustainable and regenerative production system that also delivers ecosystem services. Recent reviews (Reicosky and Janzen, 2019; Friedrich, 2020; Reicosky, 2020; Reicosky and Kassam, 2021; Kassam, 2022; Kassam et al., 2022) support the integration of primary principles of CA as the form of sustainable agriculture with responsibility of maintaining food security and environmental protection within agricultural ecosystems, and, participation of all societies is required to help preserve and protect the other precious ecosystems we have while abiding by the relevant nature's laws. There must be a radical "global societal" effort acting soon to maintain our quality of life in this time of global crises involving the breaching of several safe planetary boundaries including ecosystem degradation and climate

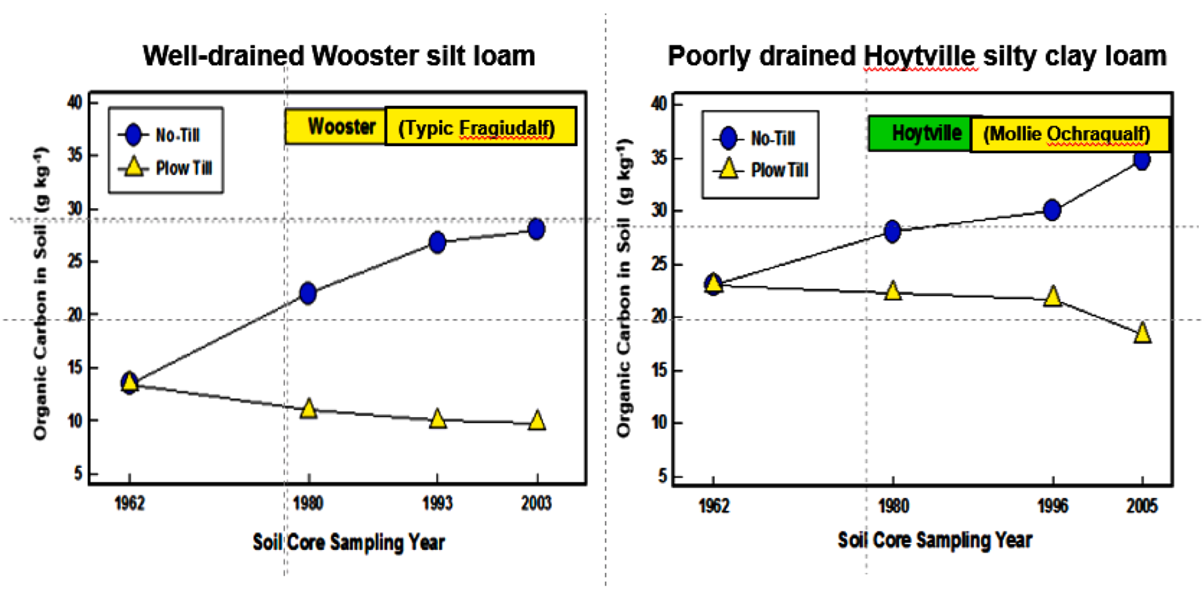

Fig. 2. The effect of tillage and soil type on soil C changes in the eastern corn belt of the US. Data from Dick et al. (1986a, 1986b), charts via personal communication.

breakdown (Rockström et al., 2020).

Nature provides us with everything we need, the sun, soil, water, air, intellect, and biodiversity as the primary resources to sustain our existence on our "living planet" as these vital resources are finite. Nature thus requires that we learn to preserve and protect these resources for future generations, and this calls for understanding and collaborating with 'Mother Nature' to maintain our food security. In this regard, for agriculture to work with nature, the tillage consciousness is of prime importance. This consciousness must be underpinned by the following awareness about the way nature maintains soil productivity and function.

Nature rarely disturbs or inverts the soil to promote vegetation growth and reproduction, suggesting that nor or minimum soil disturbance is a critical factor to maintain the "living soil" over the many years of soil development. Nature restores and regenerates itself constantly with an ingenious and elegant performance. Thus, nature has some operational principles, rules or laws that regulate the properties, processes, and functions in our natural ecosystems. Our awareness of the power and the impact of nature should lead us to a better understanding our management role in utilizing these valuable resources and the need for conservation practices to preserve and protect all resource functions.

Considering the existential importance of our natural resources and the complexity of our global system with emphasis on the "living soil", C functions, and impacts of tillage disturbance on soil and ecosystem services, we propose that the following five nature's laws of declining soil productivity (Derpsch et al., 2006).

1. Any land-based agricultural production system that involves continuous reduction in soil organic matter content of the soil is not ecologically sustainable and leads to poor soils and farmers.
2. Under repeated and intensive soil tillage the organic matter is mineralized at rates that are greater than the recovery rates that are possible in nature, causing a reduction of organic matter content which leads to a gradual decrease of productivity of soils.
3. Intensive and repeated soil tillage that leaves the soil bare and unprotected from climate extremes leads to a reduction in water infiltration into the soil, water and/or wind erosion and soil losses at rates greater than natural regeneration rates. This results in nutrient, soil water and organic matter losses and in a reduction of crop productivity that leads to poor soils and farmers.
4. Intensive and repeated tillage that buries or removes crop residues, leads to a destruction of stable soil aggregates and soil structure, leading to a decrease in soil moisture retention, increases the temperature amplitude of the soil, reduction in soil flora and fauna and disruption of soil biological processes. This has negative effects on physio-chemical processes in the soil, resulting in a loss of soil quality and productivity.
5. Any tillage agricultural production system in which losses of important nutrients occur, be it by extraction without replacement (e.g., agricultural exploitation/mining), volatilization (e.g., frequent burnings), surface runoff and/or by lixiviation (e.g., fallow periods without crops and bare soils), will result in poor soils and farmers.

The following section elaborates on how nature's laws of declining soil productivity are managed in CA which results in sustainable and regenerative multi-functional agricultural land use systems offering a range of productivity, economic, environmental and social benefits to both large and small landowners globally.

Conservation Agriculture

Utilization of nature's resources requires us also to preserve and protect them for present and future generations suggesting that we need to obey "nature's laws." Environmental sustainability is now a central concern of agriculture production to sustain soil and landscape productivity and integrity within planetary boundaries to meet the needs of the global society. In the past five decades paradigms of agriculture production have changed from a mindset that considered "*Soil tillage to be necessary to produce crops*" (until the 1960s) to "*Soil tillage to be the root cause of agricultural land degradation*" (e.g., Huggins and Reganold, 2008; FAO, 2008; Reicosky, 2015). However, about 13 years later the paradigm has changed further to "*Soil-based production involving soil tillage practices is not sustainable as it harms soils and must be abandoned*" (from 2021 onwards) (e.g., ECAF, 2021). In relation to soil tillage, "*science has shown that agricultural land degradation is one of the most serious environmental problems worldwide which poses a threat to food production and rural livelihoods*" (Huggins and Reganold, 2008). Therefore, a new model of agriculture must be addressed in order to comply with nature's laws and face the needs to produce more food, intensify plant species variability, and look for better nutritional quality. This new model of agriculture is illustrated by what is now called Conservation Agriculture, a no-till mulch based diversified cropping system (Kassam et al., 2022).

Worldwide, the first farmer to adopt the no-tillage practice on his farm was Harry Young in the year 1962 in Herdon, Kentucky, USA. Ten years later the practice reached Rolandia, Brazil, where in 1972, Herbert Bartz began practicing No-tillage. It is important to understand that while No-tillage is a relatively 'new' practice historically, at the same time it is 50 or 60 years old. It was also, before colonization and arrival of the plough, the common form of agriculture in South America allowing farming under difficult climatic and geographic conditions for a long time. Adoption of this practice has been a farmer-led process (de Freitas, 2000). Initially, farmers did not have the necessary tools for adoption of no-tillage practice, nor did they have the know-how, nor the machines, nor the herbicides. This kept the initial acceptance rates low.

After 1990, the adoption of CA took off globally and in 1997, the no-tillage production system evolved into the modern-day Conservation Agriculture which FAO defined as a production system based on the application of three interlinked principles (FAO, 2022; Kassam et al., 2020, 2022). These are:

1. *Continuous minimum or no mechanical soil disturbance*: implemented by the practice of no-till seeding or broadcasting of crop seeds and direct placing of planting material into untilled soil; no-till weeding; minimum soil disturbance from any cultural operation, harvest operation, or farm traffic. Sowing seed or planting crops directly into untilled soil and no-till weeding reduces runoff and soil erosion; minimises the loss of soil organic matter through oxidation; reduces disruptive mechanical cutting and smearing of pressure faces; promotes soil microbiological processes; protects and builds soil structure and connected pores; avoids impairing movement of gases and water through the soil; and promotes overall soil health.
2. *Maintaining a permanent mulch cover on the soil surface*: implemented by retaining crop biomass, rootstocks, and stubbles and biomass from cover crops and other sources of biomass from ex-situ sources. Use of crop biomass (including stubbles) and cover crops reduces runoff and soil erosion; protects the soil surface; conserves water and nutrients; supplies organic matter and carbon to the soil system; promotes soil microbiological activity to enhance and maintain soil health including structure and aggregate stability (resulting from glomalin production by mycorrhiza); and contributes to integrated weed, insect pest, and pathogen management and to integrated nutrient and water management.
3. *Diversification of species in the cropping system*: implemented by adopting a cropping system with crops in rotations, and/or sequences and/or associations (mixedcropping) involving annuals and perennial crops, including a balanced mix of legume and non-legume crops and cover crops. Use of diversified cropping systems contributes to diversity in rooting morphology and root compositions; enhances microbiological activity; enhances crop nutrition and crop protection through the suppression of pathogens, diseases, insect pests, and weeds; and builds up soil organic matter. Crops can

include annuals, short-term perennials, trees, shrubs, nitrogen-fixing legumes, and pastures, as appropriate.

The global CA community of practice defines CA as an ecosystem approach to regenerative sustainable agriculture and land management based on the practical application of the context-specific and locally adapted three interlinked principles described above. CA manages the nature's laws of declining productivity by ensuring that the application of the three interlinked principles provide a sustainable ecological foundation for regenerative agriculture. Along with complementary practices of integrated crop, soil, nutrient, water, pest and energy management, the CA system establishes a spiral of integration and enhancement to support sustainable production intensification and the delivery of ecosystem services (Kassam et al., 2022).

CA systems are present in all continents, involving rainfed and irrigated systems including annual cropland systems, perennial systems, orchards and plantation systems, agroforestry systems, crop-livestock systems pasture and rangeland systems, organic production systems, and rice-based systems.

In 2018/19, CA was being practiced on more than 205 M ha of cropland worldwide (15 % of global cropland area), across 102 countries in all land-based agroecologies, farm sizes and farm power sources. About 50 % of CA area is located in the South and 50 % in the North (Kassam et al., 2022). This demonstrates that CA is a universally applicable paradigm that is resilient, regenerative, and sustainable. A great advantage of this paradigm is its extensive acceptance by farmers worldwide who have led its development from the beginning in the 1950s.

The wealth of knowledge farmers, researchers, professors and extensionists all over the world have accumulated in these last decades about CA is remarkable (Kassam, 2020a, 2020b, 2022). This is especially so because it has been achieved across a wide range of climates, soils, and socioeconomic conditions in both developing and developed economies (Kassam et al., 2022). This means that CA is contributing to protecting and sustaining the environment and natural resource base for present and future generations. Despite this, we need to remember that in 2018/19, CA was being practiced on only about 15 % of global cropland area. Considering that CA is for the moment the only known and practical system of sustainable agriculture, this means that greater effort needs to be made at the dissemination and uptake level of CA to ensure that a much larger area or most the agricultural cropland area must be used in a sustainable way. In this regard, the 8th World Congress on Conservation Agriculture has set a target of 50 % of the global cropland area to be managed by Conservation Agriculture by 2050 (ECAF, 2021). This is equivalent to about 700 M ha of global cropland area.

Benefits of Conservation Agriculture

After many decades of practice by farmers worldwide and research support, there is adequate scientific and practical evidence to show that (Kassam, 2020a, 2020b, and 2022):

a) Tillage is not necessary to produce a crop. This can be observed in nature reserves which produce high biomass with no tillage. In tillage agriculture bare soil surface and loose topsoil with degraded soil biology cannot withstand intensive, erosive rainfall or wind, thus continuously losing soil from erosion.
b) CA has positive effects on chemical, physical, hydrological, and biological soil attributes, improving soil quality and function with time when correctly practiced and nature's laws of soil productivity are respected.
c) CA saves significant quantities of fossil fuel (up to two thirds), saves labour and time, and in general after achieving soil equilibrium shows higher productivities and economic returns than tillage-based agricultural systems.
d) CA is an efficient system for controlling land degradation and avoid soil erosion which is a robust reason for its high rates of adoption.
e) Tillage-based organic farming generally shows increasing popularity among farmers mainly because of subsides from government and the higher price achieved by farmers for their products. However, relying on intensive tillage for weed control and nutrient mineralization from soil organic matter, tillage based organic farming is not sustainable because it degrades physical, chemical and biological soil attributes as well as soil quality and causes land degradation and soil erosion. Fortunately, an increasing number of farmers are developing organic CA systems (Moyer, 2015; Lalani et al., 2017; Karbin et al., 2021). In some cases, this involves gradually reducing tillage and external chemical inputs until soil health and quality have been regenerated.

CA promotes higher biodiversity below and above the soil surface. It provides a year-round protected environment for different species, so that a build- up of pests and diseases is usually controlled by a simultaneous build-up of their natural antagonists. This results in lower crop damage, even in cases where pests are present in the crop, and with this also a decreasing need for pest control measures.

a) The use of pesticides including herbicides can be reduced and even eliminated. Crop rotations and associations involving pest and disease resistant/tolerant crops and the use of biological approaches to integrated weed, insect pest and pathogen management can be auxiliary tools to the numerous benefits of "traditional" no-till farming (Khan et al., 2020; Goddard et al., 2022). When properly chosen, crop rotations and associations can be developed that take advantage of allelopathic effects of one species over the other at the same time can enhance the growth of one species while decreasing weed population. Creative/innovative farmers will find at field level multiple possibilities of crop combinations and sequences that take advantage of the residual effect of one species over the other that follows in a sequence leading to use of beneficial insects, viruses, and others to reduce or eliminate the use of pesticides. Planting green is an example of how crop sequence can be managed without herbicides (Duiker, 2017; Gullickson, 2018).

By 1997, a large proportion of the scientific community had accepted that No-till production systems involving minimum soil disturbance, mulch cover and diversified cropping offered numerous advantages and benefits which are not possible to obtain with tillage-based agriculture (Triplett and Dick, 2008). These advantages and benefits of CA were summarized in ISTRO (1997) as follows:

- Reduced labour requirements.
- Time savings.
- Reduced machinery wear and tear.
- Fuel savings.
- Improved long-term productivity.
- Improved surface water quality.
- Reduced soil erosion.
- Higher soil moisture retention.
- Improved water infiltration.
- Improved soil tilth.
- Increased wildlife.
- Reduced release of carbon dioxide to the atmosphere.
- Increased C sequestration into the soil.
- Reduced air pollution.
- Increased biodiversity.

However, no matter how many reasons we may provide to describe the benefits of making a transition to CA, the main reason for its adoption since 1990 being so high is the fact that, at the end of the day, farmers have more money in their pockets and derive greater satisfaction from knowing that they are reducing their risks and improving their agricultural land and the broader environment. This is critically important because most farmers will not make a radical change in any production system unless it makes ecological sense, but above all economic sense.

The above list of known advantages and benefits reflects the views of many scientists and summarizes the group consensus of the benefits of no-tillage as a single practice. There has been increasing interest in the "living soil" indicating the importance of ecological agriculture concepts and their importance in C and nutrient cycling. However, as a standalone practice, no-tillage alone would not necessarily lead to a fully functioning sustainable production system (Kassam and Kassam, 2020). This requires ample species biodiversity and a set of complementary practices to enable synergistic benefits and a fully functioning soil system and the entire agro-ecosystem to deliver a wide-range of ecosystem services.

CA has been evolving as an integrated system based on 3 primary principles that required synchrony and enabled synergy to confirm the additional benefits of minimum soil disturbance and add to the benefits from the synergistic relationships as a result of enhanced management and better understanding of system concepts. There is also an element of concern about sustainably managing the agricultural landscape as a whole for the delivery of a range of ecosystem services to society in line with the nature's way by applying the above stated nature's laws and working with nature rather than against it as is the case with many conventional tillage agricultural practices. Kassam and Kassam (2020) reviewed a comprehensive set of complementary practices that enable a functioning soil system as well as the whole agro-ecosystem to deliver a range of ecosystem services and provided additional CA benefits over and above those listed for no-tillage alone (ISTRO, 1997). As the concept of systems integration in CA and the additional understanding of the importance of biodiversity in all natural systems came together, it all contributed to the evolution of CA as a complex multi-functional land management system that requires a higher level of management and understanding.

CA improves soil water balance and water use efficiency (WUE). The productivity benefits from CA are mainly associated with its positive environmental and soil effects compared to conventional systems, including reduced erosion, runoff, and surface crusting, increased aggregate distribution and stability, and increased infiltration and soil water content and WUE (Hobbs et al., 2008; Thierfelder and Wall, 2010; Farooq et al., 2011). Water conservation is considered a key element of CA, especially in moisture stress areas exposed to erratic and unreliable rainfall. The effects of mulching on infiltration of rainfall, water balance studies are needed to analyze rainfall capture, soil storage and crop water use, including simple measurements of rainfall productivity of CA compared to conventional farming methods (Rockström et al., 2009). A general tendency of improved rainfall productivity was reported under CA in dry locations, which could be explained by a water harvesting effect, leading to a strategy for in situ moisture conservation. This strategy was confirmed in various smallholder farming systems in the savannah agroecosystems of East and Southern Africa (Rockström et al., 2009). The importance of crop residue retention in the CA system for improving soil stability and water balance was also demonstrated in the highlands of Mexico (Govaerts et al., 2009).

Benefits of Conservation Agriculture to large landowners

Benefits derived from CA have led to sustainable agricultural land management; reduced income poverty; improved food security; enhanced natural resource management including energy, nutrient and WUE; reduced degradation and water pollution; improved climate adaptability and mitigation; and improved economic growth and employment (Kassam and Kassam, 2020; Llanillo et al., 2020; Wall et al., 2020; Reicosky, 2021; Goddard et al., 2022). While most of the CA benefits are common to both the large and small farmers, there can be large differences in the C footprint with the larger farms utilizing more fossil fuels, more fertilizers, more chemicals, or equipment and repair and often more labour.

Economic benefits will accrue to landscapes, farms, communities, and regions. CA increases yields, productivity, farm production and profit depending on the level of initial degradation and yield, and the agro-ecological potential of the location (Triplett and Dick, 2008). The main CA economic benefit is from decreased input costs. Mitchell et al. (2012) found anecdotal evidence from a few large landowner-early adopters of CA that suggest annual input savings ranging from $245 to $500/ha, depending on the farm type, number of crops grown, and many personal assumptions involved. Kassam and Kassam (2020) report CA decreased fertilizer use by 50 % or more, decreased pesticides and herbicide use by 20–50 %, decreasing the combined machinery, energy and labour costs, and time requirements by 70 %, and can reduce water requirement by up to 40 % thereby increasing water productivity in rainfed and irrigated conditions. Reicosky (2021) reported ~40–50 % decrease in input costs based on anecdotal data for fuel, labour, and equipment, repair and maintenance, nitrogen fertilizer, and pesticides that says nothing about less greenhouse gas generation. Just as important, CA lowers the environmental cost to society due to decreased levels of greenhouse gas emissions, decreased levels of water pollution, and decreased damage to infrastructure, riverbanks and water bodies due to reduced erosion and flooding. The unknown social costs of environmental degradation are a substantial cost that must be minimized or eliminated.

Benefits of Conservation Agriculture to small landowners

As about 80 % of global food demands are met by small-scale farms, agricultural development programs need to re-focus their programmatic activities to improve the productivity of small farms in the tropics (Fan and Rosegrant, 2008; Vargas-Lundius, 2012). However, for development and research programs to be meaningful, it is critical that socio-economic conditions be considered by following participatory approaches with specific guidelines and steps required to establish participatory research and to promote food sovereignty for small farms in West Africa as outlined by Pimbert et al. (2010). Adding challenges to improving the productivity of small farms, Findlater et al. (2019) found farmers' definition of conservation differed substantially from that of the local experts most likely to be asked to contribute adoption estimates to global monitoring efforts. Each component of the CA coherent system requires proper interpretation and there is potential for misunderstanding and miscommunication.

Early practical constraints to the adoption and spread of CA by small landowners include a lack of appropriate machinery and equipment in the need for biomass as cattle feed. Adhikary et al. (2020) reviewed the emerging concerns due to adoption of CA systems, and analyses the constraints and research needs for improvement of Conservation Agriculture in India. The technologies used in CA benefit the environment, increase crop diversification, improve efficient use of resources, save water and nutrients, increase yields, and provide opportunity to reduce the cost of production. However, there are several constraints for promotion of CA technologies, such as lack of appropriate planters especially for small and medium scale farmers, unavailability of skilled and scientific manpower burning of crop residues, competition of crop residues between their usage in CA and livestock feeding and overcoming the biased mindset about tillage. With smaller landowners and manual production systems, there can be a 50 % reduction in family labour requirement as there is much less labour required for seedbed preparation and weeding (Lindwall and Sonntag, 2010; Kassam and Kassam, 2020).

Derpsch et al. (2015) and Wall et al. (2020) indicate the relatively low rate of adoption of CA on small farms is due to a complex set of factors. They include technological issues such as competition for scarce crop residues, adoption risk, and interactions with the cropping system; social issues such as mindset, knowledge of the CA system, and conflicts with social norms – e.g., communal grazing rights; and institutional issues including input, credit and output markets, policies and subsidies, security of land tenure, equipment availability, and applicable research and extension support (Wall, 2007). In fact, these factors affect large, commercial farmers as well as smallholders, but they have been, or are, more easily overcome in regions and areas of large commercial farms.

Derpsch et al. (2015) found the vast majority of medium- and large-scale farmers in Paraguay who use tractor-based farming systems have moved from conventional tillage agriculture and adopted CA through no-tillage technologies. However, despite efforts to transmit the technology to small-scale farmers by development aid projects and local governments, widespread adoption of CA has not happened on farms that use animal traction or manual farming systems where soil fertility loss is the fundamental cause of declining crop productivity (World Bank, 2012). Several of the issues described above may lead to failure in the application of CA, resulting in poor yield of crops and economic returns that resulted in loss of motivation and further dis-adoption by small-scale farmers. Poor application of the CA production system by farmers, also resulting from a lack of understanding of many issues (e. g. importance of soil biomass cover and cover crops), risks the sustainability of agriculture. Soil degradation and loss of fertility of soils will continue to happen. Even a market approach to the diffusion of CA did not enhance adoption of CA, since other factors appear to be more important to achieve a continuous adoption. Derpsch et al. (2015) suggested lessons learned in Paraguay may help direct future development and serve to improve development strategies in other countries.

Wall et al. (2020) reviewed the principal benefits of CA with special emphasis on the benefits to society and argue for a more equitable sharing of costs and benefits from the widespread adoption of the system that assumes that market and institutional arrangements are static and fixed. Their analysis of several recent adoption studies showed the major impediments to smallholder CA adoption are often institutional (Bolliger et al., 2005; Affholder et al., 2010; Corbeels et al., 2014). Smallholder farmers generally manage farms in more marginal areas with less access to markets for inputs, services (including credit), and outputs than their larger counterparts because of their restricted and variable volume of demand, supply, and equity. Goddard et al. (2022) concluded that CA systems are successful and profitable in Africa using fewer external inputs and expending less energy reduced by 40 % and labour needs reduced by 50 %−90 %. Nitrogen and other essential elemental crop needs can be reduced by 10 %−70 % through CA systems legume cover crops. African research and farm testing have shown integrated CA cropping systems can control insect and weeds past while providing more diverse economic crops, a win-win situation. Wall et al. (2020) suggest most of the costs in the change from current conventional farming systems to CA, are currently paid by the farmer when there are considerable benefits to society. All stakeholders have responsibility to develop long-term strategies to support and embrace CA as the most appropriate means of ensuring food security and environmental services.

What compels farmers to change to Conservation Agriculture?

Acceptance of the revolutionary no-tillage and CA concepts following a tradition of 10,000 years of tillage is not without its challenges. The acceptance of new ideas and technology often takes place slowly, partly as a result of unknown risks and partly from a lack of clear understanding of the new management details. Critical to acceptance of CA principles and concepts are demonstration plots and pioneer farmer mentors and farmer to farmer communication. The success and credibility of the pioneer CA farmers and the evolution of farmer-led networks has been critical in enhancing CA acceptance (Dumanski et al., 2014; Brouder and Gomez-Macpherson, 2014; Waters-Bayer et al., 2015). Farmer-led research led to increased crop diversity, which contributed to greater resilience to environmental risk and, in most cases, involved reduced use of chemicals. From these farmer meetings and associations, we have provided some typical responses of what is important to the farmer to accept CA. The following is a list of a few examples of the types of replies we get from most farmers why they accept CA principles and practices, which are all good reasons not to return to ploughing and harrowing the soil again.

- I spend so much less time on the tractor seat.
- Now I got more time for a better management of my farm operation.
- I have been able to spend so much more time with my family.
- I need less farm power, so I can buy a smaller tractor for no-till seeding than if I had to plough the soil for crop establishment.
- By adopting the no-till system, I need fewer rural employees, decreasing production costs.
- By consolidating the CA system at farm level, I can increase the cultivated area or even provide custom agricultural services to other farmers.
- If I do not till the soil, I can double or treble the life of my tractor from about 10 to 20 or 30 years.
- The field activities would reduce my diesel costs by two-thirds.
- Using the No-till technology, I have stopped erosion and soil degradation almost completely.
- My soil tests show increasing soil organic matter content and improved soil quality.
- As a result, crop yields have increased.
- There is a bit more thinking, organizing and management involved, but it is so satisfying!
- The bottom line! My fixed and variable costs are less so I make more money!

Further, government policies can facilitate adoption of CA. A check list of things or critical steps to consider when planning the change is available in Derpsch (2007) which is a widely used source of technical information for farmers when they plan to adopt CA.

The CA adoption process involving the implementation of a planned CA cropping system, on farms that have always been managed with tillage agriculture can be visualized schematically as being comprised of broadly four reference phases (based on Sá, 2004; Derpsch, 2007), namely:

Initial phase (0–5 years): low SOM; low crop biomass soil cover; rebuilding of soil aggregates; re-establishing soil life (microorganisms and mesofauna); N may (mineral and/or biological) need to be added to the system. There is a brake on degradation processes, which increase regeneration of soil health processes and improve soil moisture conditions. There is also reduced labour and energy requirement for farm operations.

Transition phase (5–10 years): increase in structural soil density (not compaction) is observed; the amount of crop biomass soil cover as well as soil C content and phosphorus content start to increase. Soil mulch cover provides physical protection to soil and suppresses weeds and supplies biological substrates for soil microorganisms and mesofauna to establish a food web in the soil and connect with food chain being established above the ground, as agrobiodiversity below, at and above ground level is established, offering habitats to natural enemies of pests and pathogens. Further improvements observed in soil health and functions and in soil moisture and nutrient conditions, and there is improvement in productivity, economic and environmental performance of the system. Ecosystem services are in the process of being rehabilitated. Needs for the use of pesticides and fertilizer decline significantly.

Consolidation phase (10–20 years): higher amounts of crop residues as well as higher C contents are achieved, and a higher cation exchange capacity and water retention capacity are observed. Improvements in soil health and functions continue and improved water, nutrient and C cycling are established. Ecosystem services are harnessed more fully at the field and landscape levels.

Maintenance phase (>20 years of continuous no-till with mulch cover in diversified cropping): ideal conditions with maximum benefits for the soil, landscape, crops and cropping systems are achieved and less production inputs of fertilizer, herbicides and other pesticides and water are needed. The above description of the four phases is a simple conceptual illustration of what is expected to happen over a period of more than 20 years, with each phase offering benefits and changes that improve productivity (and hence profit), efficiency, resilience and ecosystem services.

The four reference phases imply that it is necessary to keep in mind a long-term perspective when managing the transformation of conventional tillage agriculture to no-till CA. The regeneration of soil and landscape health from its previous degraded state is a biological process that requires adequate time and care for all the in-situ soil processes and landscape ecosystem processes to re-establish themselves at their full agroecological potentials. There are many factors that can affect the rate of change during the transformation process, including agroclimatic conditions, initial level of soil degradation, cropping and farming system, availability of production inputs, farm mechanization, farmer knowledge base and support systems.

The multi-year duration and nature of the transformation process must be understood and respected by farmers, service providers, supporting experts and decision-makers (Kassam and Kassam, 2020). The transformation is not like a switch to be pressed to achieve an instant change. It is during this initial and transition phases that the damage (physical, biological, chemical and hydrological) to the soil from many years of conventional tillage agriculture begins to be repaired and the soil physiological-biological-chemical-hydrological functions and soil-mediated ecosystem services are re-established. A good example is the return of soil life (microbiomes and mesofauna) as CA is established and the consequent repair and functioning of the water cycle, including water infiltration into the soil and water percolation to deeper soil layers and to groundwater. Alongside this improvement is the development of soil structure and aggregate stability, and an increase in infiltration and water retention, all of which are destroyed under tillage agriculture. At the end of the initial phase after some 5 years, much of the loss in productivity potential may be restored, if the soil was not severely degraded and eroded, and often there can be an increase in yields of 100 % or more with same level of production inputs if the starting baseline yields are low and declining. At this point there is also a visible increase in the overall biodiversity. By the end of the transition phase after around 10 years, many changes are expected to occur; there is an enhancement of the agro-ecological potential and yields, and factor productivity can increase further. During the next phase of consolidation, many of the soil functions and ecosystem services begin to perform more efficiently, and greater efficiency and resilience in the production system and farm system is observed (Kassam et al., 2009, 2013; Andersson and D'Souza, 2014; Cotton and Acosta-Martínez, 2018; Thierfelder et al., 2018; Mitchell et al., 2019; Kassam, 2020a, 2020b).

Thus, it can take 10 years or more to reach a new agro-ecological 'equilibrium' but benefits and advantages begin to accrue almost immediately after the process of transformation is initiated. This is particularly true for the reduction in production costs and improvement is soil moisture conditions for crop growth. Beyond 20 years, soil and land productivity potentials, soil and landscape ecosystem functions and services, and below and above ground biodiversity and food webs would continue to offer all the benefits. The above-described transformation process and the possibility of different parts of the farm area undergoing transformation with different starting times and cropping systems means that at any given point in time, there can be different fields across the farm that are in different transformation phases. The increase in soil organic matter, however, can continue depending on soil characteristics and climate for 30 or 50 years until a new equilibrium has been reached, while the increase in overall biodiversity may continue for a century.

With all what has been stated so far, we need to be careful of not committing the error of asking farmers or convince them to abruptly stop to tilling the soil and adopt CA the next day, without adequate knowledge, understanding and field accumulated experiences of how to proceed properly to implement it. The decision to stop tilling the soil should be taken at least one year in advance of establishing the CA transformation process. This way crop rotation, use of cover crops (mainly mix/multi species), acquisition of or locating an adequate no-till seeding equipment, etc., can be made in a professional and timely way. In third world countries there is a need for permanent public-private programs to help and assist farmers in the "transition" from degrading agriculture to CA. Appropriate extension material and farmer-led networks need to be made available to farmers to avoid failures in the transition phase (Dumanski et al., 2014; Brouder and Gomez-Macpherson, 2014; Waters-Bayer et al., 2015). The most common channels of information dissemination are farmer to farmer through informal networks and spaces created for farmer-researchers and other farmers to meet and exchange their experiences (Waters-Bayer et al., 2015).

In general, we have seen and experienced farmers practicing CA aim at achieving sustainable production. A large percentage of these farmers believe in science-based innovative approaches in agriculture. Also, some farmers that have continuous commercial crops and no space to fit some cover crops species in the farming system, in order to develop a suitable rotation, are looking for some cover crop species that can be inter-seeded in maize, sorghum, sunflower, etc., and follow an adequate CA system, looking for the energy benefits of living roots in the soil year-round in a planting green concept. Other farmers located on undulated topography are eager to learn more about cover crops and how effective it is in building thick mulch layers for runoff and erosion control and to regenerate soil biology. They are aiming at enhancing environmental care and protection and have the goal of achieving sustainable land use. They aim at gradually reducing or eliminating all pesticide use including herbicides, and drastically reducing other external inputs. Other farmers are changing their farms gradually and as much as possible to biological production and are increasingly exchanging ideas and experiences with their peers including organic CA farmers. Farmers from the Argentinian no-till association have already developed a seal for sustainable production based on CA while others are aiming at achieving a certified production label for their CA crops. These are all efforts towards extensive and wise diffusion and adoption of sustainable production systems that should be supported and spread all over the world to our benefit and to the benefit of future generations.

Final remarks

In light of the above known negative effects of tillage on soil productivity and the ability of CA systems to comply with nature's laws of soil productivity, we conclude that:

(i) Any form of soil tillage violates nature's laws of soil productivity and is in opposition to sustainable land use.
(ii) Farming systems and practices that involve the tilling of soil must be abandoned.
(iii) Tillage agriculture must be replaced by CA which avoid or minimize mechanical soil disturbance and maintain adequate soil cover biomass within diversified cropping.
(iv) There is no other farming system in sight that can offer optimal biological and ecological superiority and deliver maximum economic, social and environmental benefits with minimum inputs (optimization) than CA.
(v) CA is the best path to sustainable food security that is now available in the world to satisfy the needs of present and future generations within planetary boundaries.

We must preserve and protect nature's resources. Humans are being reminded, catastrophically, that with climate extremes of hurricanes, floods, droughts, and wildfires our resources for food production are degrading. We cannot control nature and we must learn to respect nature and the global laws that have evolved. For thousands of years, agriculture and tillage were considered synonymous. It was simply not thought possible to grow crops without first tilling the soil before planting and for weed control. The use of tillage-based agriculture has led to severe soil and environmental degradation that requires new system thinking implementing biological management of the "living soil" as the foundation of our food security. The C-centric nature of CA integrating the 3 primary principles with interactive synergies between soil properties and processes yields multiple economic and environmental benefits for society. The recent data confirming energy benefits of minimum soil disturbance adds to the science foundation of CA. CA is all about sharing nature's biological resources, wisdom, power, diversity, abundance, and the "living soil" resulting in natural synergies for enhanced food security! CA represents more than a shift of practices; it is also a major paradigm shift in our basic understanding of the "living soils" and their relationship to nature as we better understand nature's laws of soil productivity and its impact on food security.

Recognizing that all life on earth is interconnected and interdependent, including soil and human life, and all are subject to the same set of operating conditions and the laws provided by nature. Soil needs to be considered as the foundation of an ecological system that is biologically alive and functional. Conservation of soil biodiversity and SOC through sustainable farming practices must be deemed essential to improve soil health and productivity. We now understand soil that is biologically active will store more water and C, having a positive impact on soil, air and water quality, biodiversity and our environment as a whole. More research on the biological processes that promote of GHG emissions from soil will allow creating opportunities for future agricultural development under environmentally friendly conditions, where soil can act as a reservoir and/or emitter of GHG, depending on the balance of inputs and outputs to help mitigate climate extremes. This review highlights the negative impacts of intensive tillage on the "living soil" and emphasizes the need for further recognition and acceptance of nature's laws.

The major challenges of the new millennia are to grow food and other economic crops in adverse weather conditions to feed the billions of rural poor and to sustain food security. CA focuses on integration of C management restoring and enhancing soil health by using principles that create more diverse soil microbiological communities. CA practices allow food growers to create an ideal subterranean home for soil microbes that, in turn, cycles and deliver nutrients to plants, improve numerous soil functions (including C and nutrient (fertility) cycling and water infiltration and storage, and increase the nutrient density of the food they produce—at far less economic and environmental cost than conventional tillage farming practices that continue to lead to soil and environmental degradation. The many advantages of CA discussed have continuously been implemented and used globally by millions of farmers with support from extensionists and scientists, professors in the private, public and civil sectors. These achievements have been well illustrated and documented by the global CA community in the three recently edited volumes entitled 'Advances in Conservation Agriculture' (Kassam, 2020a, 2020b; Kassam, 2022).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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