No-till farming and climate change mitigation: Lessons learnt from long-term no-till experiments and future perspectives

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Abstract

Rapid population increase, urbanization, soil degradation and inappropriate management practices have put tremendous pressure on natural resources, particularly on soil, water, and vegetation. Soil resource is vital for farming to provide food and nutritional security performing ecosystem functions and services and achieving Sustainable Developmental Goals (SDGs). Worldwide, $\sim$33% soil resource has been adversely degraded by diverse processes. To protect soil resource from further degradation, there is a strong need of sustainable soil management practices for enhancing soil organic carbon (SOC), soil health, and crop production in a sustainable manner. "No-till farming (NT)/conservation agriculture (CA)" has been widely practiced worldwide on about 210 million ha. The long-term NT experiments play a significant role in improving soil health, SOC sequestration, and in-depth understanding of greenhouse gas (GHG) emission, climate change mitigation and optimizing resource use efficiency, to cater for the needs of the present- and future-generations. According to FAO, *NT/CA is a farming system that promotes minimum soil disturbance (*i.e.*, no tillage), maintenance of a permanent soil cover, and diversification of plant species*. This system increases biodiversity and natural biological processes in above- and below-ground surface, which helps in enhanced water- and nutrient use-efficiency and sustained crop production. From the literature, it is evident that shift from traditional/conventional tillage (CT) with residue burning/removal to NT/CA farming has been recognized as an important soil management practice/strategy for sustaining soil health, reducing soil erosion and reversing soil degradation. This chapter deliberates the effect of NT/CA on soil health, nutrient stratification, SOC dynamics through modeling, SOC sequestration, GHG emissions, socio-economic condition in adoption and also suggesting the future perspectives on NT and CA.

Abbreviations

4PT	four per thousand (4PT)-4 per mille
BD	bulk density
C	carbon
C:N ratio	carbon:nitrogen
CA	conservation agriculture
CC	cover crops
CH_4	methane
CO_2	carbon di oxide
COP21	Conference of Parties 21
CT	conventional tillage
CTP	conventional tillage practices
DNDC	Denitrification-Decomposition model
DP	deep tillage
DSR	direct seeded rice
ES	ecosystem services
FAO	Food and Agriculture Organization
GHG	greenhouse gas
Gt	Giga tonnes
GWP	global warming potential
IGP	Indo Gangetic Plains
K	potassium
$kg\,ha^{-1}$	kilogram per hectare
$Mg\,ha^{-1}$	megagram per hectare
Mt.	metric tons
MWD	mean weight diameter
N	nitrogen
N_2O	nitrous oxide
NT	no-tillage
NUE	nutrient use efficiency
P	phosphorus
Pg	Peta Gram or 10^{15} g of carbon or 1 Gigatonne of C
POM	particulate organic matter
RR	residue retention
RT	reduced tillage
SB	stubble burned
SDG	sustainable developmental goals
SOC	soil organic carbon
SOM	soil organic matter
SQI	soil quality index
SR	stubble retention
SSM	sustainable soil management
STN	total soil nitrogen
t	tons
TN	total nitrogen
TOC	total organic carbon
WUE	water use efficiency

1. Introduction

Globally, soil degradation, accelerated erosion, declining soil health, malnutrition, and food and nutritional insecurity are pressing concerns with several consequences for the ecosystem, communities and global climate change (Dalal et al., 2021; Kopittke et al., 2021; Lal, 2020a,b, 2023). Advancing food and nutritional security in feeding about 10 billion people by 2050 is a daunting task with deteriorating natural resources (i.e., shrinking arable land area, poor water quality and loss of biodiversity), rising temperatures and greenhouse gas (GHG) emission/global warming (Stocking, 2003) coupled with disturbances in the food chain due to Covid-19 Pandemic (Chakraborty and Maity, 2020; Kakaei et al., 2022) and Russia-Ukraine War (Hassen and El Bilali, 2022). Further, urbanization is expanding at a faster rate, and along with a drastic change in diets/dietary consumption, soils are becoming increasingly degraded due to over-exploitation/-utilization (FAO, 2019; Gomiero, 2018; Zhang and Zhang, 2020) and urban encroachment (Blum, 2013). About 33% of global soils have been degraded already (FAO, 2021). Therefore, soil, crop and water management practices need to be optimized and sustained for achieving increasing food grain production while enhancing soil health and mitigating climate change. Moreover, any modifications in the existing land use and management practices lead to a loss of soil organic carbon (SOC) stock by -10% to -59% (Dalal et al., 2021; Guo and Gifford, 2002). The shift from conventional till (CT) with residue burning/removal to no-till (NT) farming with residue retention/conservation agriculture (CA) practices has been recognized as an important soil management practice for sustaining soil health and minimizing risks of soil degradation (Lal, 2003) (Fig. 1). Lal et al. (2003) reported that widespread adoption of conservation tillage practices in the United States can sequester about 24–40 Mt. C $year^{-1}$. Similarly, 25 Gt C can be sequestered by 2050, if all global croplands are converted to NT, and it will be one of the most important global strategies for reducing atmospheric CO_2 concentration (Pacala and Socolow, 2004). Worldwide, NT/CA practices have now being adopted on about 210 M ha (i.e., about 14% of the arable land (Kassam et al., 2019). CA practices have a greater potential of promoting soil health by increasing SOC, and soil aggregation, thus enhancing infiltration and decreasing erosion losses. Thus, protecting soil resources is of paramount importance as "*Healthy Soils is Healthy Life and Human well-being*" and also performs many ecosystem functions and services (Hurni et al., 2015; Lal, 2020a,b).

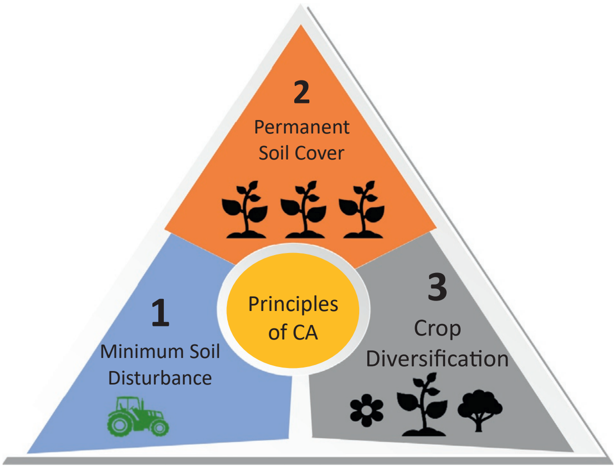

Fig. 1 Principles of conservation agriculture. *Modified from Kassam, A., Friedrich, T., Derpsch, R., 2019. Global spread of conservation agriculture. Intern. J. Environ. Stud. 76, 29–51. https://doi.org/10.1080/00207233.2018.1494927.*

Sustainable soil management practices are needed for enhancing SOC, soil health and crop production. One such sustainable management practice is "NT/CA farming," and it has been widely practiced worldwide (Dalal et al., 2021; Dalal and Jayaraman, 2021; Jayaraman et al., 2021a,b). The long-term NT experiments play a significant role in SOC sequestration, reducing GHG emission, mitigating climate change optimizing resource use efficiency, and altering management practices to cater for the needs of the present and future generations. This deliberates "NT farming and Climate Change Mitigation: Lessons learnt from long-term NT experiments and future perspectives."

2. Long-term no-till experiments: A global perspective

2.1 Historical perspectives of NT farming

In the early days, the ancient Egyptians and the Incas in the Andes of South America used a stick to make a hole in the land and put seeds by hand into unprepared soil (Derpsch, 1995; Goddard et al., 2008; Phillips and Phillips, 1984; USDA, 1975). Later, the origin of NT farming started during "The Dust Bowl" era in the Great Plains of the U.S in the early 1930s, where about 90 Mha of land was affected by severe soil erosion (Hobbs, 2007; Islam and Reeder, 2014; Triplett and Dick, 2008). Similar problems were observed in the Soviet Union Grain Belt region during 1960s (Goddard et al., 2008). Shifting agriculture in Brazil and slash mulch or "*Tapado*" in

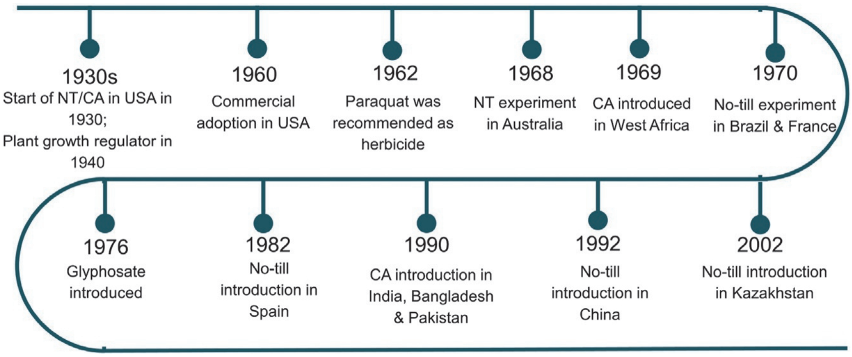

Fig. 2 Historical perspectives of No-till (NT) farming and intervention of NT or conservation agriculture (CA) in different countries with timeline. *Modified from Kassam, A., Friedrich, T., Derpsch, R., 2019. Global spread of conservation agriculture. Intern. J. Environ. Stud. 76, 29–51. https://doi.org/10.1080/00207233.2018.1494927; Authors developed from many literatures.*

Mexico have paved way for NT farming (Thurston et al., 1994) (Fig. 2). Since the availability of Paraquat and Glyphosate, NT-farming gradually gained momentum and spread across countries with the basic aim of reducing the severity of soil erosion and soil degradation (Dalal, 1989; Derpsch et al., 2010). The adoption of NT/CA farming shows an increasing trend over four decades, covering more than 180 M ha are under CA, i.e.,14% of the total global cropland area (Dalal, 2021; Kassam et al., 2019) and 210 M ha in 2023. Adoption of NT/CA has provided multiple benefits such as minimizing inputs/energy, improvement in SOC storage (Dalal et al., 2011; He et al., 2023; Henry et al., 2023) and soil health, and reducing GHG emissions (Jayaraman and Dalal, 2022; Jayaraman et al., 2021a,b, 2022; Wang and Dalal, 2015; Zhang et al., 2023a).

2.2 Long-term NT experiment: A glimpse

In addition to the large-scale adoption of NT farming in many countries, long-term field experiments were also conducted to study the effect of NT on soil properties, soil erosion, input use efficiency, carbon storage/sequestration, crop productivity, GHG emissions under different climatic scenarios (Cook and Trlica, 2016) (Table 1). Richter et al. (2007) stated that *the "long-term experiments are vital to understand how the management practices will affect the soil properties and crop yield over time."* These experiments generate information needed for optimizing inputs (nutrient, water, energy, herbicides, etc.) and identifying management practices which enhance soil health, crop productivity, carbon sequestration and ecosystem functions.

Table 1 Establishment of long-term NT experiments in different countries.

Sl. No	Location and Country	Duration (Years)	Year of establishment
1	Wooster, Ohio State University, Ohio, USA	60	1962
	South Charleston, Ohio Agricultural Research and Development Center (OARDC) Western Branch Research Farm, Ohio, USA	60	1962
	Hoytville, Ohio State University, Ohio, USA	58	1964
2	Agricultural Research Center, Kansas State University, Kansas, USA	57	1965
3	Hermitage Research Experiment, Warwick, Queensland, Australia	54	1968
4	NT experiment, Changins, Switzerland	53	1969
5	North Appalachian Experimental Watershed (NAEW) near Coshocton, Ohio, USA	51	1970
6	Lexington, Kentucky, USA	50	1970
7	40 farmers from North America follow No-Till farming	50	1970
8	INTA Experiment Station. Marcos Juárez, Córdoba, Argentina	45	1975
9	Florence, SC, Southern United States	39	1982
10	IAPAR, Agronomic Institute, Experimental Station at PatoBranco, Southwestern Paraná State, Brazil	35	1986
11	Institute of Agricultural Engineering (IAE), Harare, Zimbabwe	30	1988/1989
12	Ohio State University, USA	32	1989
13	Several no—till experiments from southern United States	23–39	1998/1982
14	Hickory Corners, Michigan, USA	39	1989
15	Alabama university (now Auburn University) 1896 (Oldest cotton experiment) but started conservation tillage since 1997	24	1997
116	Pendleton, Oregon, USA (Crop residue management under Conventional mold board plow)	110	1911

Continued

Table 1 Establishment of long-term NT experiments in different countries.—cont'd

Sl. No	Location and Country	Duration (Years)	Year of establishment
Other than No-tillage long-term experiments			
1	Broadbalk Experiment at Rothamsted Research in Hertfordshire, UK	178	1843
2	Urbana-Champaign, Illinois, USA	145	1876
3	Columbia, Missouri, USA	133	1888
4	Hermitage Research Station, Warwick, Queensland, Australia	124	1897

Modified from Jayaraman, S., Reeves, S., Wang, W., Heenan, M., Dalal, R.C., 2017. Impact of 47 years of no-tillage and stubble retention on soil aggregation and carbon distribution in a vertisol. Land Degrad. Develop. 28: 1589–1602. https://doi.org/10.1002/ldr.2689; Reeves, S.H., Somasundaram, J., Wang, W.J., Heenan, M.A., Finn, D., Dalal, R.C., 2019. Effect of soil aggregate size and long-term contrasting tillage, stubble and nitrogen management regimes on CO2 fluxes from a vertisol. Geoderma 337, 1086–1096; Authors collected data from different literature.

3. Sustainable soil management (SSM) vs sustainable development goals (SDGs)

Worldwide, large scale soil degradation has indicated the need for developing practices of sustainable soil management for restoring soil health and increasing production. One of the primary challenges of the present time is of feeding a growing and increasingly affluent world population (~10 billion by 2050) with reduced external inputs and minimal environmental impacts (Amundson et al., 2015).

Soil resources are closely linked with more than 7 SDGs (namely SDG1: End poverty, SDG2: Zero hunger, SDG3: Good health and well-being, SDG 5: Gender equality, SDG6: Glean water and sanitation, SDG7: Affordable and clean energy, SDG 9: industry, innovation, and infrastructure, SDG 11: Sustainable cities and communities, SDG 13: Climate Action, and SDG 15: Life on Land) (Lal et al., 2021) (Fig. 3). Therefore, soil resource needs to be preserved and conserved for achieving food and nutritional security as well as ecosystem services (Hou et al., 2020). Moreover, The World Soil Day (on 5th Dec of every year) and International Year of Millets 2023 have emphasized the need for healthy soils and nutrition in achieving SDGs, i.e., "*Soil management that meets the needs of the present*

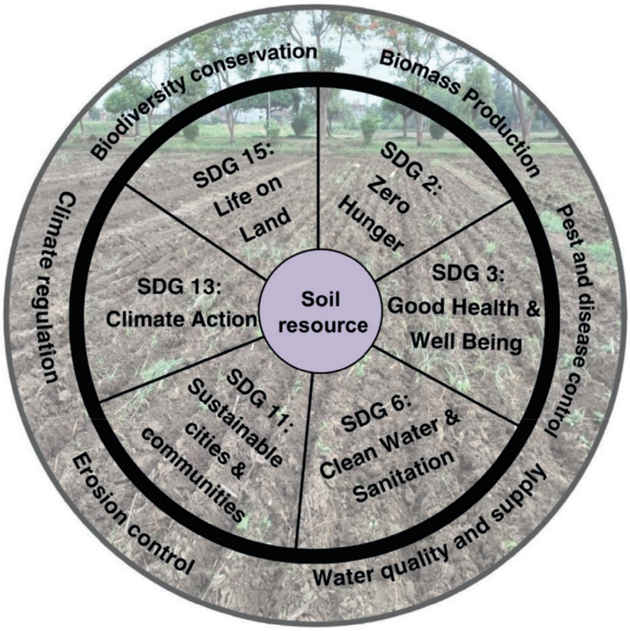

Fig. 3 Soil resource linked with sustainable developmental goals. *Photo: Authors; Modified from Lal, R., Bouma, J., Brevik, E., Dawson, L., Field, D.J., Glaser, B., Hatano, R., et al. 2021. Soils and sustainable development goals of the United Nations: an International Union of Soil Sciences perspective. Geoderma Reg. 25, e00398.*

generation without compromising the ability of the future generations to meet their own needs from that soil" in alignment with SDGs (Jayaraman et al., 2023a,b). NT farming practices aptly address sustaining crop production, soil health, SOC sequestration, reducing GHG emissions, and climate change mitigation (Jayaraman and Dalal, 2022).

4. Impact of NT experiments on soil properties

Tillage promotes soil organic matter (SOM) mineralization, suppresses weeds, loosens compacted soil, and prepares a seedbed that facilitates mechanical planting and seed-to-soil contact (Ryan et al., 2011). Therefore, in order to answer how NT affects soil health, long-term experiments are necessary to assess the effects of these practices under varying weather and climatic conditions (Varvel, 2006). In this section, effect of NT/CA on soil properties are discussed.

4.1 Soil physical properties

Soil physical properties (viz., aggregates, structure, porosity, bulk density, soil moisture and temperature regime) are strongly influenced by minimizing or reducing tillage operations (particularly intensity of tillage) with crop residue retention (Haruna and Anderson, 2023; Zhang et al., 2023a). Tillage can strongly affect soil aggregates and modify the thermostability of SOM content (Dalal and Jayaraman, 2021; Hati et al., 2021).

Based on the data from a 31-year-old NT experiment in Botucatu, Brazil, Cooper et al. (2021) reported that NT significantly increased pore connectivity while simultaneously decreasing inter-aggregate porosity, further protecting SOC stock. Not only the changes in soil physical characteristics with NT led to improved aggregate formation compared to that under CT, but also changed the composition of SOC content to a more recalcitrant fraction after the shift to NT, suggesting that aggregates were accumulating rather than mineralizing SOC content. Galdos et al. (2019) observed that soil under NT for 30 years had larger connected pores than those under CT. The absence of soil inversion and disturbance with NT systems leads to relative preservation of root channels and bioturbation, where soil organisms and burrowing animals, alter soil structure and promote the development of a continuous pore system (Dignac et al., 2017; Hangen et al., 2002; He et al., 2009; Piron et al., 2017). Cooper et al. (2021) demonstrated that although the total porosity in soil under NT decreased by 7% in the top 50 cm after 2 years of NT, after 31 years, the total porosity was 13% higher compared to those in soils under CT. Conservation tillage, especially NT, had a better pore size ratio and porosity than those under CT (Eze et al., 2020; Zhang et al., 2021a,b). Eze et al. (2020) reported that maize-based CA system increased total porosity by 5–15%, saturated hydraulic conductivity (Ksat) by 0.06–0.22 cm/min, fine pores for water storage by 3–7%, and plant available water content (PAWC) by 3–6% because of improvement in soil structure compared to that under CT system. Kumar et al. (2012) also reported that at Wooster, in central Ohio (49 years) and Hoytville (47 years) sites in northwestern Ohio, USA, assessment of soil water retention (SWR) characteristics indicated a higher volumetric water content at all matric potentials under perennial vegetation (i.e., woodlots) and NT compared to those under minimum tillage (MT) and plow tillage (PT) systems. Results further highlighted that long-term adoption of NT (47–49 years) practices in both well-drained and poorly-drained soils improved SWR, pore-size distribution, and steady state infiltration than those in soil under PT and MT practices. However, in some soil types under NT, the surface soil can hinder root growth (Martínez et al., 2008) due to the reduced soil porosity that decreases water infiltration rates and root mass compared to those under CT (Matula, 2003: Romaneckas et al., 2009).

Use of intensive tillage practices can decrease the pore size ratio in the soil surface, while the absence of tillage may improve soil conditions for crop growth. Based on a long-term study, Zheng et al. (2021) observed that the porosity of soil under CT and NT remained stable, while that under ST (subsoiling) and NCS rotation (a yearly rotation of NT, CT, and ST) increased over time. Subsoiling and tillage rotation may temporarily help to loosen the deep soil and reduce soil disturbance, and thus improve soil structure and porosity (Wang and Shangguan, 2015). An intensive tillage, such as in CT, may create a deep plow pan which has low soil porosity (Zhang et al., 2018). However, in a NT system, although the absence of tillage improves soil porosity, the traffic load from machinery such as harvesters, pest and weed control can cause soil compaction and reduce porosity (Moraes et al., 2014). However, the implementation of control traffic practices can reduce the area compacted by vehicular traffic. Overall, it is important to consider both the benefits and potential drawbacks of different tillage methods when managing soil health.

The fertility of soil in the field is also influenced by the quantity and quality of soil aggregates, which have a significant impact on soil water retention, aeration, nutrient consumption and accumulation, temperature, and tilth, leading to better crop growth (Medeiros et al., 2011). Crop residue return and crop rotation can lead to an increase in macroaggregates (Zheng et al., 2021). Crop residue serves as an organic fertilizer that promotes an increase in SOC content, which in turn enhances soil macroaggregates (Choudhury et al., 2014). Appropriate crop rotation can also promote the development of good soil aggregates (Zhang et al., 2017). Rational tillage intensity and soil disturbance can also help build better soil structure and soil nutrient distribution, which is conducive to the formation of soil aggregates (Hou et al., 2013). The majority of the aggregate size distribution, >95%, was composed of macroaggregates, which included both large and small macro-aggregates, and this trend was consistent across all tillage practices.

Jayaraman et al. (2017) assessed soil aggregation in the 0–10 cm layer in a 47 years experiment consisting of NT, stubble retention, and N fertilization (Queensland, Australia) (Fig. 4). Results indicated that large macroaggregates (>2 mm) had significantly higher organic C and N concentrations than small macroaggregates (0·25–2 mm) or microaggregates (0.053–0.25 mm). Favorable soil aggregation under NT, stubble retention and 90 kg N ha^{-1}

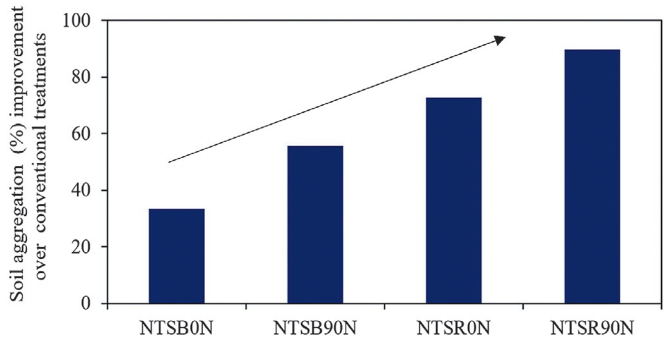

Fig. 4 Soil aggregation improvement under conservation agriculture treatments compared with conventional tillage. NT, no tillage; SB, stubble burnt; SR, stubble retained; 0 N, no nitrogen addition; 90 N, 90 kg N ha^{-1} applied. [Anova P value: Tillage (T) <0.001, Stubble management (S)-NS, and Nitrogen (N) <0.043]. *Modified from Jayaraman, S., Reeves, S., Wang, W., Heenan, M., Dalal, R.C., 2017. Impact of 47 years of no-tillage and stubble retention on soil aggregation and carbon distribution in a vertisol. Land Degrad. Develop. 28: 1589–1602. https://doi.org/10.1002/ldr.2689.*

(NTSR90N) practice is one of the possible mechanisms of SOC protection and sequestration in Vertisol. Hati et al. (2021) reported from a same experimental site [i.e., a long-term experiment (50 years) that integrating NT with stubble retention and 90 kg N ha^{-1} application resulted in the highest proportion of large macro-aggregates (31.0%), the largest mean weight diameter (MWD) (1.79 mm), and the most percentage of water stable aggregates (WSA, 90.2%), whereas the lowest values (3.15%, 0.71 mm and 72.7%, respectively) were observed in soil under CT with stubble burned and no N fertilizer(CTSBN0) treatment (Fig. 5). Moreover, long-term adoption of CA practices involving NT, stubble retention and nitrogen application favorably impact water retention and movement, and porosity for better management for crop production in a Vertisol.

Based on a long-term study on claypan soil in Missouri, NT systems increased surface water runoff by 14–20%, but resulted in seven times less soil loss than that under CT system (Ghidey and Alberts, 1998). Under temperate environments, NT and soil with residue-retention tend to dry and warm up more slowly (Buchholz et al., 1993). Thus, NT systems have cooler soil temperatures (Al-Darby and Lowery, 1987) and excess moisture during spring, which may cause lower cereal grain yields on poorly drained soils compared to those under CT management (DeFelice et al., 2006). However, in semi-arid environments, straw mulching under CA minimizes water evaporation and increases water retention, which, in turn, improves

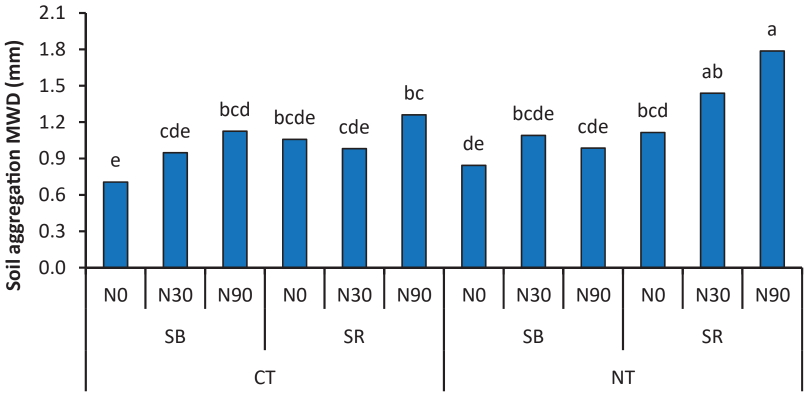

Fig. 5 Impact of tillage, stubble management and N-level on (a) mean weight diameter (MWD). [CT: conventional tillage; NT: no tillage; SB: stubble burnt; SR: stubble retained; N_0: no nitrogen application; N_{30}: N applied @ 30 kg ha^{-1}; N_{90}: N applied @ 90 kg ha^{-1}; Values followed by the same letter, are not significantly different based on a Duncan's multiple range test at $P = 0.05$. *Level of significance $P < 0.05$]. *Modified from Hati, K.M., Jha, P., Dalal, R.C., Jayaraman, S., Dang, Y.P., Kopittke, P.M., Kirchhof, G. and Menzies, N.W., 2021. 50 years of continuous no-tillage, stubble retention and nitrogen fertilization enhanced macro-aggregate formation and stabilisation in a vertisol. Soil Tillage Res. 214, 105163.*

soil water storage (Page et al., 2019; Palm et al., 2014). In some soils, long-term use of CT can result in low soil bulk density in the surface layer due to its intensive tillage methods (Agbede, 2010) but compacts the deep soil by the use of heavy machinery (Zhang et al., 2018). On the other hand, NT can reduce soil bulk density through less soil disturbance and the return of crop residue (Strudley et al., 2008). However, the farm operations such as use of harvesters, pest and weed control devices, and mechanical equipment can compact the soil and offset the benefits of NT.

4.2 Soil chemical properties

Minimal soil disturbances through NT coupled with crop residue or stubble retention influences soil chemical properties (Büchi et al., 2015; Dalal et al., 2011; Omara et al., 2019). Iqbal et al. (2021) conducted a long-term field experiment from 2008 to 2020 to evaluate different conservation tillage practices (CTPs) on soil properties, and observed that CTP treatments, including NT and crop straw mulching (SM), resulted in significantly higher levels of soil pH, SOC content, total nitrogen (N), available N, total phosphorus (P), and available P compared to those under CT. Contrastingly, 50 years of continuous NT farming coupled with stubble retention and N fertilization did not alter total P, inorganic P and Organic P (Zhang et al., 2021a,b) in a Vertisol of Queensland, Australia despite significant changes in SOC content. This observation highlights the need for an appropriate fertilizer management in the region for sustainable crop production.

Long-term NT practices can reduce soil pH compared to that under CT (Dalal, 1989; Rahman et al., 2008; Zulu et al., 2022), due to the mineralization of SOM and nitrification of urea applied to the upper soil layers. Additionally, residues and mulch left on the soil surface, along with N fertilization, can lead to the nitrification of ammonium to nitrate, causing acidic conditions (Schroder et al., 2011). Zulu et al. (2022) emphasized that long-term N fertilizer application can cause soil acidification, particularly under NT management, and liming may be necessary to mitigate the effects of acidification. Low pH levels can enhance the weathering and solubility of minerals, SOC content, and micronutrients, leading to a greater release of these micronutrients, which can further benefit plants since these micronutrients are readily available to plants. However, in the long-term, these micronutrients may cause toxicities that can negatively affect soil health, crop yields, and quality.

Based on a 12-year experiment, Zhou et al. (2021) reported that straw mulching under a NT system for an extended period increased the levels of total N, inorganic N, available P, and available K at 0–5 cm depth, along with water content at 0–5 cm and SOC content at 0–5 and 5–10 cm depth as compared to soil under straw removal. Further, straw was retained on the soil surface as mulch instead of being incorporated into the soil. Surface mulching led to the release of C and nutrients in the soil surface upon decomposition of residues (Akhtar et al., 2018). Data from a study conducted for >80 years) in the northern Great Plains (NGP) of the United States showed significant reductions in extractable P, extractable K, pH, total C, organic C, total N, and $\delta^{15}N$ of total N in the 0–15 cm layer (Malo et al., 2005). Similarly, Littrell et al. (2021) examined the long-term (10 years) effects of CT and organic crop management, using different tillage methods, on SOC content and soil aggregation. The results indicated that tillage treatments over a period of 10 years did not affect the concentrations of active and total SOC, but did impact the distribution of dry aggregate sizes and the stability of wet aggregates. These results suggest that organic cropping systems that incorporated composted manure and perennial hay, as opposed to legumes alone, accumulated the highest amount of SOC over the long-term. Use of NT in organic systems improved soil aggregation, but the effects of tillage on SOC beyond 10 years must also be studied for in-depth understanding of different management systems. However, a 10-year period may not be sufficient to observe significant differences in SOC accumulation resulting from NT (Sheehy et al., 2015). In another experiment established in 1969 involving continuous winter-wheat under CT but converted to NT from 2011 onwards, at Lahoma in Oklahoma, USA, Omara et al. (2019), reported that crop yields (5%), SOC (21%), total N (14%) were higher under NT compared to those in soil under CT.

It is argued that continuous NT management for organic systems is not yet feasible (Peigné et al., 2007). Although tillage stimulates the decomposition of crop residues, it can also promote microbial processing of residues, leading to greater SOC stabilization in soil minerals and microaggregates. However, NT management may reduce SOC loss by mineral adsorption and aggregate occlusion within macroaggregates (Sheehy et al., 2015) and thus improve macro-aggregation and porosity. Additionally, the negative effect of tillage on SOC accumulation could be mitigated by including cover crops in the system (Abdollahi and Munkholm, 2014; Lal, 2015c). In a 17-years old study by Gómez-Muñoz et al. (2021), straw retention led to an increase in C concentration by an average of 0.47 $mg\,C\,g^{-1}$ dry soil from 2002 to 2019. SOC stocks also increased in 2019, with an average of 23 $Mg\,C\,ha^{-1}$ in the soil with higher initial SOC content. Increased plant biomass production and soil C inputs in the form of residues are the primary reasons for higher SOC stock with CA systems (Schjønning et al., 2018). Bansal et al. (2021) conducted a long-term investigation spanning 16 years and suggested that minimal soil disturbance under NT practices is conducive to the storage of C in more protected and stable C pools within (occluded) microaggregates under a humid subtropical climate. Calegari et al. (2008) reported that NT management combined with winter cover cropping resulted in significantly higher SOC stocks and improved soil properties that most closely resembled to those under undisturbed forest. This system has been considered as sustainable production system (Fig. 6).

Six and Paustian (2014) proposed that the proportion of microaggregates formed within macroaggregates could serve as a reliable indicator of changes in SOC content under different management practices on a decadal time frame. Data from several experiments have shown significantly greater SOC content in the macroaggregate fraction of NT soils across various environmental contexts, suggesting that a considerable amount of the difference between NT and CT could be attributed to SOC associated with the macroaggregate fraction (Arshad et al., 1990; Jayaraman et al., 2017; Sheehy et al., 2015). Ke et al. (2016) attributed the increase in SOC content in soils

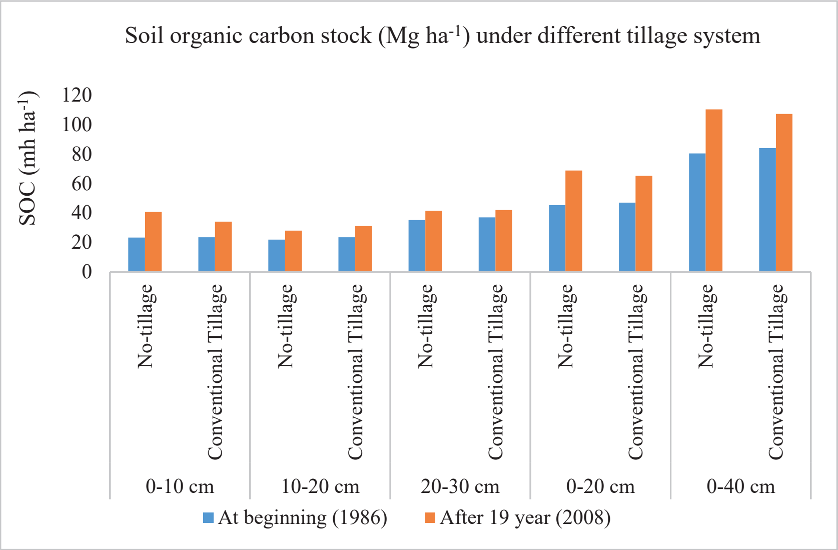

Fig. 6 The soil organic carbon stocks under different tillage system in Oxisols after 19 years of experimentation. *Modified from Calegari, A., Hargrove, W.L., Rheinheimer, D.D.S., Ralisch, R., Tessier, D., de Tourdonnet, S., de Fatima Guimarães, M., 2008. Impact of long-term no-tillage and cropping system management on soil organic carbon in an Oxisol: a model for sustainability. Agron. J. 100 (4), 1013–1019.*

under NT management to the increase in SOC in stable macroaggregates. This increase may partially be attributed to bioturbation, specifically via the surface deposition of soil by anecic earthworms, which gradually move material into sub-soil layer over time (Blouin et al., 2013). Better root growth conditions under NT also explain the differences in SOC stocks at greater depths in some soil types (Galdos et al., 2019). Sisti et al. (2004) demonstrated that greater root density below 30 cm depth in soil under NT explained the increased SOC accumulation compared to that under CT. Sa et al. (2014) compared SOC stocks in the soil profile in long-term tillage systems in a Brazilian Oxisol and observed that in the 20–40 cm layer, the C stocks under NT were 15 Mg ha^{-1} higher than those in soil under CT. The increase in SOC in the macroaggregate fraction in the long-term NT soils, along with the increase in mean weight diameter, suggests a greater potential for soil aggregation and accumulation of SOC under NT compared to that under CT management.

Previous studies have suggested that the increased SOC observed in NT soils is primarily in labile forms such as plant residues and particulate organic carbon (POC), which could potentially be decomposed if NT practices were discontinued and the soil was reverted to CT (Powlson et al., 2014). In comparison with soils under CT, those under NT management are typically cooler and wetter and experience less mechanical disturbance, resulting in slower rates of macroaggregate turnover and a higher proportion of labile SOM content in macroaggregates (Page et al., 2020; Salem et al., 2015). However, it is also possible that the retention of crop residues under NT may create more favorable soil moisture conditions for SOC decomposition (Corbeels et al., 2016). Higher soil moisture content under NT may explain the findings of Zhang et al. (2023b) who observed from a 48-year old experiment that the concentrations of SOC and total N in both the bulk soil and various aggregate sizes were did not different significantly among different tillage practices. These findings are in contrast with the expected outcomes of aggregate hierarchy theory, which proposes an elevation in SOC concentration with an increase in aggregate size (Tisdall and Oades, 1982). The process of macroaggregate formation is critical to protecting organic matter from enzymatic degradation by microbes in soil (Devine et al., 2014; Hati et al., 2021; Sarker et al., 2018). The adsorption of organic matter to clay particles also offers protection from degradation, particularly in soils with high clay content like the one examined in their study (Dungait et al., 2012). Therefore, Zhang et al. (2023b) finding that tillage practices did not significantly affect SOC concentrations across different aggregate sizes is likely due to the similarity of aggregate size distribution under both tillage practices. After adopting NT for 47 years on a Vertisol of north-eastern Australia, Page et al. (2020) observed that the use of NT, stubble retention (SR) and N fertilizer had improved SOC (by 12.8%) and total N stocks (by 31.7%) in the 0–10 cm layer compared to those in soil under CT, stubble burnt (SB) and no N fertilizer treatment. Further, combined application all three treatments led to highest SOC stocks (Fig. 7). In this study, a decline in SOC (~20%) and total N (~25%) was observed in all treatments over a 34-year period (Fig. 8), although less so in the NT system, indicating that changes in management were unable to stop the loss of SOM over time in this farming system (Dalal et al., 2011; Jayaraman et al., 2017; Page et al., 2020).

Response of agronomic yield to NT vs CT is affected by a range of factors such as climate, duration of NT, irrigation, residue retention, and crop rotation (Büchi et al., 2015, 2017; Gathala et al., 2015; Pittelkow et al., 2015). Jat et al. (2020) concluded from a meta-analysis (9686 paired site-year comparisons) that there was improved yield (5.8%), water use efficiency (12.6%), economic return (25.9%) and reduction of global warming

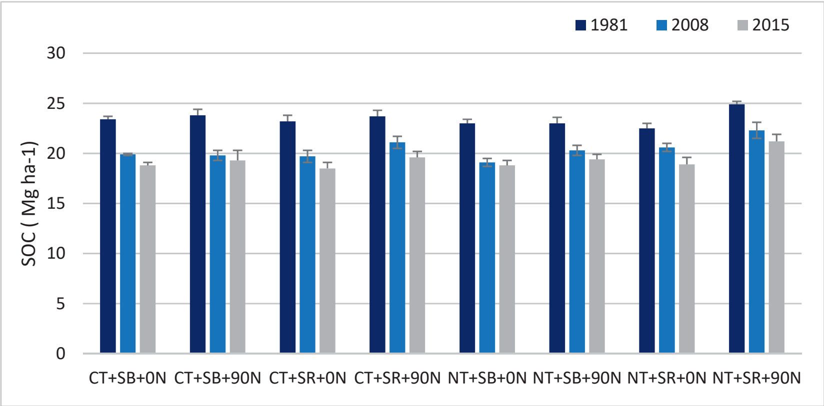

Fig. 7 Changes in total SOC stock (Mg ha^{-1}) after 47 years at Hermitage No-till experiment, Australia (for samples at the 0–0.1 m depth in 1981, 2008, and 2015). [CT = conventional tillage; NT = no-tillage; SB = stubble burnt; SR = stubble retained; 0 N = 0 kg-N ha^{-1}; 90 N = 90 kg-N ha^{-1}]. *Modified from Dalal, R.C., 1989. Long-term effects of no-tillage, crop residue and nitrogen application on properties of a vertisol. Soil Sci. Soc. Am. J. 53, 1511–1515; Dalal, R.C., Allen, D.E., Wang W.J., Reeves, S., Gibson, I., 2011. Organic carbon and total nitrogen stocks in a vertisol following 40 years of no-tillage, crop residue retention and nitrogen fertilisation. Soil Tillage Res. 112: 133–139. https://doi.org/10.1016/j.still.2010.12.006; Jayaraman, S., Reeves, S., Wang, W., Heenan, M., Dalal, R.C., 2017. Impact of 47 years of no-tillage and stubble retention on soil aggregation and carbon distribution in a vertisol. Land Degrad. Develop. 28: 1589–1602. https://doi.org/10.1002/ldr.2689; Page, K.L., Dalal, R.C., Reeves, S.H., Wang, W.J., Jayaraman, S., Dang, Y.P., 2020. Changes in soil organic carbon and nitrogen after 47 years with different tillage, stubble and fertiliser management in a vertisol of North-Eastern Australia. Soil Res. 58 (4), 346–355.*

potential (12–33%) when CA practices adopted either separately or in combination. Similarly, Sun et al. (2020) conducted a meta-analysis of 260 experiments worldwide and found that the effects of CA on SOC sequestration and yield are modified by climate conditions, with arid regions showing an increase in yields and C sequestration, and cold humid regions showing the opposite effect. Therefore, it is not necessarily true that SOC storage and crop yields would increase after a long-term adoption of CA in all soil types and environments.

4.3 Soil biological properties/soil microbial biodiversity

Soil biological properties play a crucial role in biogeochemical processes of crop growth and nutrient cycling and sustainable farming (Wang et al., 2017). Soil biological properties provide sensitivity indicators to changes in management practices (Gianfreda and Ruggiero, 2006; Joergensen and

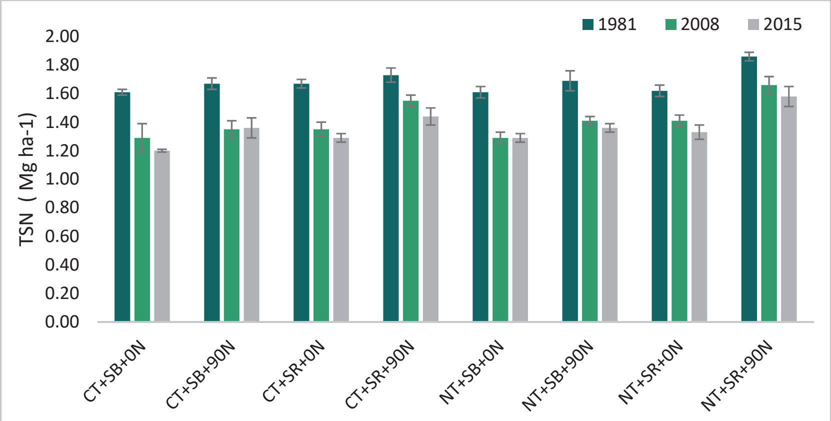

Fig. 8 Changes in soil total nitrogen (STN) (Mg ha^{-1}) in 47 years at Hermitage No-till experiment, Australia (for samples at the 0–0.1 m depth in 1981, 2008, and 2015). [CT = conventional tillage; NT = no-tillage; SB = stubble burnt; SR = stubble retained; 0 N = 0 kg N ha^{-1}; 90 N = 90 kg N ha^{-1}]. *Modified from Dalal, R.C., 1989. Long-term effects of no-tillage, crop residue and nitrogen application on properties of a vertisol. Soil Sci. Soc. Am. J. 53, 1511–1515; Dalal, R.C., Allen, D.E., Wang W.J., Reeves, S., Gibson, I., 2011. Organic carbon and total nitrogen stocks in a vertisol following 40 years of no-tillage, crop residue retention and nitrogen fertilisation. Soil Tillage Res. 112: 133–139. https://doi.org/10.1016/j.still.2010.12.006; Jayaraman, S., Reeves, S., Wang, W., Heenan, M., Dalal, R.C., 2017. Impact of 47 years of no-tillage and stubble retention on soil aggregation and carbon distribution in a vertisol. Land Degrad. Develop. 28: 1589–1602. https://doi.org/10.1002/ldr.2689; Page, K.L., Dalal, R.C., Reeves, S.H., Wang, W.J., Jayaraman, S., Dang, Y.P., 2020. Changes in soil organic carbon and nitrogen after 47 years with different tillage, stubble and fertiliser management in a vertisol of North-Eastern Australia. Soil Res. 58 (4), 346–355.*

Emmerling, 2006) and soil quality (Bastida et al., 2008). Tillage practices such as NT and crop residue retention favor soil microbial diversity, soil bacterial community and lower C/N ratio (Luo et al., 2020). Based on a 12-year study, Iqbal et al. (2021) found that enzymatic activities (i.e., invertase, acid phosphatase, urease, catalase, β-glucosidase, cellulase) were significantly higher in soils under NT than those under CT, with lower enzyme activities at deeper than in surface soil depths. Management practices have varying impacts on the soil environment, affecting the habitat of soil microorganisms in different ways (Jayaraman et al., 2021c; Luo et al., 2020). The microbial community plays a crucial role in SOM dynamics (Acosta-Martinez et al., 2003; Alvaro-Fuentes et al., 2013). Microbial residues, which are the end product of decomposition in the soil, can protect SOM by either providing biochemical stability or physical protection within soil aggregates, making them resistant to further degradation (Jastrow et al., 2007; Schimel and

Schaeffer, 2012; Six et al., 2006). Understanding the decomposition rates influenced by management practices is fundamental to improving SOM management in cropping systems (West and Post, 2002). Soils under NT management have a more favorable microclimate and greater microbial abundance compared to those under CT (Johnson and Hoyt, 1999; Kaschuk et al., 2010; Martens, 2001). However, the degree of increase in microbial biomass in soil under NT compared to that under CT varied greatly, with a 17% increase reported by Das et al. (2014) and a 98% increase reported by Balota et al. (2004). In contrast, de Gennaro et al. (2014) reported no difference in microbial biomass among tillage systems. Although there is a general agreement of greater amounts of microbial biomass C in soil under NT systems, measures of microbial activity exhibit much wider variation. While Balota et al. (2004) reported smaller microbial activity under NT compared to CT systems, Babujia et al. (2010) found no differences between CT and NT practices. Both MBC and MBN measurements indicated a decrease in microbial biomass in soil under CT in comparison to that under NT. Studies such as Balota et al. (2004) and Kaschuk et al. (2010) have also reported a greater microbial biomass in soil under NT due to the more favorable environmental conditions for microbes. According to a meta-analysis conducted by Zuber and Villamil (2016), the only microbial property that was found to be greater in soil under CT compared to that under NT was the metabolic quotient. This trend suggests that microbes are more active in soil under CT, possibly due to increased access to crop residues, although this effect may be only short-term. On the other hand, all of the enzyme activities were greater in soil under NT compared to those under CT systems (Gianfreda and Ruggiero, 2006; van Capelle et al., 2012), which was possibly due to higher substrate availability and functional diversity.

Zheng et al. (2021) emphasized the connection between soil microbial community characteristics and SOC accumulation rate under long-term NT management. The abundance of bacterial rather than fungal groups can be positively correlated with SOC stocks under different tillage practices (Sun et al., 2018). In contrast, a meta-analysis by Chen et al. (2020) showed that the biomass ratios of fungi to bacteria did not significantly differ among NT and CT practices. Hydbom and Olsson (2021) demonstrated that soil under NT had a positive impact on arbuscular mycorrhizal fungi but not on saprotrophic fungi and bacteria, indicating that the effects of tillage practices on microbial composition are influenced by several factors. A network analysis could identify important microbial groups in soil and their relationship with tillage practices and straw management, with potential impacts on SOC dynamics. For instance, Banerjee et al. (2016) observed that use of a straw amendment promotes keystone taxa, such as *Acidobacteria*, *Frateuria*, and *Gemmatimonas* in bacteria, and *Chaetomium*, *Cephalotheca*, and *Fusarium* in fungi, which have strong links with SOM decomposition rates. Other studies have associated specific fungal and bacterial taxa with SOM decomposition and transformation in agricultural soils (Banerjee et al., 2016; Li et al., 2017). The preference of bacteria and fungi for particular residue compounds may affect long-term soil C dynamics. Furthermore, Zheng et al. (2022) found that both bacterial and fungal diversity in 0–10 cm soil layer was significantly affected by 17 years of tillage practices, likely reflecting differences in substrate availability. The alteration of tillage practices over a long period leads to changes in the co-occurrence networks of microorganisms. The network of bacteria in NT with crop residue integrated and NT with residue mulched and the network of fungi in soil under NT with residue mulching were more intricate, with higher average connectivity and more links than in soil under CT with residue removed. This trend could be due to the increase in SOC and total N pools and decomposition rates supported by an increase microbial biomass, which results in more interactions among microbial taxa (Zhou et al., 2020). These negative interactions possibly indicate competition for nutrient resources (Ghoul and Mitri, 2016), which increases the stability of networks (de Vries et al., 2018). In general, adding residue under NT practice increases SOC and total N levels (Giambalvo et al., 2018) as well as microbial metabolic activity (Zhang et al., 2016), leading to an increase in soil microbial diversity. However, the response of microbial diversity is not only due to increased C input but it can also lead to SOC accumulation. For example, NT can promote nutrient availability, particularly N, which can stimulate SOC storage by enhancing plant growth and C input (Huang et al., 2020). Furthermore, high N availability can facilitate SOC storage by decreasing the activity of ligninase, a critical enzyme for the breakdown of resistant C fraction (Macdonald et al., 2018). Finally, the increase in microbial diversity and MBC can prompt the release of microbial by-products and the formation of microbial necromass, both of which contribute to the stable SOC pool (Prommer et al., 2020). These compounds may also encourage soil aggregate formation, which, in turn, promotes SOC accumulation (Wiesmeier et al., 2019).

Zhang et al. (2023b) reported that the tillage practices did not have a significant impact on the β-glucosidase and phenol oxidase which are associated with C cycling in soil. Additionally, there was no correlation observed between the concentrations of these enzymes and the magnitude of SOC content. The lack of change in SOC concentration due to tillage may have contributed to this observation. Zhang et al. (2023b) suggested that the lack of change in enzyme activities may be due to the high clay content and drier climate at their experimental site, which can limit the activity of soil enzymes.

4.4 Nutrient stratifications

Tillage systems may directly or indirectly influence nutrient distribution in soil profiles and behave differently when fertilizer nutrients are applied at or near the soil surface (Jayaraman and Dalal, 2022; Jayaraman et al., 2020; Kushwah et al., 2016). When the fertilizer is applied through broadcasting under NT, it remains at or near the soil surface, unlike CT (Houx et al., 2011), leading to nutrient stratification (Franzluebbers and Hons, 1996; Kushwah et al., 2016). Higher stratification of SOC and nutrients (e.g., P, K, Ca, Mg, and micronutrients) in soil under NT compared to that under CT has been widely observed (Du Preez et al., 2001; Duiker and Beegle, 2006; Houx et al., 2011; Jayaraman et al., 2022). Similarly, nutrient management is challenging under higher residue levels in the surface layers and when there are reduced options for the application of nutrients, mainly through manure application (Jayaraman et al., 2020) (Fig. 9).

NT modifies the SOM distribution through vertical stratification (Wacker et al., 2022). Consequently, it might cause alterations in both soil microbial biomass and microbial community structure. Over time, NT leads to the development of depth gradients in parameters such as SOC, total N, and potential mineralizable N (Büchi et al., 2017; Dang et al., 2015; Kandeler et al., 1999; Luo et al., 2010; Selles et al., 1997). As a consequence,

Fig. 9 Need for adoption of contrasting nutrient management with residue (left) and without crop residue (right). *Courtesy: Somasundaram Jayaraman.*

plant root growth is primarily restricted to the topsoil, limiting the explored soil volume and the absorption and translocation of water and nutrients from the soil to the aerial parts of the plants (Grzesiak et al., 2012). The concentration of plant roots in the topsoil not only affects nutrient uptake but also has implications for crop yield, especially during short periods of drought (Hamza and Anderson, 2005). To address these challenges, reducing the vertical stratification of SOC and nutrients can play a crucial role in promoting root growth in subsurface soil layers within long-term NT fields. By encouraging root development in deeper soil horizons, crops may become more resilient to drought conditions and exhibit improved overall productivity. For example, there has been evidences of changes in N turnover as a consequence of CA. Specifically, in the NT topsoil, there have been observed increases in net N mineralization and nitrification potential (Kandeler et al., 1999), which may exhibit a distinct stratification pattern (Franzluebbers, 2002).

However, the impact of NT on N mineralization dynamics could vary among studies. Some investigations have reported net N immobilization effects under NT systems, which are attributed to increased microbial activity in the residue-rich topsoil layer, consequently leading to increased demand for N assimilation, particularly after the harvest period (Laine et al., 2017). In contrast, a soil under CT system may exhibit a more even distribution of C and N along the soil depths. These observations emphasize the complexity of N dynamics in CA systems and underscore the necessity of considering multiple factors when evaluating the effects of diverse management practices on soil nutrient cycling. Similarly, NT contributes to increased stratification of immobile nutrients, such as that of P (Alam et al., 2018). Although NT increases P stratification near the soil surface, it does not necessarily improve grain yield (Alam et al., 2018). However, P stratification is not consistently reported with NT (Buah et al., 2000). Jones et al. (2007) conducted an extensive experiment with different tillage treatments, and indicated that tillage practices did not alter vertical P stratification patterns, nor was there a consistent pattern of P stratification. Interestingly, in some cases, P stratification was observed close to the soil surface (0–2.5 cm layer) (Eltz et al., 1989) or up to 5 cm (Cowie et al., 1996), and even up to 10 cm depth (Howard et al., 1999). In dry areas and sandy soils, where immobile nutrients are stratified near the soil surface due to NT practices, the availability of nutrients may be limited by moisture scarcity during crop growth in these areas. As a result, P deficiency for crop growth is likely to occur if there is low extractable P in the subsoil or if root growth is constrained by other factors.

In a separate study conducted in Texas, reduced tillage practices were found to be correlated with increased stratification of soil nutrients, which, in turn, led to significantly higher lint yield of cotton (Wright et al., 2007). While the overall stock of SOC is crucial for nutrient storage and water retention, the stratification of SOC seems to play a more vital role in establishing a stable surface structure capable of resisting soil and nutrient losses through runoff. Additionally, this stratification fosters the development of a resilient surface habitat that promotes efficient nutrient cycling and facilitates strong microbial interactions with underlying roots. These findings suggest that managing SOC stratification may offer valuable insights for identifying optimal agricultural practices, enhancing soil quality, and improving crop productivity in the context of reduced tillage systems. Adoption of CA accentuates the need to manage the availability of less mobile nutrients, such as P and K due to reduced mixing of fertilizers in the root zone, decreased mineralization of SOM, and increased nutrient stratification near the soil surface. Proper nutrient management strategies become critical to ensuring optimal crop growth and productivity under these CA practices. Li et al. (2022) indicated that the introduction of one of deep tillage (DT) into RT resulted in a 5.6% reduction in soil bulk density in the 20–30 cm layer and a 20–30% decrease in nutrient stratification rates. As a consequence, soil exhibited a more even distribution of nutrients in the topsoil layer. This change in soil structure favored deep root growth, as evidenced by a higher root length density in the sub-soil layers. This, in turn, led to enhanced soil water use and improved crop production, especially under conditions of limited water supply. In addition, long-term NT can also lead to stratification of other nutrients such as Ca and Mg with increase in soil depth (Dang et al., 2015; Ismail et al., 1994; Rahman et al., 2008). Kettler et al. (2000) and Quincke et al. (2007) indicated that one-off strategic tillage can effectively alleviate nutrient stratification in soil under NT. By conducting a one-off tillage operation, it is possible to redistribute the higher concentrations of Ca and Mg that tend to accumulate near the soil surface in soils of Swartland and southern Cape in South Africa (Liebenberg et al., 2020). Selective one-off tillage interventions can be a viable strategy to manage nutrient stratification in soil under NT systems without compromising overall soil health and crop productivity (Conyers et al., 2019). Farming practices (e.g., incorporation of crop residues, limestone, fertilizers) can decrease the stratification of nutrients in soil under NT systems (Blanco-Canqui and Wortmann, 2020). Additionally, the application of limestone without incorporation near the soil surface can lead to an increase in soil pH (Barth et al., 2018). By implementing NT in combination with soil fertility management and crop diversification, it is possible to further reduce stratification of nutrients and SOM. These practices can also promote root growth in sub-soil layers, mitigate soil compaction through the in-depth incorporation of limestone, and creation of biopores formed by plant roots. These measures could also collectively contribute to minimizing damage resulting from water stress and enhance overall soil health and agronomic productivity.

4.5 Processes affecting soil health

Soil performs vital ecosystem functions and services namely primary productivity, water regulation and purification, carbon sequestration and regulation, habitat for functional and intrinsic biodiversity and nutrient cycling and provision. Soil processes and functions are greatly influenced by the different farm practices as well as land use change or management (Dalal et al., 2021; Lal, 2020a,b).

In four major eco-regions (namely Atlantic North, Pannonian, Continental, and Mediterranean North) of Europe, Ghaley et al. (2018) observed that CT had negative effects on soil functions with a median score of 0.50 while CA had positive effects with a median score between 0.80 and 0.83. Based on a 8-year study, Naorem et al. (2023) reported that a higher soil quality index (SQI) was recorded under NT and RT with residue retention compared to that under CT in Vertisols of Central India. Similar results were reported by several researchers in CA based systems involving rice-wheat and other cropping systems in Indo-Gangetic plains (IGP), India (Biswas et al., 2022; Datta et al., 2022; Rao et al., 2022). In contrast, Amami et al. (2021) observed no improvement in soil quality in NT than CT in a Fluvisol, Tunisia.

In a study conducted by Karlen et al. (1994) in the Orthic Luvisol soils, Wisconsin, USA, the implementation of NT agricultural practices resulted in higher SQI than that under CT. De Bona et al. (2008) assessed the Carbon Management Index, which considers both total carbon stock and carbon lability, across diverse tillage systems. De Bona and colleagues observed that the implementation of NT practices led to an enhancement in soil quality when compared to CT practices. Mbuthia et al. (2015) utilized soil assessment framework (SMAF) tool to evaluate soil properties' quality indices based on their functions. After 31 years of testing a range of tillage options, cover crops, and N rates, the overall SQI differed only among different cover crop treatments. There was no notable response to tillage and N rate changes in the overall SQI, despite observed treatment-induced changes in individual parameter quality scores. However, two factors stood out: total SOC and β-glucosidase; SMAF quality scores were significantly higher in soil under NT compared to that under CT.

Aziz et al. (2013) observed that within SQIs, the component related to soil biological quality exerted a greater influence on the SQI compared to those related to soil chemical and physical attributes, respectively. The Soil Biological Quality (SBQ) significantly contributes, along with other properties, to vital functions such as organic residue decomposition, facilitating nutrient cycling, metabolizing labile carbon, synthesizing humic substances, promoting macroaggregation and structural stability, and safeguarding SOM as particulate organic matter (POM) (Aziz et al., 2009; Dexter, 2004; Melero et al., 2009). As a result, enhancements in soil biological properties correspond to improvements in soil chemical and physical properties, leading to an overall enhancement in soil quality. Zobeck et al. (2008) used the Soil Conditioning Index (SCI) and determined that all NT systems exhibited statistically similar but tending to be higher SCI values when compared to the CT continual corn system.

Soil is critical in providing key functions that have a significant impact on human welfare. These services are a result of the complex interactions between soil properties, the environment, and land management, as well as the relationships between them (Ghaley et al., 2014). Five key soil functions have been recognized within this framework: (a) the capacity to promote plant growth; (b) the regulation and purification of water; (c) the capture and storage of carbon; (d) the provision of a habitat for various life forms; and (e) the cycling and provision of plant nutrients (Coyle et al., 2016). The provision of other essential ecosystem services (ESs) as well as agricultural output are directly impacted by these processes. An effective soil management is crucial to determining whether soils can carry out these diverse roles without causing ecological degradation. The goal of enhancing certain soil functions (i.e., primary productivity within the agricultural domain while potentially not impairing other ESs) depends on the requirements at a regional or national level. Notable among these include meeting C sequestration goals, as well as the more localized requirements for these other functions (e.g., ensuring access to clean drinking water). Toward improving the delivery of soil functions, CA is adopted in several parts of the world. Adoption of CA can maximize the use of natural resources (such as soil, water, physical, chemical, and biological components) while reducing the need for external inputs and preventing soil degradation (Fereres et al., 2014). Despite its numerous benefits (e.g., increased soil fertility, better crop growth, better water penetration, increased biological activity, reduced soil erosion, and lower labor, equipment, and fuel costs), its widespread use in various regions is still limited (Kertész and Madarász, 2014). Therefore, it is essential to understand how conventional practices and CA affect soil functioning. Using expert scoring methods, Ghaley et al. (2018) conducted a comparison between CA and conventional practices on some of the key soil functions across four significant environmental zones in Europe: Atlantic North, Pannonian, Continental, and Mediterranean North. Conventional practices were found to have predominantly adverse impacts on soil functions, as indicated by an average median score of 0.50. In contrast, CA exhibited overall positive effects, with median scores ranging from 0.80 to 0.83.

Data from several studies, that investigated the impact of different farming practices on soil erosion and sediment input into water bodies, agree with the favorable outcomes of NT in comparison to CT (Gaiser et al., 2008; Todorovic et al., 2014; Vogel et al., 2016). These conclusions can be partially attributed to the higher stability of aggregates in topsoil under NT (Urbanek et al., 2014), in spite of the often-denser surface layer characterized by increased bulk density in some soil types (Van Gaelen et al., 2014), in comparison to plowed and unprotected CT surfaces. Furthermore, protecting the soil surface through the presence of crop residue and cover crops is also identified as a significant contributing factor to these observed outcomes (Armand et al., 2009). However, soil types differ in response to NT practice. Mueller et al. (2009) examined the influence of tillage, rotation, and traffic on the topsoil structure and revealed that on a loamy sand field site in Germany, the topsoil under NT had lower infiltration rates, inferior structure, and higher bulk density in comparison to those in soil under CT. Similarly, a German study by Buczko et al. (2003) provided similar observations, where they compared water infiltration and macroporosity among two different tillage systems. In the case of a silt loam soil, CT exhibited a higher saturation infiltration rate. However, the opposite trend was observed for infiltration rate below a depth of 30 cm, reaching down to 1.2 m.

NT is often linked to an increased presence of earthworms, positively impacting soil structural qualities. However, recent studies that compare earthworm populations across diverse management practices have yielded somewhat conflicting outcomes. For example, Hubert et al. (2007) conducted a study in France, investigating changes in pore morphology due to mechanical and biological processes in a silty soil's surface layers. Their findings indicated that under NT, the total macroporosity of the soil was significantly lower compared to that under CT, potentially hindering earthworm activity. Similarly, Garbout et al. (2013) observed more extensive pore networks, branches, and junctions in soil under CT. This trend was attributed to greater compaction in NT-treated soil than that under CT. Interestingly, studies on sandy loams/silty soils such as by Peigné et al. (2013) showed a higher prevalence of vertical macropores in NT-managed soils, suggesting the presence of vertically burrowing earthworms that could potentially enhance water drainage and transmission, thus affecting soil hydraulic conductivity and infiltration rates. Piron et al. (2017) used a visual soil structure method and observed a higher occurrence of bioturbation due to earthworm activity in soil under NT systems compared to those under CT, particularly on a loamy sandy clay and a silty loam soil. These differing results underline the complex interplay between tillage practices, earthworm behavior, and soil structure, highlighting the need for a comprehensive understanding of these relationships on various soil types.

4.6 Reversing land degradation

Montgomery (2007) observed that the process of soil formation unfolds gradually, spanning a considerable timeframe of 700–1500 years to form 1 in. (2.5 cm) of soil (i.e., 0.032 mm of soil layer in a year). In contrast, soil faces a rapid degradation through erosion when subjected to inappropriate soil management practices (Lal, 2003, 2009; Nelson, 1997). Devastating soil erosion and land degradation in the region of Great Plains of U.S (Dust Bowl) during the 1930s (Hobbs, 2007) and Soviet Union Grain Belt region in 1960s (Goddard et al., 2008) are the classical examples of mismanagement of finite but extremely fragile soil resource (Lal, 2009). It is precisely in this context that NT/CA concepts have emerged for the very purpose of controlling erosion and reversing soil degradation (Islam and Reeder, 2014; Lal et al., 2007; Rimal and Lal, 2009) (Table 2). Based on 39 studies comparing NT and CT on soil erosion, Montgomery (2007) found that NT decreased erosion rates by up to 98%, even in long-term experiments with NT corn plantings. With NT, soil particle detachment and suspended solid losses were reduced (Larsen et al., 2014), reducing soil erosion and pollutant transport (Carkovic et al., 2015). In comparison with CT, Choi et al. (2016) reported a 64.9% decrease in runoff ratio and a 66.4–88.3% increase in non-point source sediment loads under NT.

According to a 16-year study conducted in Hungary, NT reduced surface runoff by 75% and soil loss by 95%. A significant difference in mean annual soil erosion was found between plowing (2.8 Mg ha^{-1}) and NT

Table 2 Comparison of conservation tillage/CA practices and conventional tillage on soil erosion ($Mg\,ha^{-1}$).

Year of experiment	Location	Cropping system	Type of soil	Conventional tillage	Conservation tillage/CA practices	References
2007–2011	Dehradun, India	Maize-wheat	Coarse textured soil	7.2	3.5	Ghosh et al. (2015)
2001	Kathmand, Nepal	Maize	Acidic and sandy soil	16.7	14.5	Atreya et al. (2006)
2001	Kathmand, Nepal	Maize + soybean	Acidic and sandy soil	18.1	14.7	Atreya et al. (2006)
2002	Kathmand, Nepal	Maize	Acidic and sandy soil	15.0	7.0	Atreya et al. (2006)
2002	Kathmand, Nepal	Maize + soybean	Acidic and sandy soil	16.5	8.2	Atreya et al. (2006)
1990–1993	Vasad, India	Green gram–mustard and pearl millet + pigeon pea	Coarse loamy soil	8.4	3.6	Kurothe et al. (2014)
1995–2001	Vasad, India	Cowpea–mustard and cowpea–castor	Coarse loamy soil	7.3	6.0	Kurothe et al. (2014)
2005–2007	North Ethiopia	Wheat–Teff (NT on raised beds)	Calcic Vertisol	24	5.0	Araya et al. (2011)
2014–2017	Zurich, Switzerland	Fallow land–winter wheat	Loamy cambisols	2.66[a]	0.49[a]	Seitz et al. (2019)
2017–2018	Northeast Italy	Wheat-soybean–maize	Silty loam	3.37	0.41	Carretta et al. (2021)
1978–1988	Queensland Australia	Wheat	Fine textured soil	64	4	Freebairn et al. (1993)

Continued

Table 2 Comparison of conservation tillage/CA practices and conventional tillage on soil erosion (Mg ha^{-1}).—cont'd

Year of experiment	Location	Cropping system	Type of soil	Conventional tillage	Conservation tillage/CA practices	References
July 1997 June 2000 July 1997	North Carolina	Corn and soybean	Sandy clay loam and clay loam (fine mixed, active, thermic, Ultic Hapludalfs)	241.8 92.9 62.6	2.5 2.3 1.1	Raczkowski et al. (2009)
1984–1987	Nigeria	Maize Cowpea	Oxic Paleustalf	6.90 4.90	0.46 0.72	Lal (1997)
2001–2004	North eastern Oregon, USA	Winter wheat-fallow-winter chickpea	Typic Haploxerolls	11[b]	0.21[b]	Williams et al. (2009)
1995 1996 1996/97	Daruvar, Central Crotia	Maize Soybean Winter wheat	Stagnic Luvisols	146.3 110.1 86.7	22.8 13.6 0.21	Kisic et al. (2002)
1970–1973	Ohio, USA	Maize	Silt Loam	23.9	0.26	Harrold and Edwards (1974)

[a]Mean data of 4 years in t/ha.
[b]Mean data t/ha/year.
Modified from Jayaraman, S., Dang, Y.P., Naorem, A., Page, K.L. and Dalal, R.C., 2021a. Conservation agriculture as a system to enhance ecosystem services. Agri, 11 (8), p. 718; Jayaraman, S., Sinha, N.K., Mohanty, M., Hati, K.M., Chaudhary, R.S., Shukla, A.K., Shirale, A.O., Neenu, S., Naorem, A.K., Rashmi, I. et al., 2021b. Conservation tillage, residue management, and crop rotation effects on soil major and micro-nutrients in semi-arid Vertisols of India. J. Soil Sci. Plant Nutr. 21, 523–535.

(0.2 Mg ha^{-1}). Moreover, crop residues from previous crops contributed significantly to increased surface roughness and reduced soil loss (Adimassu et al., 2019; Lal, 2009; Nelson, 1997). As a result of NT and minimum tillage coupled with residue retention, soil loss was lower at 16 Mg ha^{-1} compared with that under CT without residue. However, even the reduced soil loss under NT remains higher than the tolerable range of 2–10 Mg ha^{-1} for the Ethiopian highlands, possibly not providing sufficient crop residue for soil surface cover.

Quinton and Catt (2004) reported from a 10-year study that soil loss was not significantly different among the two cultivation directions (i.e., across and up- and downslope cultivation). The across-slope/minimal tillage treatment combination had a significantly smaller ($P < 0.05$) event soil loss (67 kg ha^{-1}) than the up- and downslope/standard tillage (278 kg ha^{-1}) and up- and downslope/minimal tillage (245 kg ha^{-1}) combinations. However, mean event runoff from the across-slope/minimal tillage treatment combination (0.58 mm) was significantly less ($P < 0.01$) than from the up- and downslope/minimal tillage (1.41 mm), up- and downslope/standard tillage (1.24 mm), and across-slope/standard tillage (1.07 mm) treatment combinations. Runoff from the across-slope/standard treatment combination was significantly ($P < 0.05$) less than from the up- and downslope/minimal tillage treatment.

5. NT/CA effect on weed population and dynamics

The influence of tillage on the magnitude of the weed seedbank is influenced by multiple factors (Mohler, 1993), which results in varying outcomes in empirical studies. Some studies have found that tillage has no impact on the weed seedbank (Barberi and Lo, 2001), while others have reported a reduction (Clements et al., 1996; Murphy et al., 2006) or an increase (Büchi et al., 2015; Cardina et al., 2002; Sosnoskie et al., 2006) in weed seedbank densities. Moreover, the response of weed seedbank to tillage varies depending on the weed species (Buhler et al., 1996; Farooq et al., 2011; Moyer et al., 1994). Mohler (1993) pointed out that the effect of tillage on weeds involves a complicated interplay of various factors such as weather patterns, the length of the experiment, and the long-term history of the field. Shrestha et al. (2002) showed that long-term changes in weed flora were determined by a combination of factors, including tillage, environment, crop rotation, crop type, and the timing and method of weed management.

Reduced tillage in CA means that the vertical distribution of weed seeds in the soil profile is influenced only by the depth of sowing and the type of seeding machine used. In Australia, Chauhan et al. (2006) suggested that when using NT systems, a significant proportion of the weed seed bank may remain on the soil surface after sowing in CA. Similarly, Clements et al. (1996) and Swanton et al. (2000) found that in NT, depending on the soil type, 60–90% of weed seeds were located in the top 5 cm of soil. The size of the weed seed bank can be significantly decreased through seed predation.

Franke et al. (2001) stated that the emergence of *P. minor* was reduced under NT systems regardless of the density of the weed seed bank. The difference in moisture levels between NT and CT could be a reason for the lower emergence of *P. minor* in fields sown using the NT method. Cussans (1976) found that there was an increase in dicot weeds with greater intensity of tillage. However, Wrucke and Arnold (1985) reported similar occurrences of broadleaf weeds in both CT and NT systems. In a study by Swanton et al. (1999), *Chenopodium album* L. and *Amarathus retroflexus* L. were found to be associated with CT, while *Digitaria sanguinalis* L. was linked to the NT system. According to Teasdale and Mohler (1993), the emergence of certain weed species declines steadily as the amount of residue increases, while for other species, emergence increases at low residue amounts before decreasing at high residue amounts. High levels of residue may either delay or prolong weed emergence, which can have implications for weed management in NT. Delayed weed emergence can give crops a competitive edge over weeds, and these weed seedlings are likely to have a lesser impact on crop yield loss and weed seed production. However, in some cases, the presence of crop residue may stimulate weed seed germination. For instance, *A. fatua* and *Avena sterilis* subsp. *ludoviciana* growth and germination were promoted by wheat residues. Organic matter and surface cover can increase the moisture on the surface layer and decrease soil temperature, creating favorable conditions for the germination of some weed species (Young and Cousens, 1999). Although the presence of crop residues can decrease the germination of various weed species, a higher quantity than that typically found in dryland fields is required to substantially suppress weed germination and growth (Chauhan and Johnson, 2009, 2010).

The practice of intercropping legume crops that grow quickly and mature early with long duration and widely spaced crops can cover the ground more quickly and suppress emerging weeds more effectively. In a study conducted by Baumann et al. (2001), it was found that a leek-celery intercrop reduced the relative soil cover of weeds by 41%, decreased the density of *Senecio vulgaris* L. by 58%, and increased the total crop yield by 10% when compared to sole cropping. Cereal-legume intercrops have also been shown to improve weed suppression in various environments (Ofori and Stern, 1987). Crop residues are typically absent during pre-emergence herbicide application in CT systems, unlike in NT systems where residues may intercept the herbicide and reduce its efficacy. This interception leads to a decrease in the amount of herbicide that can reach the soil surface and kill germinating seeds, thereby reducing the herbicide's effectiveness (Hartzler and Owen, 1997). The effectiveness of herbicides in NT systems may also vary depending on their formulation. Granular formulations of pre-emergence herbicides, such as alachlor, cyanazine, and metolachlor, provide better weed control than liquid formulations in NT systems (Johnson et al., 1989). In addition, granules of trifluralin were found to be more effective than liquid formulations in controlling *Setaria viridis* L. and *S. glauca* L. in a NT system with $7.5\,\mathrm{Mg\,ha^{-1}}$ of stubble and 84% ground cover (Endres and Ahrens, 1995).

The persistence of herbicides in NT systems also depends on various factors such as climatic conditions and herbicide application methods, including pre-plant incorporation by NT sowing tines or post-sowing pre-emergence without incorporation by sowing tines (Curran et al., 1992). Herbicides with high vapor pressure, such as trifluralin and pendimethalin, are particularly susceptible to volatilization loss from the soil surface (Chauhan et al., 2006). The chemical environment of weed seeds can be altered by surface residues through allelopathy. Wheat and rice residues have been found to exhibit genetically controlled allelopathy that could be used for weed control (Khanh et al., 2007; Wu et al., 2001). Some studies have indicated that surface residues are more effective than incorporated residue in suppressing plant growth, according to Roth et al. (2000). The effectiveness of allelopathic weed control is influenced by environmental conditions and may only last for a short period (Cochran et al., 1977; Kimber, 1973). Residue present on the soil surface acts as a barrier between the soil and atmosphere, reducing water evaporation and maintaining moisture, thus safeguarding seeds from drying out in environments where water is scarce. However, in environments with sufficient moisture, residue may lead to faster seed decay, as there is increased microbial activity and biomass under residue (Doran, 1980; Govaerts et al., 2007: Yang et al., 2013). This could result in higher rates of seed losses due to decay under residue (Derksen et al., 1996; Kennedy and Kremer, 1996; Chee-Sanford et al., 2006). Effective weed management is critical during the transition to NT systems, as it may take between 4 and 10 years for yields, soil characteristics, and weed populations to reach equilibrium (Swanton et al., 1993). In several regions worldwide, NT is being adopted in stages, with reduced tillage often serving as the starting point (Andersson and D'Souza, 2014; Giller et al., 2009; Kienzler et al., 2012). This gradual adoption of NT/CA may create additional challenges in controlling weeds, as it fails to capitalize on the synergistic benefits that arise from the combined implementation of all three CA principles.

In NT system, weed seed predation can be promoted by managing bunds and dryland areas around fields. To provide forage for seed predators, crop residue can be left in the field instead of being removed or burned (Chauhan and Johnson, 2010). These techniques can be incorporated into existing practices without adding extra expenses for growers. Preventative measures for weeds include using clean crop seeds, using clean agricultural implements, and managing weeds on bunds, unused/fallow lands or levees and roads. Sheley et al. (2002) highlighted that a vehicle driving through a *Centaurea biebersteinii* DC. infestation picked up about 2000 seeds of *C. biebersteinii*, of which 90% dropped within 16 km. The study concluded that minimizing soil disturbance by vehicles, machinery, wildlife, and livestock is crucial in preventing the establishment of noxious weeds. In NT systems, a stale seedbed practice can be an effective way to reduce weed pressure. This technique involves lightly irrigating the field, which encourages weed seeds to germinate. Non-selective herbicides are then used to kill emerging seedlings. Since most weed seeds remain in the topsoil layer and germinate and emerge from the top 3 cm of soil, a flush of weed seedlings can appear within a week after irrigation. This method has proven to be very effective in NT wheat in the northwestern Indo-Gangetic Plains (Mahajan et al., 1999). In addition to this, in NT system, the time of sowing can be adjusted to avoid providing favorable ecological conditions for the germination of weed seeds. For instance, growers in the northwestern Indo-Gangetic Plains advanced wheat seeding by 2 weeks to get a head start over the noxious weed *Phalaris minor* Retz (Singh et al., 1999). Finally, earlier seeding of spring crops can enhance their ability to compete effectively with weeds.

6. Effect of NT system on greenhouse gas emissions

The atmospheric CO_2 concentration has reached at 418–420 ppm in Sep 2023 and increased by about 150% of the pre-industrial level (IPCC, 2022). The use of fossil fuels for agricultural inputs and crop management practices, as well as plant respiration and SOM decomposition, account for around 10–12% of all anthropogenic GHG emissions (Govaerts et al., 2009). Soils are essential component in the emission of greenhouse gases (Soane et al., 2012). As a practical way to cut GHG emissions and encourage carbon sequestration in agricultural soils, CA, including the use of NT, has been advocated (Ruis et al., 2022; Sanderman et al., 2010). The global adoption of NT practices has the potential to store SOC at a rate equal to around one-third of the present global CO_2 emissions from burning fossil fuels (FAO, 2008). In contrast to CT, there are still questions about the rate of carbon sequestration and the long-term durability of this carbon sink associated with NT (Sanderman et al., 2010). The existing research on the yield and environmental performance of NT systems offers variable and oftentimes contradictory conclusions (Soane et al., 2012). Moreover, GHG emissions were highly variable and greatly influenced by intricate interaction of soil properties such as, volumetric water content, soil matric potential, relative diffusivity, air permeability and water-filled pore space, soil structure, pore continuity and size, and substrate availability (Ball, 2013; Soane et al., 2012). Besides, larger differences in GHG values may be due to variation in experimental methods as well as the lack of standardized processes for describing various tillage systems.

6.1 N_2O emissions

The application of NT practices has a considerable impact on the dynamics of soil N in a number of ways (Conen and Neftel, 2010). Regarding the relative contribution of CT and NT to N_2O emissions, studies have produced a range of findings depending on the soil type and management practices used. Some studies observed increasing N_2O emissions in NT systems (Abdalla et al., 2013; Ussiri et al., 2009), while others reveal a higher contribution from CT (Almaraz et al., 2009; Wang et al., 2011). Lemke et al. (1999) in Alberta, Canada, observed that N_2O emissions from wheat systems under NT were comparable to or lower than those under CT. However, Bavin et al. (2009) found no appreciable difference between the two tillage systems in terms of GHG emissions. On heavy clay and silty clay loam soils in Quebec, Canada, MacKenzie et al. (1997) found that NT systems had almost 38% higher annual N_2O flux compared to CT, with equal N application rates. Mummey et al. (1998) analyzed the regional variability of agricultural N_2O emissions in the United States and highlighted that NT in warm, wet locations may have equivalent or lower N_2O emissions than CT, whereas

NT may result in higher N_2O emissions in drier regions. According to Six et al. (2004), the potential of NT to reduce GHG emissions in temperate areas is eventually realized in the long-term. Even while NT tended to have reduced emissions, particularly with crop rotations, after three decades, there was no discernible difference in N_2O emissions between NT and CT. However, Venterea and Stanenas (2008) found greater N_2O emissions under NT, particularly when N fertilizer was applied topically. According to Liu et al. (2006), CT caused lower N_2O emissions but higher CH_4 emissions than NT. NT results in greater soil moisture content and lower aeration, particularly after rainfall, in areas where heavy, poorly drained soils are typical. When compared to CT, this condition increases denitrification and N_2O emissions (Regina and Alakukku, 2010). However, wet soil conditions lead to the conversion of N_2O to N_2. Besides, soil moisture differences, the stronger relationship between N_2O emission and total C and N contents may also explain the higher reported N_2O fluxes in NT soils. Further, Six et al. (2004) observed that N_2O emissions increased for the first 10 years after the adoption of NT but then gradually decreased after 20 years. This pattern can be linked to slow changes in soil structure and drainage under NT. With NT, Linn and Doran (1984) observed an increase in water-filled pore space as well as higher CO_2 and N_2O emissions. However, Van Kessel et al. (2013) observed no overall difference in N_2O emissions between CT and NT systems in their meta-analysis. Nevertheless, over 10 years, NT showed a 27% lower N_2O emission rate in drier periods.

Long-term NT may result in a decrease in N_2O emissions due to the accumulation of soil organic matter, which enhances aggregate stability and porosity, and decreases anaerobic microsites (Six et al., 2004; Wang et al., 2011) (Fig. 10). Although NT is associated with enhanced soil moisture (Alvarez and Steinbach, 2009), it may not result in increased N_2O emissions (Grandy et al., 2006a). As compared to CT with *Tephrosia* ssp. addition, N_2O emissions were decreased in Kenya when NT was implemented simultaneously with the addition of *Tephrosia* ssp. branches and leaves (brown manuring) (Baggs et al., 2006). Eight weeks after *Sesbania sesban* leftovers were added to an improved fallow system in Zimbabwe, NT resulted in lower N_2O emissions (Chikowo et al., 2004). N fertilizer form and placement, as well as soil moisture content, in NT systems, influence N losses and GHG emissions, with surface mulch application reducing volatilization (Ball, 2013; Mengel et al., 1982; Soane et al., 2012; Wulf et al., 1999).

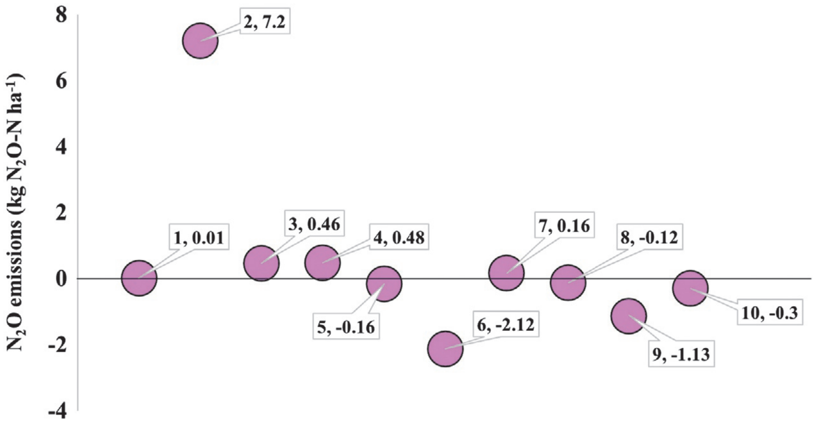

Fig. 10 Difference in N_2O emissions (kg N_2O-N ha^{-1}) between conventional tillage (CT) and zero tillage (NT). Each data callout represents two numbers (the first number is the serial code of the study, the second is the difference of N_2O emissions). The studies shown in this figure are 1 = Hao et al. (2001); 2 = Choudhary et al. (2002); 3 = Chatskikh and Olesen (2007); 4 = Oorts et al. (2007); 5 = Ahmad et al. (2009); 6 = Baggs et al. (2003); 7 = Drury et al. (2006); 8 = Grandy et al. (2006a); 8 = Escobar et al. (2010); 9 = Kessavalou et al. (1998).

6.2 CO_2 emissions

Aeration, temperature, soil moisture content, soil porosity, bulk density, soil aggregation and the mixing of crop residues (i.e., increase in C substrate) within the soil matrix are important factors influencing CO_2 emissions (Kladivko, 2001; Ussiri et al., 2009). Studies have shown that soil and air temperatures are positively correlated with CO_2 fluxes, while soil moisture content is negatively correlated with CO_2 fluxes (Jarecki and Lal, 2006).

Various studies demonstrated that NT practices resulted in lower CO_2 emissions compared to CT (e.g., Al-Kaisi and Yin, 2005; Bauer et al., 2006; Sainju et al., 2008). CT disrupts soil aggregates, exposing organic matter to microbial decomposition and releases CO_2 (Six et al., 2002). O'Dell et al. (2015) observed that under NT, a winter wheat cover crop led to a net accumulation of 257 g CO_2-C m^{-2}, while tilled plots without cover crops emitted 197 g CO_2-C m^{-2}, and untilled plots without cover crop emitted even higher rates of 235 g CO_2-C m^{-2}. Oorts et al. (2007) reported 29% higher CO_2 emissions under NT due to increased moisture conservation and subsequent biological activity. Abdalla et al. (2015), in a global meta-analysis, found that CT soils emitted 21% more CO_2 than NT, particularly in sandy and arid climates.

Reductions in CO_2 fluxes under NT compared to CT have also been observed in soils of the Spanish plateau (Sanchez et al., 2002, 2003). However, under specific conditions, higher CO_2 emission rates have been observed under NT than those under CT (Almaraz et al., 2009). For example, CO_2 emissions from long-term NT were higher than those from CT, with values of 4064 and 3160 kg CO_2-C ha^{-1}, respectively (Oorts et al., 2007). The increased emission under NT was attributed to the decomposition of old residues present at the surface, likely influenced by unusually warm weather during the monitoring period.

Another study by Yamulki and Jarvis (2002) also observed increased CO_2 efflux under NT compared to CT, although they did not explain the reason for difference between tillage treatments. CO_2 emissions from soil are influenced by various processes, including short-term effects immediately after plowing and longer-term effects during the growing season (Oorts et al., 2007). Short-term effects result from physical soil disturbance and crop residue disruption, while long-term effects involve changes in soil properties over multiple years. Most studies primarily focus on short-term effects, while long-term CO_2 emissions are influenced by complex interactions among factors such as temperature, rainfall, water content, SOM, and crop residues (Oorts et al., 2007).

CT typically increases CO_2 flux during the initial days after soil disturbance, with relatively minor long-term differences between tillage treatments (Chatskikh and Olesen, 2007). Similarly, Lopez-Garrido et al. (2009) found that CT caused a sharp rise in soil CO_2 emissions immediately after tillage. Cumulative carbon losses through CO_2 emissions throughout the year were higher under CT compared to NT (Alvaro-Fuentes et al., 2004, 2007a,b, 2008). Just after tillage, soil CO_2 emissions were 40% higher under CT than under NT, as CO_2 accumulated in soil pores was released into the atmosphere. Additionally, CT has a cumulative effect during the entire growing season by increasing microbial decomposition, resulting in 20% higher soil CO_2 emissions as compared to NT. Increased root respiration under CT, particularly in warmer months, may partially contribute to this effect (Almaraz et al., 2009).

CO_2 fluxes are significantly higher after tillage compared to NT, with tillage increasing CO_2 emissions by 3–15 times in semiarid Mediterranean agroecosystems (Alvaro-Fuentes et al., 2007a). NT systems generally exhibit lower and steadier soil CO_2 fluxes throughout the study period compared to other tillage practices (Reicosky et al., 2008). Different tillage practices have varying effects on soil CO_2 evolution during the growing period, with NT typically showing higher CO_2 evolution compared to CT (Franzluebbers et al., 1995) (Table 3). In contrast, Sapkota et al. (2015) reported that CA-based rice-wheat systems produced 10–15% less GHG emissions compared to CT systems.

Table 3 Effect of CT (conventional tillage) and NT (no-tillage) on carbon dioxide emissions (CO_2-C efflux MgCO_2-C ha^{-1}) in different locations and soil types.

Crop	Location	Soil type	Duration	CT	NT	CT-NT	References
				CO_2-C efflux Mg CO_2-C ha^{-1}			
Wheat (*Triticum aestivum*)	Canada	Clay Loam	3 years	5.75	6.09	−0.34	Abdalla et al. (2013)
No crop	Morocco	Clay	3 months	1.55	0.06	1.49	Moussadek et al. (2011)
Barley (*Hordeum vulgare*)	Denmark	Loamy sand	3.71 month	4.29	3.3	0.99	Chatskikh and Olesen (2007)
Wheat (*Triticum aestivum*)	Argentina	Loamy	40 days	2.33	1.75	0.58	Alvarez et al. (2001)
Maize (*Zea mays*)	Colorado, USA	Loamy	3 months	0.21	0.37	−0.16	Liu et al. (2006)
Maize (*Zea mays*)–soybean (*Glycine max*)	Iowa, USA	Loamy	3 years	0.51	0.4	0.11	Al-Kaisi and Yin (2005)
Rice (*Oryza sativa*)	India	Silt clay Loam	1 season	7.64	7.62	0.02	Ahmad et al. (2009)
Forage grass–rice (*Oryza sativa*)	Brazil	Clay	6 months	8.69	6.12	2.57	Passianoto et al. (2003)
Maize (*Zea mays*)–soybean (*Glycine max*)–clover (*Trifolium* spp.)	Albama	Loamy Sand	80 h	1.59	0.56	1.03	Reicosky et al. (1999)
Wheat (*Triticum aestivum*)	Canada	Silt Loam	1 year	3.64	2.81	0.83	Curtin et al. (2000)
Wheat (*Triticum aestivum*)	Argentina	Loam	40 days	2.33	1.75	0.58	Alvarez et al. (2001)
Sugarcane (*Saccharum officinarum*)	Brazil	Clayey	30 days	13.62	5.24	8.38	La Scala et al. (2006)

The use of fuel in NT operations is generally lower compared CT, although the extent of the difference depends on factors such as soil type, plowing depth, and secondary cultivations. Estimates of fuel savings with NT compared to plowing and secondary cultivations vary across studies, ranging from 50% (Khaledian et al., 2010) to 84% (Arvidsson, 2010). Tebrugge and Bohrnsen (1997) reported that the average fuel consumption for growing small grains in Germany ranged from 43.55 L ha^{-1} for plowing, secondary cultivation, and sowing to 6.8 L ha^{-1} for NT (sowing and plant protection), resulting in a potential fuel saving of 37 L ha^{-1} or 84%.

Soil type also plays a significant role in fuel savings with NT. For instance, on a clay soil in Sweden, Henryfuel consumption for plowing and cultivating was 54 L ha^{-1}, whereas it was only 9 L ha^{-1} for NT. On silty loam soil, the corresponding values were 27- and 7-L ha^{-1}, respectively, resulting in savings of 45 and 20 L ha^{-1} for NT (Arvidsson, 2010). Similarly, in Germany, fuel consumption savings with NT compared to plowing, cultivating, and sowing were 27, 34, and 53 L ha^{-1} for sandy, loam, and clay soils, respectively (Koeller, 1989).

The production and consumption of tractor fuel emit approximately 376 kg of CO_2 and other greenhouse gases per 100 L of diesel (Tebrugge, 2001). Therefore, an average fuel saving of 40 L ha^{-1} by using NT instead of plowing would result in reduced emission of 41 kg CO_2-C ha^{-1} for each crop season. Tebrugge (2001) suggests that if NT were adopted on 40% of the EU land area, it could potentially reduce CO_2 emissions by 4.2 Tg per year solely due to lower fuel consumption. The true mitigation of global warming potential (GWP) through NT practices depends on whether the increased carbon sequestration outweighs the net emissions of the major biogenic GHGs. Some studies suggest that the higher emissions of GHGs, especially N_2O, from NT, may counterbalance the benefits of increased carbon storage (Bhattacharyya et al., 2018; Oorts et al., 2007), especially on poorly drained and fine-textured agricultural soils (Rochette, 2008). Therefore, effective N management to reduce N_2O emissions is crucial for maximizing the potential benefits of increased carbon sequestration with NT (Six et al., 2004; Wang and Dalal, 2015), particularly on poorly aerated soils. More research is needed to enhance our understanding and confidence in predicting the overall benefits of NT practices in reducing N_2O emissions and overall global warming potential (GWP). Additionally, studies must consider the differences in tractor fuel usage, N fertilizer application and placement, and herbicide use.

6.3 CH_4 fluxes

Ball et al. (1999) found that CH_4 oxidation was higher under NT compared to that under plowing, but the rates were low and unlikely to have a significant impact on the GHG budget. In the United States, NT practices have been shown to increase CH_4 oxidation compared to minimum and CT (Ussiri et al., 2009). However, other studies have indicated that NT soils may emit CH_4 at a higher rate than CT (Alluvione et al., 2009). Regina and Alakukku (2010) suggest that NT has a weak effect on CH_4 fluxes, which may vary depending on soil conditions and could result in either a slightly positive or negative flux. Well-structured soil acts as a sink for CH_4, while waterlogged soil becomes a source of CH_4 (Ball, 2013; Jarecki and Lal, 2006).

Snyder et al. (2009) concluded that there is no clear positive or negative response in terms of GHG mitigation when comparing NT to CT. The net GWP can decrease in regions where organic matter increases with NT, but it can slightly increase in other areas. It is worth noting that CH4 fluxes data can be highly variable in the short-term and are often reported for different periods during the crop season, which can present challenges in drawing definitive conclusions.

Ussiri et al. (2009) conducted a study comparing NT, chisel till, and mouldboard plowing, and their effect on CH_4 emissions. They found that NT acted as a sink for CH_4, with an average oxidation rate of 0.32 kg CH_4-C h^{-1} $year^{-1}$. In contrast, chisel till (2.26 kg CH_4-C h^{-1} $year^{-1}$) and mouldboard (2.76 kg CH_4-C h^{-1} $year^{-1}$) plowing as a source of CH_4 resulted in higher CH_4 emissions. However, it's important to note that other studies have reported contrasting results. For example, Omonode et al. (2007) and Venterea et al. (2006) found opposite trends when they conducted studies involving the application of anhydrous ammonia as a fertilizer.

Furthermore, several studies have examined the differences in total CH_4 flux between CT and NT and have reported relatively small or insignificant differences in CH_4 emissions (Bayer et al., 2012; Jacinthe and Lal, 2005; Mosier et al., 2006; Yamulki and Jarvis, 2002). It is important to consider that different factors, such as fertilizer application or specific soil conditions, can influence CH_4 emissions and oxidation, leading to variations in the observed CH_4 fluxes across different studies. The meta-analysis conducted by Maucieri et al. (2021) showed that, on average, NT significantly decreased CH_4 emissions from paddy fields, with emissions reduced from 12.39 to 9.55 mg m^{-2} h^{-1} ($P < 0.05$). However, in maize-cultivated fields, NT exhibited a slight but non-significant tendency to increase CH_4 emissions compared to CT, with an average increase from $-0.15\,mg\,m^{-2}\,h^{-1}$ in CT to $0.05\,mg\,m^{-2}\,h^{-1}$ in NT. Other factors that were examined, such as climate, soil class, and years since the conversion to NT, had weak regulatory effects on soil CH_4 emissions, except for a slight tendency (not significant) of NT to reduce emissions in humid subtropical climates, with average fluxes of $3.90\,mg\,m^{-2}\,h^{-1}$ in NT compared to $5.01\,mg\,m^{-2}\,h^{-1}$ in CT. However, the effect of climate was often confounded by the choice of crop, highlighting the need for cautious interpretation.

Climate plays a significant role in regulating net CH_4 emissions from soils. Huang et al. (2018) conducted a meta-analysis and observed a reduction in CH_4 emissions and an increase in CH_4 uptake with NT in humid climates, defined by an aridity index >0.65. However, it is important to note that the sole consideration of climatic zone may not fully explain the differences between tillage treatments when studies are not adequately balanced in terms of soil moisture conditions and cultivated crops. This is particularly relevant when analyzing agroecosystems with specific dynamics such as paddy fields, which may have a significant influence on the overall CH_4 fluxes. The effects of tillage on CH_4 emissions can be influenced by various factors, including soil texture. Soils with coarser texture generally exhibit greater CH_4 uptake due to lower tortuosity, which facilitates faster diffusion of atmospheric CH_4 into the soil. This faster diffusion leads to increased CH_4 uptake. Additionally, coarser soils often have better drainage conditions, resulting in lower average soil water content. Lower soil water content can limit methanogenesis, the process by which CH_4 is produced, further contributing to lower CH_4 emissions.

Understanding the complex interplay between climate, soil properties, management practices, and specific crop dynamics is crucial for comprehensively assessing the effects of tillage on CH_4 emissions. Integration of various research approaches and consideration of multiple factors are necessary to obtain a more nuance understanding of the processes involved and to develop effective mitigation strategies for CH_4 emissions in different agroecosystems.

An alternative technique known as direct seeded rice (DSR) shows promising potential for reducing CH_4 emissions. DSR serves as an alternative to the traditional method of puddled transplanting and offers advantages such as labor, fuel, time, and water savings. Gupta et al. (2016) conducted research within the rice-wheat system in the Indo-Gangetic Plains (IGP) and reported significantly lower GWP per unit of grain yield (GHG intensity) for DSR compared to traditional puddle transplanting. Similar observations were made for wheat, particularly in the case of the DSR combined with NT and neem oil-coated urea treatment. Among the various rice-wheat treatments examined, DSR in combination with NT and the DSR with residue retention followed by NT exhibited significantly lower GHG intensities. This indicates that adopting DSR followed by NT could considerably reduce GWP per unit of crop yield.

7. Impact of long-term NT farming on carbon sequestration and climate change mitigation

Agriculture plays an important role in the global carbon cycle and GHG. The adoption of sustainable farming practices, such as NT, has been suggested as a possible strategy to mitigate climate change by increasing carbon sequestration and reducing GHG emissions (Dalal et al., 2011, 2021; Hassan et al., 2022; Henry et al., 2023; Lal, 2015a,b,c; Ogle et al., 2019).

7.1 Carbon storage/sequestration: A long-lasting or transient effect

Adoption of long-term NT farming practices can lead to a significant increase in carbon sequestration, primarily due to the retention of crop residues on the soil surface and the reduced disturbance due to NT, which promote accumulation of SOC in surface layers in comparison to CT systems (Jayaraman et al., 2020; Lal, 2015a,b; Smith et al., 2008; Tang et al., 2019).

The improvement in SOC levels resulting from the adoption of NT practices varies and depends on several factors, such as climate, soil type, management practices, and crop rotation (Jarecki and Lal, 2005). The climate is having a variable impact on soil carbon accumulation due to NT (Ogle et al., 2019). Compared to CT, NT led to a significant rise in SOC stock up to 38% in the 0–5 cm soil layer and a lesser 6% increase in the 5–10 cm layer and no change beyond 10 cm. The temperate climate had nearly twice the improvement in SOC stock in the 0–5 cm layer compared to other climates, while the tropical climate favored sub-surface accumulation (Mondal et al., 2023).

Different soil textures, including fine (5.17–7.89 $Mg\,C\,ha^{-1}$), medium (2.44–11.44 $Mg\,C\,ha^{-1}$), and coarse soils (6.44–8.43 $Mg\,C\,ha^{-1}$), exhibited different SOC improvements over 10–20 or more years (Mondal et al., 2023). In tropical and warm temperate climates, loamy, silty, and clayey soils were more affected by tillage, with the impact extending deeper into the soil profile compared to sandy soils in the same climates. In cool temperate climates, the trend was reversed, with significant impacts on SOC stock around 20 cm for loamy, silty, and clayey soils, but extending to depths around 40 cm for sandy soils (Ogle et al., 2019). Different soil types and climatic conditions result in varying responses to tillage practices, emphasizing the need for region-specific approaches to soil management and conservation.

Conversion of CT to NT can sequester $0.57 \pm 0.14\,\mathrm{Mg\,C\,ha^{-1}\,year^{-1}}$ with maximum sequestration rates occurring between 5 and 10 years based on 67 long-term agricultural experiments (West and Post, 2002). Assuming that the equilibrium was obtained in 20 years, this would result in a 28% increase in SOC. Conversion of CT to NT could increase SOC storage by 10% and 16% over 20 years in temperate dry and temperate moist climates, respectively (Ogle et al., 2005). However, some of the studies indicated that the potential increase in SOC storage would be 3% and 12% in cool dry climates, and cool moist climates, respectively (Smith et al., 2008).

Management practices, including the use of cover crops, crop rotation, and the application of organic amendments, can significantly influence carbon sequestration under NT. These practices contribute to the input of organic matter into the soil, thereby enhancing SOC levels (Farooqi et al., 2018; Singh et al., 2018). In an NT farming system where biomass production is less, the rate of SOC sequestration may be negative. Thus, the SOC sequestration rates for NT farming in diverse ecosystems vary widely among ecosystems and range from 0 to $1000\,\mathrm{kg\,ha^{-1}\,year^{-1}}$ (De Moraes Sá et al., 2001; Lal, 2004). The SOC increase due to C release from cover crops in Mediterranean olive orchard range from 482 to $2157\,\mathrm{kg\,ha^{-1}}$ (de Torres et al., 2021). The rates of SOC sequestration vary with soil layers, with peak sequestration rates in the soil surface layer (Lal, 1997), up to 40 cm soil profile (Hussain et al., 2021; Jat et al., 2012).

However, some of the studies reported that conversion of CT to NT with crop residue retention did not increase SOC stocks/sequestration (Srinivasarao et al., 2015) and the SOC stock improvement of NT was concentrated on the top soil layer (Govaerts et al., 2009; Luo et al., 2010; Wang et al., 2020b; Zhang et al., 2023b). C sequestration under reduced or NT is only apparent in surface soil layers and may not always lead to C sequestration when the whole soil profile is considered (Angers and Eriksen-Hamel, 2008; Luo et al., 2010). However, increasing the quantity of C input could enhance soil C sequestration or reduce the rate of SOC loss, depending mainly on the local soil and climate conditions (Jayaraman et al., 2020; Pasricha, 2017; Tiwari et al., 2018).

Cai et al. (2022) carried out a meta-analysis on the accumulation of SOC in surface soil and soil profile under NT involving 1061 pairs of published experimental data comparing NT and CT. They found NT increased SOC storage at the soil surface (0–10 cm, 3.47 $Mg\,ha^{-1}$) relative to CT but reduced it in deeper soil layers (10–60 cm,) ranging from 0.28 to $-2.29\,Mg\,ha^{-1}$, resulting in slightly reduced total SOC storage in the entire soil profile (0.24 $Mg\,ha^{-1}$) compared with CT. Differences in SOC storage were not found between NT and CT below 60 cm. The relative SOC increases in the surface soil and decreases at depth under NT relative to CT diminished over time, indicating that NT-driven SOC changes diminish over time and net SOC sequestration in 0–60 cm soil profile approached zero when the experimental duration was 14 years. These results demonstrate that SOC sequestration under NT was limited to the surface soil and was only visible in the early years of adoption and when deeper soil layers were accounted for, NT led to decreases in SOC storage in the entire soil profile compared with CT, although these decreases were alleviated over time. However, after 14 years, SOC accumulation is seen in the entire soil profile under NT but to a limited extent (0–1.07 $Mg\,ha^{-1}$). Limited increase in SOC at lower depths due to the adoption of NT could be due to slower incorporation of crop residue into the deeper soil layers, possibly increased soil compaction and stratification limiting root growth and the amount of added plant carbon inputs under NT (Six et al., 2004). Higher mean annual precipitation and lower initial SOC concentration were more beneficial for SOC sequestration under NT compared with CT, suggesting potential targeted areas where NT can lead to the best outcomes of SOC sequestration at regional scales (Sun et al., 2020).

SOC sequestration under NT management is affected by soil depth (Button et al., 2022; Powlson et al., 2014). NT could increase SOC content in the surface layers by decreasing SOC mineralization (Kan et al., 2022). However, at lower depths, most soils often reported neutral or even negative trends—which means decreased SOC content under NT (Angers and Eriksen-Hamel, 2008). Tillage mixes organic matter from the surface into plow depth, directly increasing SOC in deeper soil, especially when crop residues are returned. Furthermore, more roots grow deeper after tillage because it loosens soils and turns nutrients deeper, allowing fast water penetration into the subsoil and increasing crop productivity (Schneider et al., 2017), thereby increasing carbon input at depth (Zhang et al., 2023a,b).

A comparison of 69 sets of paired data for NT and CT, where the soil had been sampled to 40 cm depth, found that NT practices did not lead to an overall increase in SOC stock. While there were increased SOC stocks only in the surface 20 cm under NT, these gains were offset by smaller quantities in the 20–40 cm depth range (Luo et al., 2010). In another global meta-analysis (Govaerts et al., 2009), SOC stock under CA was greater than under CT practice in about half of the cases but not different in 40% of the cases. Similarly, in a meta-analysis of experiments in Mediterranean climatic conditions, it was found that NT led to small increases in SOC stock of about 0.3–0.4 Mg C $ha^{-1} year^{-1}$ (Agulilera et al., 2013), and NT led to no increase in SOC stock in 41 years in northern France (Dimassi et al., 2014).

7.2 The permanence of stocks due to NT

Long-term carbon (C) storage or sequestration in agricultural systems, particularly through the adoption of NT practices, is crucial for mitigating climate change and achieving sustainable agriculture. However, the extent to which C storage in NT systems is long-lasting or transient is still debated (Smith et al., 2020).

The rate of carbon sequestration under NT is an S-shaped phenomenon connected to adoption time, peaking 5–10 years after NT is started and reaching a constant state after 15–30 years (Alvarez, 2005; West and Post, 2002). It is unclear how long SOC gain will last under NT, and as time goes on, the rate of SOC gain slows as it gets closer to a new steady state (Janzen et al., 1997; Page et al., 2020). The long-term C storage potential of NT farming depends on various factors, including soil depth, management practices, climate conditions, and the duration of NT adoption. NT practices promote the accumulation of SOC, which contributes to C storage (Dalal et al., 2011; Poeplau and Don, 2015). The formation of stable soil aggregates and associations between organic carbon and soil minerals (mineral associated organic matter) further enhances the durability of C storage in NT systems (Paustian et al., 2016). However, the persistence of C storage may be influenced by factors such as land-use changes, crop rotation, and nutrient management (Wang et al., 2019, 2020a).

Carbon stored due to long-term NT farming practices has the potential to be long-lasting, especially when compared to CT systems. NT farming fosters the accumulation of SOM over time (Dalal et al., 2011). Crop residues, cover crops, and their roots contribute to the continuous input of organic material into the soil (Austin et al., 2017; Jayaraman et al., 2020). This organic matter contains C that can be stabilized and stored in the soil. As long as the inputs of organic matter are maintained, the C storage in the soil can persist for an extended period. NT farming minimizes soil disturbance, which helps to prevent the release of C from the soil, thus reducing the C loss from the NT system. By preserving crop residues and maintaining a cover on the soil surface, NT practices effectively reduce carbon loss.

Soil C sinks resulting from sequestration activities are not permanent and will continue as long as the soil carbon stock is increasing (Smith, 2005) and NT practice is maintained. If a land-management or land-use change is reversed or discontinued, the C accumulated will be lost, usually more rapidly than it was accumulated, indicating that it is not a permanent process (Arrouays et al., 2002; Smith et al., 1996). Changes in land use and management practices can lead to the loss of C from soils, which needs to be replenished or increased through continuous input of carbon. The benefit of NT in improving SOC is primarily restricted to the surface layer, which is potentially exposed, and therefore an increase in SOC could be short-lived if NT practice is discontinued. Nevertheless, a gain in SOC is likely to enhance soil quality and crop productivity.

7.3 Greenhouse gas (GHG) emission: Source or sink

NT is considered an important approach for mitigating GHG emissions by way of minimal soil disturbance. However, research conducted worldwide has yielded diverse findings regarding the effects of NT systems on GHG emissions. NT is generally considered a practice that helps reduce GHG emissions. However, there are situations where NT farming is the source of emissions, particularly for N_2O emissions.

A global meta-analysis based on 50 peer-reviewed publications indicated that NT was found to increase CO_2, N_2O, and CH_4 emissions by approximately 7.1%, 12.0%, and 20.8%, respectively, when compared to CT (Shakoor et al., 2021). Huang et al. (2018) conducted a meta-analysis on the effect of NT on GHG emissions and opined that the precise effects of NT on soil GHG emissions greatly vary (Van Kessel et al., 2013; Zhao et al., 2016). Some studies showed a substantial decrease in soil CO_2, CH_4, and N_2O emissions with NT (e.g., Drury et al., 2012; Lu et al., 2016), while others reported a significant increase or no difference (e.g., Oorts et al., 2007). For example, a long-term study in a Mediterranean dryland agroecosystem exhibited a 50% increase in CO_2 emission but no difference in N_2O emission in NT compared to CT (Plaza-Bonilla et al., 2014). Kim et al. (2016) reported that total CH_4 flux from NT rice fields decreased by 20–27% in the first and second years after NT imposition, but it was approximately 36% higher than that from CT fields by the fifth year. Zhang et al. (2016) also observed a substantial decline in CH_4 and CO_2 emissions from NT rice fields compared to CT fields. The GHG emissions vary across locations, cropping systems, and climates (Huang et al., 2018; Mondal et al., 2023).

Several hypotheses have been proposed to explain the different soil GHG emission responses due to NT. For example, a decrease in soil CO_2 emission in NT might be due to carbon protection associated with enhanced soil aggregation and decreased soil temperature (He et al., 2011; Lu et al., 2016), while an acceleration in soil CO_2 emission might be due to enhanced microbial activity caused by greater soil moisture availability (Plaza-Bonilla et al., 2014). Elevated CH_4 emission could be attributed to a greater abundance of organic substrates and coincident formation of anaerobic microsites (Zhang et al., 2015). Reduced CH_4 emission might be associated with improved soil porosity and gas diffusivity, facilitating the transport of CH_4 to methanotrophs (Ball et al., 1999). NT-induced increase in soil carbon and water content (and therefore higher water-filled pore space) could favor denitrification, ultimately resulting in elevated soil N_2O emission (Ma et al., 2013; Sheehy et al., 2013). In contrast, factors that may contribute to decreased N_2O emission include improved soil structure, lower soil temperature, a limited pool of decomposable organic carbon and low availability of mineral N due to a slow rate of soil organic matter (SOM) mineralization or rapid plant uptake (Chatskikh and Olesen, 2007; Grandy et al., 2006a,b). Appropriate N application rate, crop type, and water management are crucial to effectively mitigate GHG emissions without compromising crop yield in NT systems. By optimizing the combination of these management factors, farmers can maximize the benefits of NT, such as improved soil carbon sequestration and reduced GHG emissions, while ensuring crop productivity and overall sustainability in agricultural systems.

7.4 Sink for greenhouse gas emissions

Huang et al. (2018) conducted a comprehensive meta-analysis using data from 740 paired measurements in 90 peer-reviewed articles to evaluate the impact of NT on crop yield, greenhouse gas (GHG) emissions, and GWP in major cereal cropping systems which indicated that, compared to CT, NT led to reduced GHG emissions and increased crop yield in dry climates (Gangopadhyay et al., 2023; García-Marco et al., 2016) but showed no significant effect in humid climates (Van Kessel et al., 2013). Additionally, NT decreased GWP in sites on acidic soils. Across different cropping systems, NT significantly improved barley yield by 49%, particularly in dry climates.

It also reduced the GWP of rice fields by 22% due to a simultaneous reduction in CO_2 and CH_4 emissions (Huang et al., 2018). NT can be an effective climate-smart agriculture (CSA) management practice, as it has the potential to mitigate climate change while enhancing crop productivity. However, the net effect of NT relative to CT was found to be influenced by various environmental and agronomic factors, such as climatic conditions, tillage duration, soil texture, pH, and crop species. It is important to consider the site-specific conditions and optimize NT practices to maximize its benefits in different agricultural systems (Feng et al., 2020; Maucieri et al., 2021).

7.5 Climate change mitigation: Slicing the myth

Agriculture is the second largest source of GHGs with annual GHG emissions of 9.3 Gt CO_2 equivalent (Tubiello and Conchedda, 2021). The historical C loss from global cropping soils has not only contributed to increased GHG emissions and ongoing climate change but also threatens food production and worsened water quality, biodiversity, and many other ecosystem services (Sanderman et al., 2017). Whether agricultural technological innovations and conservation-based management shifts can reverse this trend remains highly uncertain (Cai et al., 2022).

It is widely acknowledged that long-term NT farming has the potential to aid in the mitigation of climate change. NT farming can offset atmospheric CO_2 levels and mitigate climate change by increasing C sequestration and decreasing GHG emissions (Ogle et al., 2019; Pacala and Socolow, 2004). However, several other studies have also shown that NT farming does not have much influence on climate change mitigation, and its benefits on mitigating GHG are overstated (Baker et al., 2007; Mondal et al., 2023; Powlson et al., 2014). NT farming over long periods has the potential to improve C sequestration, reduce GHG emissions, reduce erosion, enhance soil health, and may aid in the fight against climate change. The effectiveness of NT farming as a mitigation strategy is greatly influenced by several factors such as climate, soil type, management practices, and crop rotation (Klein et al., 2013). Integrative management practices that maximize C sequestration while minimizing potential trade-offs are essential to maximize the potential benefits of NT farming for the mitigation of climate change.

The extent of climate change mitigation due to NT is minimal and scientific studies have shown varying results. In summary, while NT can contribute to certain environmental benefits, it alone cannot be relied upon as a comprehensive solution to mitigate climate change. A combination of sustainable agricultural practices, along with broader changes in energy systems and consumption patterns, is necessary to address the challenges posed by climate change. Thus, NT may be promoted as a sustainable agricultural management practice rather than emphasizing its role as a potential climate change mitigation option (Powlson et al., 2014; VandenBygaart, 2016).

8. NT farming vs 4 per thousand (4PT) program: A reality or myth

SOC sequestration has been considered as a potential solution to mitigate climate change, to draw down atmospheric CO_2 and convert it into SOC, which is long-lived. As soil stores 2–3 times more C than the atmosphere, a relatively small increase in the stocks could play a significant role in mitigating GHG emissions. Increasing SOC has been proposed to mitigate climate change with the additional benefit of improving soil structure (Lal, 2004, 2016). The 4 per mille or 4 per 1000 launched during COP21 in December 2015 aspires to increase global SOM stocks by 0.4% per year as compensation for the global emissions of GHG by anthropogenic sources (Lal, 2015c, 2016). This 4 per mille blanket value cannot be applied everywhere as soils vary widely in terms of C storage, which includes deserts, peatlands, wetlands, mountains, etc. Soil types, aboveground vegetation, climate, and how quickly the soil biota uses the carbon collectively impact C storage/sequestration.

Conservation agriculture/NT increases SOC and may increase crop yield (Zhao et al., 2016) and reduce yield variability since the SOC accumulation not only sequestrates atmospheric CO_2 but also increases soil fertility and soil water holding capacity (Franzluebbers, 2002). Healthy soils are key to developing sustainable crop production systems that are resilient to the effects of climate change. NT farming may have some value as a climate change mitigation strategy in some situations, especially in soil erosion control but its impact varies greatly between sites (i.e., showing positive and negative C gains, positive and negative N_2O and CH_4 emissions), and the magnitude of the impact should not be overestimated. The impact of NT/CA on SOC in different locations and climatic conditions is presented in Table 4.

To offset or mitigate the stimulating effect of C emissions on global warming, NT practices are recommended to potentially increase C stock in agricultural soils (Luo et al., 2010). Globally, agricultural soils are estimated to potentially sequester 0.4–0.8 Pg C per year ($Pg = 10^{15}$ g of carbon) by adopting NT practices, which represent 33.3–100% of the total potential

Table 4 Effect of No tillage on carbon sequestration.

S. No.	Location	Climate	Duration of experiment (years)	Depth (cm)	No tillage treatments	Increased over conventional practice	Remarks	References
1	Kazakhstan	Hot summer continental	8	30	Conservation agriculture with cover crops	0.95% $year^{-1}$	CA allowed for the annual C sequestration of 300 kg ha^{-1} and for achieving the objective of the "4 per 1000" initiative under the current climatic conditions	Valkama et al. (2020)
2	Finland	Boreal	14	30	No-tillage	0.71 % $year^{-1}$	CA has the potential to significantly reduce the CO_2 concentration in the atmosphere related to human activities, achieving C sequestration rate of 0.4 % $year^{-1}$	
3	Italy	Humid subtropical	21	30	Vertical tillage at 15 cm/No tillage	0.1 % $year^{-1}$	CA and CA + CC prevented SOC decline and kept it on a slightly positive level, however, the objective of the "4 per 1000" initiative could not be accomplished	
4	Karnal, India	Subtropical monsoon climate	10	15	No tillage + residue (NT + R)	75.42 % $year^{-1}$	Reduced tillage with residue has a significant advantage over conventional tillage without residue	Singh et al. (2019)
5	Tripura, India	Hot and humid summer, and a mild and dry climate	4	30	No-till with 100% residue retention with mulch	450.2 kg ha^{-1} $year^{-1}$	No-till with 100% residue retention with mulch sequestration rate 450.2 kg ha^{-1} $year^{-1}$	Yadav et al. (2019)

Continued

Table 4 Effect of No tillage on carbon sequestration.—cont'd

S. No.	Location	Climate	Duration of experiment (years)	Depth (cm)	No tillage treatments	Increased over conventional practice	Remarks	References
6	Indo-Gangetic Plains	Tropical	Meta-analysis	15–30	Crop diversification	0.47 Mg C ha^{-1} $year^{-1}$ (193.75% $year^{-1}$)	Practices constituting CA cause some increase in SOC stock. CA practices will deliver only a small degree of climate change mitigation through soil carbon sequestration. Soil C sequestration can lead to an exaggerated view of the opportunities for climate change mitigation through CA or related practices with too little attention given to other approaches that may have greater potential and be more easily achieved in practice	Powlson et al. (2016)
7	Sub-Saharan Africa	Tropical	Meta-analysis	60	Reduced tillage (NT)	0.96 Mg C ha^{-1} $year^{-1}$ (42.86% $year^{-1}$)		
8	Worldwide	139 plots at 37 different sites	54	22	Cover crops	0.32 ± 0.08 Mg ha^{-1} $year^{-1}$	Compensate for 8% of the direct annual greenhouse gas emissions from agriculture	Poeplau and Don (2015)
9	Global	Data from 69 paired-experiments		40	No tillage	No significant difference between CT and NT	Adopting NT did not enhance soil total C stock down to 40 cm	Luo et al. (2010)

of C sequestration in world soils (Lal, 2004). However, NT has become a controversial contribution to a portfolio of options for mitigating climate change. Regardless, NT is still a prominent part of GHG mitigation discussions. The adoption of NT management on croplands has become a controversial approach for storing C in soil due to conflicting findings. Yet, NT is still promoted as a management practice to stabilize the global climate system from further change due to anthropogenic GHG emissions, including the 4 per mille initiative promoted through the UN Framework Convention on Climate Change. Two principal components of the "4 per Thousand" (4p1000) initiative (INRA et al., 2016), driven by sequestration of SOC, are mitigation of climate change and achievement of food security. The 4 per mille is an ambitious aspiration, however, for the first time, this initiative is setting a global goal to promote good soil management that can help mitigate climate change. Agricultural areas hold about 600 Gt of C in their top 1 m of soil. Increasing SOC stocks for all of these areas by 4 per mille (about 2.5 Pg C year^{-1}) can offset about 30% of global GHG emission. There is some scope globally to increase SOC. The challenge for farmers is to find a new generation of practices that will further improve soil conditions and deliver increased SOC. We need innovative technologies that can help agricultural practices to soak up more C in the soil, create soil security to achieve food security and mitigate climate change.

SOC storage can be higher under NT management in some soil types and climatic conditions even with redistribution of SOC and contribute to reducing net GHG emissions. However, uncertainties tend to be large, which may make this approach less attractive as a contributor to stabilizing the climate system compared to other options. Consequently, NT may be better viewed as a method for reducing soil erosion, adapting to climate change, and ensuring food security, while any increase in SOC storage is a co-benefit for society in terms of reducing GHG emissions.

SOM content in the root zone is an important determinant of soil quality and agronomic yield, and it has a vast hidden potential (FAO, 2017). NT enhanced macroaggregate stability and microaggregate formation and occlusion within macroaggregates that leads to greater protection of C from microbial decomposition. Reduced amounts of SOC deeper in soils may offset an increased amount of SOC near the soil surface with NT management. Therefore, we cannot conclude that soils managed with NT have more SOC than soils managed with CT for these soil types and climates. In general, NT reduces soil disturbance and increases aggregate stability, and enhances SOC in surface soils. However, there are constraints on the physical protection of SOC in colder environments due to soil freezing and thawing that disrupts soil aggregates, and in drier environments due to rewetting of soils that can accentuate SOC mineralization. Such processes may reduce the positive effect of NT on C storage in soils that occur in drier and cooler climates.

9. Modeling soil processes under NT farming

The complexity of soil and its importance to a variety of ecosystem services presents major challenges to the modeling of soil processes. Although major progress in soil models has occurred in the last decades, models of soil processes remain disjointed between disciplines or ecosystem services, with considerable uncertainty remaining in the quality of predictions and several challenges that remain yet to be addressed. These models consisted mostly of analytical solutions of partial differential equations for well-defined soils and porous media, numerical solutions of single partial differential equations, or conceptual models that were solved with analog or digital computers. Notwithstanding the considerable progress from early modeling efforts, fundamental soil processes and their interactions remain lacking and deficient, such that it hampers the prediction and quantification of key soil functions and services. Moreover, the integration and quantification of available knowledge on soil processes remain sketchy due to a lack of coherence and limited communication among research communities.

Soil organic C dynamics are typically conceptualized by multicompartment approaches, where each compartment is composed of organic matter with similar chemical composition or degradability (Bricklemyer et al., 2007). Nitrogen turnover is strongly related to C turnover, and both are often part of an overall model of C, N, and nutrient cycling in terrestrial ecosystems (Batlle-Aguilar et al., 2011). During the last 20 years, dynamic modeling is considered an effective approach to estimating SOC stock and loss from cropland under global warming scenarios. Several biogeochemical models have been designed and developed for this purpose. These models include CANDY (Franko, 1996), ROTHC (Jenkinson et al., 1987), CENTURY (Parton, 1996), DAISY (Mueller et al., 1996), DNDC (Li, 1996), and NCSOIL (Molina et al., 1983).

Lembaid et al. (2021) used Denitrification–Decomposition (DNDC) model to assess the impacts of alternative management practices on SOC stock under two tillage systems, in a semi-arid region of Morocco on local climate, soil and management conditions. Validated results showed a good agreement between model-simulated and observed values, based on the normalized root mean square error (RMSE) and Pearson correlation coefficient (r). This agreement indicates that the DNDC model could capture patterns and magnitude changes across the climate zone, soil type, and management practices. Under NT practice, the SOC content increased by 30% compared to CT. During the simulated period (9 years), the SOC sequestration potential was greatly improved with increased crop residue rate and application of farmyard manure. This increase ranged from 415 to 1787 $kg\,C\,ha^{-1}$ under NT practice, and from 150 to 818 $kg\,C\,ha^{-1}$ under CT practice. In contrast, increasing the fertilizer rate had a low to negligible effect on SOC stock. On the other hand, SOC sequestration potential declined by 107–335 $kg\,C\,ha^{-1}$ and by 177–354 $kg\,C\,ha^{-1}$ under NT and CT practices, respectively, when decreasing N fertilizer rates. An increase in crop residue rate returned at the surface after harvest and application of organic fertilizer, especially under NT practice, can substantially improve SOC stock in a semi-arid region.

Fiorini et al. (2020) used the DNDC model to stimulate and evaluate the cumulative flux of N_2O for the entire soybean and maize cropping season under different tillage systems (CT vs NT rye and vetch-15) and with different cover crops under NT. The DNDC model (version 95; http://www.dndc.sr.unh.edu), which simulates soil C and N cycling, is based on sub-models for soil and climate, crop growth, and organic matter decomposition (Li et al., 1994). Major soil processes for N_2O production such as nitrification and denitrification are included in other sub-models (Li et al., 2006). Soil temperature, water content, water flow, water uptake by plants, nitrification and denitrification are described and calculated on either a daily or hourly basis within the model, while DNDC outputs are provided daily (Congreves et al., 2016). The DNDC model was calibrated and validated and then used to estimate the annual cumulative N_2O emissions in different treatments. Overall, N_2O emissions in NT were 40–55% lower than in CT, for both in situ measurements and modeled simulations. These differences could be ascribed to the higher water filled pore space (WFPS) and soil nitrate availability in CT than in NT system. NT also increased SOC content (28% at 0–5 cm) and earthworm abundance (5 times) compared with CT.

ECOSSE was developed in 2007 to examine the impact of changes in land-use and climate on thin organo-mineral soils with <50 cm surface organic horizon, which tend to undergo more land-use changes than the deeper peat soils and are more accessible for agriculture (Smith et al., 2010). In particular, Smith et al. (2010) aimed to simulate how land-use and climate change affect

SOC and GHG emissions from organo-mineral, mineral, and peat soils. ECOSSE simulates the major below-ground C and N turnover in mineral and highly organic soils using concepts derived from two well-established models, RothC (Coleman and Jenkinson, 1996) and SUNDIAL (Bradbury et al., 1993). In ECOSSE, SOM is described containing five pools: active pools of humus (HUM), biomass (BIO), resistant plant material (RPM) and decomposable plant material (DPM), and an inert organic matter (IOM) pool.

Begum et al. (2022) used the modified process-based ecosystem model ECOSSE in the European project *Diverfarming* and evaluated it in four long-term experiments (>8 years) to assess the impact of crop diversification and agricultural management in SOC dynamics. ECOSSE was able to simulate SOC under dry conditions in Mediterranean regions in Spain and Italy. At the sites of Murcia, Spain, the addition of manure and cover crops in the diversified systems produced an increase of SOC in 9 years, when compared with the conventional management (16% measured increase, 32% simulated increase). The effect of tillage management on SOC stock in dry soil, in Foggia, Italy and Huesca, Spain, was also modeled, and a positive impact on SOC was predicted when NT was practiced. Finally, ECOSSE was used to understand the impact of diversifications in Boreal regions, Finland, where different proportions of legumes and grass were considered in a 4-year crop rotation compared with conventional cereal rotations. Experiments and modeling showed that the loss of SOC in CT practiced cereal was compensated when grass was introduced in the rotations. A good agreement (RMSE < 10%) and a nonsignificant bias were observed between the model and experimental data for all sites. Mitigation scenarios considered in the modeling analysis for the test site Huesca showed that integrated management of NT and manure is the best strategy to increase SOC, ~51% over 20 years, compared with the baseline scenario (current farmers' practice). This study demonstrated the ability of the modified version of ECOSSE to simulate SOC dynamics in diversified cropping systems, with various soil management practices and different climatic conditions.

Global ecosystem models (GCM) have a limited capacity to simulate the various effects of tillage. For the decomposition of SOM, they either assume a constant increase due to tillage or ignore the effects of tillage. Hence, they do not allow for analyzing the effects of tillage and cannot evaluate, for example, reduced tillage or NT practices as mitigation practices for climate change. Lutz et al. (2019) described the implementation of tillage-related practices in the global ecosystem model LPJmL. The extended model was evaluated against reported differences between CT and NT management on several soil properties. This model was recently extended to also cover the terrestrial N cycle, accounting for N dynamics in soils and plants and N limitation to plant growth (LPJmL5; von Bloh et al., 2018). The LPJmL model simulates the C, N, and water cycles by explicitly representing biophysical processes in plants (e.g., photosynthesis) and soils (e.g., mineralization of N and C).

Error in models and their inputs can be propagated to outputs. This is important for modeling soil processes because soil properties used as parameters commonly contain errors in the statistical sense, that is, variation. A model error can be assessed by validation procedures, but tests are needed for the propagation of (statistical) error from input to output. Input error interacts with non-linearity in the model such that it contributes to the mean of the output as well as its error. This can lead to seriously incorrect results if input error is ignored when a non-linear model is used.

10. Socio-economic factors impact NT farming

The techniques to apply the NT practice will differ in different situations and will vary with biophysical and system management conditions and farmer circumstances (Verhulst et al., 2010). This implies that the whole range of agricultural practices, including handling crop residues, sowing, and harvesting, water and nutrient management, and disease and pest control, need to be evolved and evaluated through adaptive research with active farmers' involvement on participatory mode. The key challenges relate to the development, standardization and adoption of farm machinery/implements for seeding amidst crop residues with minimum soil disturbance; developing crop harvesting and management systems with residues maintained on the soil surface; and developing and continuously improving site-specific soil, crop, nutrient and pest management strategies that will optimize the benefits of the NT/CA systems (Fig. 11).

11. Lessons learnt, future strategies and perspectives

No-till farming has now been practiced on different soil types, and climates, for over half-a-century in the United States and Australia, and over 25 years in many parts of the world. The original objectives of NT farming and crop residue retention were the control of soil erosion, and increasing infiltration and storage of water in the soil profile for crop production, mostly in rainfed/semi-arid regions. These objectives having been successfully achieved,

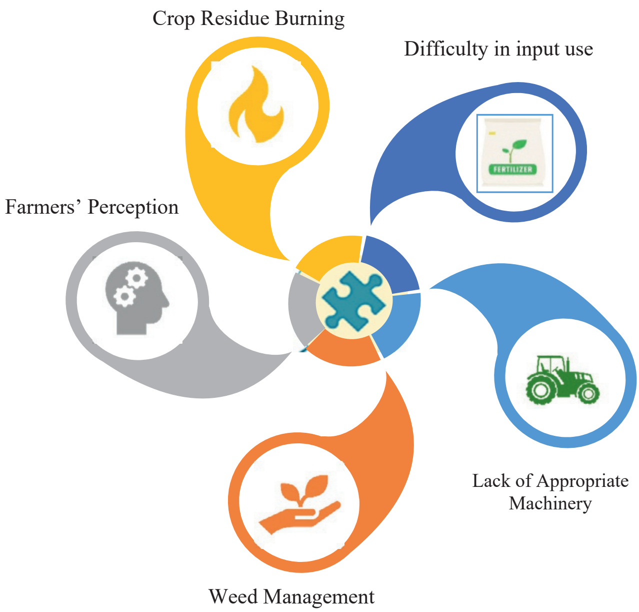

Fig. 11 Key challenges in adoption of no-till farming/conservation agriculture.

it was also found that minimum disturbance of the soil under NT reduces the aggregate breakdown and SOC entrapped within the aggregates decomposes slower than the easily accessible SOC by microorganisms and extracellular enzymes. Therefore, NT has now been considered as a GHG mitigation strategy due to its C sequestration potential although it has been found to be not effective on soil types and regions (Ogle et al., 2019). In addition, NT saves on fossil fuel and labor, thereby reducing the GHG emissions compared to CT. Since, on many soil types, NT improves soil aggregation, and hence increases soil air porosity, thereby reduces N_2O emissions and increases CH_4 uptake. However, the challenge remains to identify soil types and climatic regions where NT practice is effective in increasing C sequestration and CH_4 uptake, and reducing N_2O emissions, thereby it becomes an accepted practice for GHG mitigation (Locker et al., 2019; Wang et al., 2011).

Future strategies include the incorporation of NT practice in the holistic farming systems, including climate-smart conservation agriculture, regenerative agriculture, and even organic (natural) farming. Strategic tillage every 5–10 years may need to be incorporated to control herbicide-resistant weeds, minimize nutrient stratification and allow potentially deep-placement of key nutrients especially relatively immobile nutrients such as P. Incorporation of artificial intelligence in NT operations, remote-sensing technologies including unmanned vehicles and drones, and autonomous surface seeding, fertilization, integrated pest management, and harvesting operations will lead to reduced costs as well as other social, natural resource, and environmental benefits in future, and thus ensuring long-term soil and food security.

11.1 Future perspectives of NT/CA

- No-till farming or CA has been recognized globally as an alternative and sustainable solution to address various challenges such as soil erosion, soil moisture stress, crop residue burning, soil degradation, and environmental pollution (Jayaraman and Dalal, 2022; Jayaraman et al., 2020; Kassam et al., 2019).
- The adoption of NT practices combined with selected cover crops presents a promising strategy for achieving the ambitious goals of the EU Green Deal and Sustainable Development by FAO (Dynarski et al., 2020)
- This approach promotes CO_2 sequestration in agricultural soils, supports food production, and reduces fertilizer consumption by nutrient recycling through crop residue retention (Malecka et al., 2012). Both climate and soil type play crucial roles in influencing GHG emissions under NT practice. Consequently, farmers must adapt and adjust their NT practice under the prevailing climate and soil conditions.
- In response to the increasingly severe climate challenges in agriculture, it is imperative for global efforts to prioritize the development and adoption of NT practices that are tailored to local conditions. By implementing NT practices that are specifically adapted to the unique environmental and agronomic contexts of different regions, agriculture can become more resilient and sustainable in the face of climate change.
- Comprehensive and detailed studies are essential for understanding how different tillage practices alter soil characteristics and effectively enhance tillage systems while mitigating adverse impacts. Short-term implementation of NT/CA approaches has shown limitations in improving SOC and soil health, highlighting the need for longer-term research in a wider range of environmental conditions. Therefore, conducting long-term studies of over 10 years is necessary to establish significant and reliable differences between cropping systems and tillage types/management practices (balanced fertilization/crop residue retention) across different agro-ecologies are urgently required. Such research efforts require stable source of funding for research programs.

- Additional investigations could explore whether conducting deep soil sampling is necessary to fully characterize SOC accumulation under NT practices. If deep sampling proves to be essential, it may be necessary to reevaluate the results of previous studies that only utilized shallow sampling methods (Baker et al., 2007; Dalal et al., 2021). This would ensure accurate estimation and accounting of SOC stocks across the entire soil profile.
- Future research in NT practices can prioritize studying degraded landscapes as potential sites for long-term research collaborations among different institutions. This would allow for comprehensive investigations into the effectiveness of NT in rehabilitating and restoring degraded soils, leading to a better understanding of its applicability and potential benefits (carbon sequestration/carbon credits and trading) in challenging environmental conditions.
- The urgency for drawdown solutions is increasing, and climate experts must consider soil carbon sequestration through improved agricultural management practices. These practices not only promote carbon sequestration but also have additional benefits such as improving soil aggregate stability, water retention capacity, soil fertility, and ensuring food security. Therefore, prioritizing and implementing these practices can address multiple challenges simultaneously, making them highly valuable in sustainable agriculture and climate mitigation efforts.
- Promoting NT/CA requires efforts to change the socio-economic and political environment through improved research, education, and extension systems. The adoption of NT is a dynamic and iterative process that requires sustainable technological changes to emerge gradually. This highlights the importance of conducting research at various locations across the globe, that is, different soil types and environments to arrive at comprehensive conclusions regarding the successful expansion of NT/CA.
- The global community of NT/CA must persist in enhancing the quality and effectiveness of NT systems, while also conducting strategic research to enable the operation of biologically or organically based NT/CA systems that minimize the use of synthetic agrochemicals or avoid them altogether. Encouragingly, there are already promising indications that such NT systems are viable, albeit on limited scale, creating opportunities for farmers to embrace CA-based organic farming practices. This dual approach of improving NT systems and promoting organic farming within the NT framework can contribute to sustainable and eco-friendly

agricultural practices. Equally important is the provision of support and incentives for small landholder farmers as they transition from CT systems to NT/CA systems, enabling them to attain improved financial returns and incentivized environmental benefits.

12. Conclusions

Soil health has deteriorated due to faulty management practices, loss of SOC and biodiversity, mining of nutrients, accelerated erosion and land degradation. It is the need of the hour to protect soil resource, which is important for farming to provide food and nutritional security and ecosystem function/services. No-till farming has created a revolution in agriculture in terms of saving energy, cost of cultivation, improvement in SOC, sustaining soil health and crop production by reversing soil erosion/land degradation as compared to conventional farming system. Besides, NT farming may offset atmospheric CO_2 levels and mitigate climate change by increasing C sequestration and decreasing GHG emissions. Thus, NT/CA has now been considered as a GHG mitigation strategy due to its C sequestration potential although it has been found to be effective not on soil types and regions. Since, on many soil types, NT improves soil aggregation, and hence increases soil air porosity, thereby reduces N_2O emissions and increases CH_4 uptake. However, it is important to consider the underlying biophysical processes to understand its limitations to site-specific conditions and optimize NT/CA practices to maximize its benefits in different agricultural systems/agro-ecological regions.

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References

Abdalla, M., Osborne, B., Lanigan, G., Forristal, D., Williams, M., Smith, P., Jones, M.B., 2013. Conservation tillage systems: a review of its consequences for greenhouse gas emissions. Soil Use Manage. 29 (2), 199–209. https://doi.org/10.1111/sum.12030.

Abdalla, K., Chivenge, P., Ciais, P., Chaplot, V., 2015. No-tillage lessens soil CO_2 emissions the most under arid and sandy soil conditions: results from a meta-analysis. Biogeosci. 13 (12), 3619–3633.

Abdollahi, L., Munkholm, L.J., 2014. Tillage system and cover crop effects on soil quality: I. Chemical, mechanical, and biological properties. Soil Sci. Soc. Am. J. 78 (1), 262–270.

Acosta-Martinez, V., Zobeck, T.M., Gill, T.E., Kennedy, A.C., 2003. Enzyme activities and microbial community structure in semiarid agricultural soils. Biol. Fertil. Soils 38, 216–227.

Adimassu, Z., Alemu, G., Tamene, L., 2019. Effects of tillage and crop residue management on runoff, soil loss and crop yield in the humid highlands of Ethiopia. Agric. Sys 168, 11–18.

Agbede, T.M., 2010. Tillage and fertilizer effects on some soil properties, leaf nutrient concentrations, growth and sweet potato yield on an Alfisol in southwestern Nigeria. Soil Tillage Res. 110, 25–32.

Agulilera, E., Lassaletta, L., Gattinger, A., Gimeno, B., 2013. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a meta-analysis. Agric. Ecosyst. Environ. 168, 25–36.

Ahmad, S., Li, C., Dai, G., Zhan, M., Wang, J., Pan, S., Cao, C., 2009. Greenhouse gas emission from direct seeding paddy field under different rice tillage systems in Central China. Soil Tillage Res. 106, 54–61.

Akhtar, K., Wang, W., Ren, G., Khan, A., Feng, Y., Yang, G., 2018. Changes in soil enzymes, soil properties, and maize crop productivity under wheat straw mulching in Guanzhong, China. Soil Tillage Res. 182, 94–102. https://doi.org/10.1016/j.still.2018.05.007.

Alam, M.K., Bell, R.W., Salahin, N., Pathan, S., Mondol, A.T.M.A.I., Alam, M.J., Rashid, M.H., Paul, P.L.C., Hossain, M.I., Shil, N.C., 2018. Banding of fertilizer improves phosphorus acquisition and yield of zero tillage maize by concentrating phosphorus in surface soil. Sustainability 10, 3234. https://doi.org/10.3390/su10093234.

Al-Darby, A.M., Lowery, B., 1987. Seed zone soil temperature and early corn growth with three conservation tillage system. Soil Sci. Soc. Am. J. 51, 768–774.

Al-Kaisi, M.M., Yin, X.H., 2005. Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn–soybean rotations. J. Environ. Qual. 34, 437–445.

Alluvione, F., Halvorson, A.D., Del Grosso, S.J., 2009. Nitrogen, tillage and crop rotation effects on carbon dioxide and methane fluxes from irrigated cropping systems. J. Environ. Qual. 38, 2023–2033.

Almaraz, J.J., Zhou, X., Mabood, F., Madramootoo, C., Rochette, P., Ma, B.L., Smith, D.L., 2009. Greenhouse gas fluxes associated with soybean production under two tillage systems in southwestern Quebec. Soil Tillage Res. 104 (1), 134–139.

Alvarez, R., 2005. A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. Soil Use Manage. 21 (1), 38–52.

Alvarez, R., Steinbach, H.S., 2009. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the argentine pampas. Soil Tillage Res. 104, 1–15.

Alvarez, R., Alvarez, C.R., Lorenzo, G., 2001. Carbon dioxide fluxes following tillage from a mollisol in the argentine rolling pampa. Eur. J. Soil Biol. 37, 161–166.

Alvaro-Fuentes, J., Lopez, M.V., Gracia, R., Arrue, J.L., 2004. Effect of tillage on shortterm CO_2 emissions from a loam soil in semi-arid Arago ´ n (NE Spain). Opt. Mediterraneennes, Serie A 60, 51–54.

Alvaro-Fuentes, J., Cantero-Martinez, C., Lopez, M.V., Arrue, J.L., 2007a. Soil carbon dioxide fluxes following tillage in semiarid Mediterranean agro ecosystems. Soil Tillage Res. 96, 331–341.

Alvaro-Fuentes, J., López, M.V., Arrue, J.L., Cantero-Martinez, C., 2007b. Management effects on soil carbon dioxide fluxes under semiarid Mediterranean conditions. Soil Sci. Soc. Am. J. 72, 194–200.

Alvaro-Fuentes, J., Lopez, M.V., Cantero-Martinez, C., Arrue, J.L., 2008. Tillage effects on soil organic carbon fractions in Mediterranean dry land agro ecosystems. Soil Sci. Soc. Am. J. 72, 541–547.

Alvaro-Fuentes, J., Morell, F.J., Madejon, E., Lampurlanes, J., Arrue, J.L., Cantero-Martinez, C., 2013. Soil biochemical properties in a semiarid Mediterranean agro ecosystem as affected by long-term tillage and N fertilization. Soil Tillage Res. 129, 69–74.

Amami, R., Ibrahimi, K., Sher, F., Milham, P.J., Khriji, D., Annabi, H.A., Abrougui, K., Chehaibi, S., 2021. Effects of conservation and standard tillage on soil physico-chemical properties and overall quality in a semi-arid agrosystem. Soil Res. 60 (6), 485–496.

Amundson, R., Berhe, A.A., Hopmans, J.W., Olson, C., Sztein, A.E., Sparks, D.L., 2015. Soil and human security in the 21st century. Science 348, 1261071. https://doi.org/10.1126/science.1261071.

Andersson, J.A., D'Souza, S., 2014. From adoption claims to understanding farmers and contexts: a literature review of conservation agriculture (CA) adoption among smallholder farmers in southern Africa. Agric. Ecosyst. Environ. 187, 116–132.

Angers, D.A., Eriksen-Hamel, N.S., 2008. Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. Soil Sci. Soc. Am. J. 72, 1370–1374. https://doi.org/10.2136/sssaj2007.0342.

Araya, T., Cornelis, W.M., Nyssen, J., Govaerts, B., Bauer, H., Gebreegziabher, T., Oicha, T., Raes, D., Sayre, K.D., Haile, M., Deckers, J., 2011. Effects of conservation agriculture on runoff, soil loss and crop yield under rainfed conditions in Tigray, Northern Ethiopia. Soil Use Manag. 27 (3), 404–414.

Armand, R., Bockstaller, C., Auzet, A., Vandijk, P., 2009. Runoff generation related to intra-field soil surface characteristics variability application to conservation tillage context. Soil Tillage Res. 102, 27–37.

Arrouays, D., Balesdent, J., Germon, J.C., Jayet, P.A., Chenu, C., Houot, S., De Cara, S., Gabrielle, B., Guichard, L., Chartier, A., and Soussana, J.F., 2002. Mitigation of the greenhouse effect-Increasing carbon stocks in French agricultural soils? In: Scientific Assessment Unit for Expertise. Synthesis of an Assessment Report by the French Institute for Agricultural Research (INRA) on Request of the French Ministry for Ecology and Sustainable Development.

Arshad, M.A., Schnitzer, M., Angers, D.A., Ripmeester, J.A., 1990. Effects of till vs no-till on the quality of soil organic matter. Soil Biol. Biochem. 22, 595–599. https://doi.org/10.1016/0038-0717(90)90003-I.

Arvidsson, J., 2010. Direct drilling possible with a good preceding crop. Arvensis J. Swedish Rural Econ. Agric. Soc. 4, 9–10.

Atreya, K., Sharma, S., Bajracharya, R.M., Rajbhandari, N.P., 2006. Applications of reduced tillage in hills of Central Nepal. Soil Tillage Res. 88 (1–2), 16–29.

Austin, E.E., Wickings, K., McDaniel, M.D., Robertson, G.P., Grandy, A.S., 2017. Cover crop root contributions to soil carbon in a no-till corn bioenergy cropping system. Glob. Change Biol. Bioenergy. 9 (7), 1252–1263.

Aziz, I., Mahmood, T., Raut, Y., Lewis, W., Islam, R., Weil, R.R., 2009. Active organic matter as a simple measure of field soil quality. In: ASA International Meetings, Pittsburg, PA.

Aziz, I., Mahmood, T., Islam, K.R., 2013. Effect of long term no-till and conventional tillage practices on soil quality. Soil Tillage Res. 131, 28–35. https://doi.org/10.1016/j.still.2013.03.002.

Babujia, L.C., Hungria, M., Franchini, J.C., Brookes, P.C., 2010. Microbial biomass and activity at various soil depths in a Brazilian Oxisol after two decades of no- tillage and conventional tillage. Soil Biol. Biochem. 42, 2174–2181.

Baggs, E.M., Stevenson, M., Pihlatie, M., Regar, A., Cook, H., Cadish, G., 2003. Nitrous oxide emissions following application of residues and fertilizer under zero and conventional tillage. Plant Soil 254, 361–370.
Baggs, E.M., Chebii, J., Ndufa, J.K., 2006. A short-term investigation of trace gas emissions following tillage and no-tillage of agro forestry residues in western Kenya. Soil Tillage Res. 90, 69–76.
Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration—what do we really know? Agric. Ecosyst. Environ. 118 (1–4), 1–5.
Ball, B.C., 2013. Soil structure and greenhouse gas emissions: a synthesis of 20 years of experimentation. Eur. J. Soil Sci. 64 (3), 357–373.
Ball, B.C., Scott, A., Parker, J.P., 1999. Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil Tillage Res. 53, 29–39.
Balota, E.L., Colozzi Filho, A., Andrade, D.S., Dick, R.P., 2004. Long-term tillage and crop rotation effects on microbial biomass and C and N mineralization in a Brazilian Oxisol. Soil Tillage Res. 77, 137–145.
Banerjee, S., Kirkby, C.A., Schmutter, D., Bissett, A., Kirkegaard, J.A., Richardson, A.E., 2016. Network analysis reveals functional redundancy and keystone taxa amongst bacterial and fungal communities during organic matter decomposition in an arable soil. Soil Biol. Biochem. 97, 188–198. https://doi.org/10.1016/j.soilbio.2016.03.017.
Bansal, S., Yin, X., Sykes, V., Lee, J., Jagadamma, S., 2021. Soil aggregate-associated organic carbon and nitrogen response to long-term no-till crop rotation, cover crop, and manure application. Soil Sci. Soc. Am. J. 85 (6), 2169–2184. https://doi.org/10.1002/saj2.20329.
Barberi, P., Lo, C.B., 2001. Long-term tillage and crop rotation effects on weed seed bank size and composition. Weed Res. 41 (4), 325–340. https://doi.org/10.1046/j.1365-3180.2001.00241.x.
Barth, V.P., Reardon, C.L., Coffey, T., Klein, A.M., McFarland, C., Huggins, D.R., Sullivan, T.S., 2018. Stratification of soil chemical and microbial properties under no-till after liming. Appl. Soil Ecol. 130, 169–177. https://doi.org/10.1016/J.APSOIL.2018.06.001.
Bastida, R., Zsolnay, A., Hernandez, T., Garcia, C., 2008. Past, present and future of soil quality indices: a biological perspective. Geoderma 147, 159–171.
Batlle-Aguilar, J., Brovelli, A., Porporato, A., Barry, D.A., 2011. Modelling soil carbon and nitrogen cycles during land use change. Sust. Agri. 2, 499–527.
Bauer, P.J., Frederick, J.R., Novak, J.M., Hunt, P.G., 2006. Soil CO_2 flux from a Norfolk loamy sand after 25 years of conventional and conservation tillage. Soil Tillage Res. 90, 205–211.
Baumann, D.T., Bastiaans, L., Kropff, M.J., 2001. Effects of intercropping on growth and reproductive capacity of late-emerging Senecio vulgaris L., with special reference to competition for light. Ann. Bot. 87, 209–217.
Bavin, T., Griffis, T., Baker, J., Venterea, R., 2009. Impact of reduced tillage and cover cropping on the greenhouse gas budget of a maize/soybean rotation ecosystem. Agric. Ecosyst. Environ. 134, 234–242.
Bayer, C., Gomes, J., Vieira, F.C.B., Zanatta, J.A., de Cassia Piccolo, M., Dieckow, J., 2012. Methane emission from soil under long-term no-till cropping systems. Soil Tillage Res. 124, 1–7.
Begum, K., Zornoza, R., Farina, R., Lemola, R., Álvaro-Fuentes, J., Cerasuolo, M., 2022. Modeling soil carbon under diverse cropping systems and farming management in contrasting climatic regions in Europe. Front. Environ. Sci. 10, 139.
Bhattacharyya, R., Bhatia, A., Das, T.K., Lata, S., Kumar, A., Tomer, R., Singh, G., Kumar, S., Biswas, A.K., 2018. Aggregate-associated N and global warming potential

of conservation agriculture-based cropping of maize-wheat system in the north-western indo-Gangetic Plains. Soil Tillage Res. 182, 66–77.
Biswas, S., Das, T.K., Bhattacharyya, R., Das, S., Dwivedi, B.S., 2022. Biological soil quality and seasonal variation on enzyme activities under conservation agriculture-based rice–mustard system in the indo-Gangetic Plains of India. Soil Res. 60 (6), 470–484.
Blanco-Canqui, H., Wortmann, C.S., 2020. Does occasional tillage undo the ecosystem services gained with no-till? A review. Soil Tillage Res. 198, 104534. https://doi.org/10.1016/j.still.2019.104534.
Blouin, M., Hodson, M.E., Delgado, E.A., Baker, G., Brussaard, L., Butt, K.R., Brun, J.J., 2013. A review of earthworm impact on soil function and ecosystem services. Eur. J. Soil Sci. 64, 161–182.
Blum, W.E., 2013. Soil and land resources for agricultural production: general trends and future scenarios—a worldwide perspective. Int. Soil Water Cons. Res. 1 (3), 1–14.
Bradbury, N.J., Whitmore, A.P., Hart, P.B.S., Jenkinson, D.S., 1993. Modelling the fate of nitrogen in crop and soil in the years following application of 15N-Labelled fertilizer to winter wheat. J. Agric. Sci. 121, 363–379. https://doi.org/10.1017/S0021859600085567.
Bricklemyer, R.S., Miller, P.R., Turk, P.J., Paustian, K., Keck, T., Nielsen, G.A., 2007. Sensitivity of the century model to scale-related soil texture variability. Soil Sci. Soc. Am. J. 71, 784–792. https://doi.org/10.2136/sssaj2006.0168.
Buah, S., Polito, T.A., Killorn, R., 2000. No-tillage corn response to placement of fertilizer nitrogen, phosphorus, and potassium. Commun. Soil Sci. Plant Anal. 31, 3121–3133.
Buchholz, D., Palm, E., Thomas, G., Pfost, D.L., 1993. No-till planting systems. University of Missouri Extension.
Büchi, L., Amossé, C., Wendling, M., Sinaj, S., Charles, R., 2015. Introduction of no till in a long-term experiment on soil tillage in Switzerland. Aspec. Appl. Biol. 128, 49–55.
Büchi, L., Wendling, M., Amosse, C., Jeangros, B., Sinaj, S., Charles, R., 2017. Long- and short-term changes in crop yield and soil properties induced by the reduction of soil tillage in a long-term experiment in Switzerland. Soil Tillage Res. 174, 120–129. https://doi.org/10.1016/j.still.2017.07.002.
Buczko, U., Bens, O., Hangen, E., Brunotte, J., Hüttl, R.F., 2003. Infiltration and macroporosity of a silt loam under two contrasting tillage systems. Landbauforschung Völkenrode 53, 181–190.
Buhler, D.D., Mester, T.C., Kohler, K.A., 1996. The effect ofmaize residues and tillage on emergence of *Setaria faberi, Abutilon theophrasti, Amaranthus retroflexus*, and *Chenopodium album*. Weed Res. 36, 153–165.
Button, E.S., Pett-Ridge, J., Murphy, D.V., Kuzyakov, Y., Chadwick, D.R., Jones, D.L., 2022. Deep-C storage: biological, chemical and physical strategies to enhance carbon stocks in agricultural subsoils. Soil Biol. Biochem. 170, 108697.
Cai, A., Han, T., Ren, T., Sanderman, J., Rui, Y., Wang, B., Smith, P., Xu, M., 2022. Declines in soil carbon storage under no tillage can be alleviated in the long run. Geoderma 425, 116028.
Calegari, A., Hargrove, W.L., Rheinheimer, D.D.S., Ralisch, R., Tessier, D., de Tourdonnet, S., de Fatima Guimarães, M., 2008. Impact of long-term no-tillage and cropping system management on soil organic carbon in an Oxisol: a model for sustainability. Agron. J. 100 (4), 1013–1019.
Cardina, J., Herms, C.P., Doohan, D.J., 2002. Crop rotation and tillage system effects on weed seed banks. Weed Sci. 50, 448–460.
Carkovic, A.B., Pasten, P.A., Bonilla, C.A., 2015. Sediment composition for the assessment of water erosion and nonpoint source pollution in natural and fire-affected landscapes. Sci. Total Environ. 512, 26–35.

Carretta, L., Tarolli, P., Cardinali, A., Nasta, P., Romano, N., Masin, R., 2021. Evaluation of runoff and soil erosion under conventional tillage and no-till management: a case study in Northeast Italy. Catena 197, 104972.
Chakraborty, I., Maity, P., 2020. COVID-19 outbreak: migration, effects on society, global environment and prevention. Sci. Total Environ. 728, 138882.
Chatskikh, D., Olesen, J.E., 2007. Soil tillage enhanced CO_2 and N_2O emissions from loamy sand soil under spring barley. Soil Tillage Res. 97, 5–18.
Chauhan, B.S., Johnson, D.E., 2009. Influence of tillage systems on weed seedling emergence pattern in rainfed rice. Soil Tillage Res. 106, 15–21.
Chauhan, B.S., Johnson, D.E., 2010. Opportunities to improve cultural approaches to manage weeds in direct-seeded rice. In: 17th Australasian Weeds Conference. New Zealand Plant Protection Society, Christchurch, New Zealand, pp. 40–43.
Chauhan, B.S., Gill, G.S., Preston, C., 2006. Tillage system effects on weed ecology, herbicide activity and persistence: a review. Aust. J. Exp. Agric. 46 (12), 1557–1570.
Chee-Sanford, J.C., Williams, I.I., Davis, M.M., Sims, A.S.G.K., 2006. Do microorganisms influence seed-bank dynamics? Weed Sci. 54, 575–587.
Chen, H., Dai, Z., Veach, A.M., Zheng, J., Xu, J., Schadt, C.W., 2020. Global meta-analyses show that conservation tillage practices promote soil fungal and bacterial biomass. Agric. Ecosyst. Environ. 293, 106841. https://doi.org/10.1016/j.agee.2020.106841.
Chikowo, R., Mapfumo, P., Nyamugafata, P., Giller, K.E., 2004. Mineral N dynamics, leaching and nitrous oxide losses under maize following two-year improved fallows on a sandy loam soil in Zimbabwe. Plant Soil 259 (1–2), 315–330.
Choi, Y., Won, C., Shin, M., Park, W., Lee, S., Shin, Y., et al., 2016. Effect of no-till practice on runoff and nonpoint source pollution from an intensively farmed field in Korea. Irrigation Drain. 65, 175–181.
Choudhary, M.A., Akramkhanov, A., Saggar, S., 2002. Nitrous oxide emissions from a New Zealand cropped soil: tillage effects, spatial and seasonal variability. Agric. Ecosyst. Environ. 93, 33–43.
Choudhury, S.G., Srivastava, S., Singh, R., Chaudhari, S.K., Sharma, D.K., Singh, S.K., 2014. Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice-wheat cropping system under reclaimed sodic soil. Soil Tillage Res. 136, 76–83.
Clements, D.R., Beniote, D., Murphy, S.D., Swanton, C.J., 1996. Tillage effects of weed seed return and seed bank composition. Weed Sci. 44, 314–322.
Cochran, V., Elliott, L., Papendick, R., 1977. The production of phytotoxins from surface crop residues. Soil Sci. Soc. Am. J. 41, 903–908.
Coleman, K., Jenkinson, D.S., 1996. RothC-26.3-a model for the turnover of carbon in soil. In: Evaluation of Soil Organic Matter Models: Using Existing Long-Term Datasets. Springer, Berlin, Heidelberg, pp. 237–246.
Conen, F., Neftel, A., 2010. Nitrous oxide emissions from land-use and land-management change. In: Smith, K. (Ed.), Nitrous Oxide and Climate Change. Earth scan, London, UK, pp. 143–161.
Congreves, K.A., Grant, B.B., Dutta, B., Smith, W.N., Chantigny, M.H., Rochette, P., Desjardins, R.L., 2016. Predicting ammonia volatilization after field application of swine slurry: DNDC model development. Agric. Ecosyst. Environ. 219, 179–189.
Conyers, M., van der Rijt, V., Oates, A., Poile, G., Kirkegaard, J., Kirkby, C., 2019. The strategic use of minimum tillage within conservation agriculture in southern New South Wales, Australia. Soil Till. Res. 193, 17–26.
Cook, R.L., Trlica, A., 2016. Tillage and fertilizer effects on crop yield and soil properties over 45 years in southern Illinois. Agron. J. 108 (1), 415–426.
Cooper, H.V., Sjögersten, S., Lark, R.M., Girkin, N.T., Vane, C.H., Calonego, J.C., Rosolem, C., Mooney, S.J., 2021. Long-term zero-tillage enhances the protection of

soil carbon in tropical agriculture. Eur. J. Soil Sci. 72 (6), 2477–2492. https://doi.org/10.1111/ejss.13111.

Corbeels, M., Marchão, R.L., Neto, M.S., Ferreira, E.G., Madari, B.E., Scopel, E., Brito, O.R., 2016. Evidence of limited carbon sequestration in soils under no-till age systems in the Cerrado of Brazil. Sci. Rep. 6, 21450. https://doi.org/10.1038/srep21450.

Cowie, B.A., Hastie, M., Hunt, S.B., Asghar, M., Lack, D.W., 1996. Surface Soil Nutrient Distribution Following Minimum Tillage and Traditional Tillage Management. Available online: www.regional.org.au/au/asa/1996/contributed/160cowie.htm (accessed on 5 August 2023).

Coyle, C., Creamer, R.E., Schulte, R.P.O., O'Sullivan, L., Jordan, P., 2016. A functional land management conceptual framework under soil drainage and land use scenarios. Environ. Sci. Poll. 56, 39–48.

Curran, W.S., Liebl, R.A., Simmons, F.W., 1992. Effects of tillage and application method on clamazone, imazaquin and imazethapyr persistence. Weed Sci. 40, 482–489.

Curtin, D., Wang, H., Selles, F., McConkey, B.G., Campbell, C.A., 2000. Tillage effects on carbon fluxes in continuous wheat and fallow-wheat rotations. Soil Sci. Soc. Am. J. 64, 2080–2086.

Cussans, G.W., 1976. The influence of changing husbandry on weeds and weed control in arable crops. In: Proceedings of British Crop Protection Conference-Weeds, Brighton, UK, pp. 1001–1008.

Dalal, R.C., 1989. Long-term effects of no-tillage, crop residue and nitrogen application on properties of a vertisol. Soil Sci. Soc. Am. J. 53, 1511–1515.

Dalal, R., 2021. A half century of no-tillage practice for growing cereal crops in subtropical Australia. Agric. Sci. 32 (2), 65–69.

Dalal, R.C., Jayaraman, S., 2021. Soil organic carbon sequestration and turnover in semi-arid tropics and subtropics in relation to agronomic yield and sustainability. In: Lal (Ed.), Soil Organic Carbon and Feeding the Future. CRC Press, pp. 287–311.

Dalal, R.C., Allen, D.E., Wang, W.J., Reeves, S., Gibson, I., 2011. Organic carbon and total nitrogen stocks in a vertisol following 40 years of no-tillage, crop residue retention and nitrogen fertilisation. Soil Tillage Res. 112, 133–139. https://doi.org/10.1016/j.still.2010.12.006.

Dalal, R.C., Thornton, C.M., Allen, D.E., Owens, J.S., Kopittke, P.M., 2021. Long-term land use change in Australia from native forest decreases all fractions of soil organic carbon, including resistant organic carbon, for cropping but not sown pasture. Agric. Ecosyst. Environ. 311, 107326. https://doi.org/10.1016/j.agee.20 21.107326.

Dang, Y.P., Moody, P.W., Bell, M.J., Seymour, N.P., Dalal, R.C., Freebairn, D.M., Walker, S.R., 2015. Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: II. Implications for agronomy, soil and environment. Soil Tillage Res. 152, 115–123. https://doi.org/10.1016/j.still.2014.12.013.

Das, A., Lal, R., Patel, D.P., Idapuganti, R.G., Layek, J., Ngachan, S.V., Ghosh, P.K., Bordoloi, J., Kumar, M., 2014. Effects of tillage and biomass on soil quality and productivity of lowland rice cultivation by small scale farmers in north eastern India. Soil Tillage Res. 143, 50–58.

Datta, A., Nayak, D., Smith, J.U., Sharma, P.C., Jat, H.S., Yadav, A.K., Jat, M.L., 2022. Climate smart agricultural practices improve soil quality through organic carbon enrichment and lower greenhouse gas emissions in farms of bread bowl of India. Soil Res. 60 (6), 455–469.

De Bona, F.D., Bayer, C., Dieckow, J., Bergamaschi, H., 2008. Soil quality assessed by carbon management index in a subtropical Acrisol subjected to tillage systems and irrigation. Soil Res. 46 (5), 469. https://doi.org/10.1071/sr08018.

de Gennaro, L.A., de Souza, Z.M., Weill, M., de Souza, G.S., Alves, M.C., 2014. Soil physical and microbiological attributes cultivated with the common bean under two management systems. Rev. Cienc. Agron. 45, 641–649.

De Moraes Sá, J.C., Cerri, C.C., Dick, W.A., Lal, R., Filho, S.P.V., Piccolo, M.C., Feigl, B.E., 2001. Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian Oxisol. Soil Sci. Soc. Am. J. 65, 1486–1499.

de Torres, M.A.R.R., Carbonell-Bojollo, R.M., Moreno-García, M., Ordóñez-Fernández, R., Rodríguez-Lizana, A., 2021. Soil organic matter and nutrient improvement through cover crops in a Mediterranean olive orchard. Soil Tillage Res. 210, 104977.

de Vries, F.T., Griffiths, R.I., Bailey, M., Craig, H., Girlanda, M., Gweon, H.S., Hallin, S., Kaisermann, A., Keith, A.M., Kretzschmar, M., Lemanceau, P., Lumini, E., Mason, K.E., Oliver, A., Ostle, N., Prosser, J.I., Thion, C., Thomson, B., Bardgett, R.D., 2018. Soil bacterial networks are less stable under drought than fungal networks. Nat. Commun. 9. https://doi.org/10.1038/s41467-018-05516-7.

DeFelice, M.S., Carter, P.R., Mitchell, S.B., 2006. Influence of tillage on corn and soybean field in the United States and Canada. Crop Manag. 5 (1), 1–17. https://doi.org/10.1094/CM-2006-0626-01-RS.

Derksen, D., Blackshaw, R., Boyetchko, S., 1996. Sustainability, conservation tillage and weeds in Canada. Can. J. Plant Sci. 76, 651–659.

Derpsch, R., 1995. The "hill planting" of placing seeds in individual holes—as well as weed removal and harvesting by hand—permitted the use of mixed cultures, such as with beans, maize, and squash in the same garden or field. [from J. Harlan, 1995, The living fields, Cambridge Univ. Press. See also J. Diamond, 1997, Guns, Germs, and Steel, Norton & Co.].

Derpsch, R., Friedrich, T., Kassam, A., Hongwen, L., 2010. Current status of adoption of no-till farming in the world and some of its main benefits. Int. J. Agric. Biol. Engg. 3, 1–26.

Devine, S., Markewitz, D., Hendrix, P., Coleman, D., 2014. Soil aggregates and associated organic matter under conventional tillage, no-tillage, and forest succession after three decades. PLoS One 9, 1–12.

Dexter, A., 2004. Soil physical quality part III: unsaturated hydraulic conductivity and general conclusions about S-theory. Geoderma 120, 227–239.

Dignac, M.F., Derrien, D., Barré, P., Barot, S., Cécillon, L., Chenu, C., Chevallier, T., Freschet, G.T., Garnier, P., Guenet, B., Hedde, M., 2017. Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. Agron. Sustain. Dev. 37, 1–27.

Dimassi, B., Mary, B., Wylleman, R., Labreuche, J., Couture, D., Piraux, F., Cohan, J.P., 2014. Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. Agric. Ecosyst. Environ. 188, 134–146.

Doran, J., 1980. Microbial changes associated with residue management with reduced tillage. Soil Sci. Soc. Am. J. 44, 518–524.

Drury, C.F., Reynolds, W.D., Tan, C.S., Welacky, T.W., McLaughlin, N.B., 2006. Emissions of nitrous oxide and carbon dioxide: influence of tillage type and nitrogen placement depth. Soil Sci. Soc. Am. J. 70, 570–581.

Drury, C., Reynolds, W., Yang, X., McLaughlin, N., Welacky, T., Calder, W., Grant, C., 2012. Nitrogen source, application time, and tillage effects on soil nitrous oxide emissions and corn grain yields. Soil Sci. Soc. Am. J. 76, 1268–1279.

Du Preez, C.C., Steyn, J.T., Kotze, E., 2001. Long-term effects of wheat residue management on some fertility indicators of a semi-arid Plinthosol. Soil Tillage Res. 63, 25–33. https://doi.org/10.1016/S0167-1987(01)00227-6.

Duiker, S.W., Beegle, D.B., 2006. Soil fertility distributions in long-term no-till, chisel/disk and moldboardplow/disk systems. Soil Tillage Res. 88, 30–41. https://doi.org/10.1016/j.still.2005.04.004.

Dungait, J.A.J., Hopkins, D.W., Gregory, A.S., Whitmore, A.P., 2012. Soil organic matter turnover is governed by accessibility not recalcitrance. Glob. Chang. Biol. 18, 1781–1796. https://doi.org/10.1111/j.1365-2486.2012.02665.x.

Dynarski, K.A., Bossio, D.A., Scow, K.M., 2020. Dynamic stability of soil carbon: reassessing the "permanence" of soil carbon sequestration. Front. Environ. Sci. 8, 218. https://doi.org/10.3389/FENVS.2020.514701/BIBTEX.
Eltz, F.L.F., Peixoto, R.T.G., Jaster, F., 1989. Effects of soil tillage systems in an Oxisol physical and chemical characteristics. Rev. Bras. Ciênc. Solo 12, 259–267.
Endres, G.J., Ahrens, W.H., 1995. Fall-applied trifluralin granules in conservation-till spring wheat (*Triticum aestivum*). Weed Technol. 9, 703–709.
Escobar, L.F., Amado, T.J.C., Bayer, C., Chavez, L.F., Zanatta, A.J., Fiorin, J.E., 2010. Postharvest nitrous oxide emissions from a subtropical Oxisol as influenced by summer crop residues and their management. Rev. Bras. Ciênc. Solo 34, 435–442.
Eze, S., Dougill, A.J., Banwart, S.A., Hermans, T.D., Ligowe, I.S., Thierfelder, C., 2020. Impacts of conservation agriculture on soil structure and hydraulic properties of Malawian agricultural systems. Soil Tillage Res. 201, 104639.
FAO, 2008. Investing in Sustainable Agricultural Intensification. The Role of Conservation Agriculture. A Framework for Action. Food and Agriculture Organization of the United Nations, Rome.
FAO, 2017. Soil Organic Carbon: The Hidden Potential. Food and Agriculture Organization of the United Nations, Rome, Italy.
FAO, 2019. Soil Erosion: The Greatest Challenge to Sustainable Soil Management. FAO, Rome, Italy.
FAO, 2021. World Food and Agriculture - Statistical Yearbook 2021. FAO, Rome, Italy, https://doi.org/10.4060/cb4477en.
Farooq, M., Flower, K.C., Jabran, K., Wahid, A., Siddique, K.H.M., 2011. Crop yield and weed management in rainfed conservation agriculture. Soil Tillage Res. 117, 172–183.
Farooqi, Z.U.R., Sabir, M., Zeeshan, N., Naveed, K., Hussain, M.M., 2018. Enhancing carbon sequestration using organic amendments and agricultural practices. In: Carbon Capture, Utilization and Sequestration. 17.
Feng, Q., An, C., Chen, Z., Wang, Z., 2020. Can deep tillage enhance carbon sequestration in soils? A meta-analysis towards GHG mitigation and sustainable agricultural management. Renew. Sustain. Energy Rev. 133, 110293.
Fereres, E., Orgaz, F., Gonzalez-Dugo, V., Testi, L., Villalobos, F.J., 2014. Balancing crop yield and water productivity tradeoffs in herbaceous and woody crops. Funct. Plant Biol. 41, 1009–1018.
Fiorini, A., Maris, S.C., Abalos, D., Amaducci, S., Tabaglio, V., 2020. Combining no-till with rye (Secale cereale L.) cover crop mitigates nitrous oxide emissions without decreasing yield. Soil Tillage Res. 196, 104442.
Franke, A.C., McRoberts, N., Marshall, G., Malik, R.K., Singh, S., Nehra, A.S., 2001. The contribution of zero tillage for the management of *Phalaris minor* in the Indian rice-wheat system. In: Brighton Crop Protection Conference-Weeds 2, pp. 901–906.
Franko, U., 1996. Modelling approaches of soil organic matter turnover within the CANDY system. In: Evaluation of Soil Organic Matter Models: Using Existing Long-Term Datasets. Springer, Berlin, Heidelberg, pp. 247–254.
Franzluebbers, A.J., 2002. Soil organic matter stratification ratio as an indicator of soil quality. Soil Tillage Res. 66, 95–106.
Franzluebbers, A.J., Hons, F.M., 1996. Soil-profile distribution of primary and secondary plant available nutrients under conventional and no tillage. Soil Tillage Res. 39, 229–239. https://doi.org/10.1016/S0167-1987(96)01056-2.
Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1995. Tillage and crop effects on seasonal dynamics of soil CO_2 evolution, water content, temperature, and bulk density. Appl. Soil Ecol. 2, 95–109.
Freebairn, D.M., Loch, R.J., Cogle, A.L., 1993. Tillage methods and soil and water conservation in Australia. Soil Tillage Res. 27 (1–4), 303–325.

Gaiser, T., Stahr, K., Billen, N., Mohammad, M.A.R., 2008. Modeling carbon sequestration under zero tillage at the regional scale. I. The effect of soil erosion. Ecol. Model. 218, 110–120.
Galdos, M.V., Pires, L.F., Cooper, H.V., Calonego, J.C., Rosolem, C.A., Mooney, S.J., 2019. Assessing the long-term effects of zero-tillage on the macroporosity of Brazilian soils using X-ray computed tomography. Geoderma 337, 1126–1135.
Gangopadhyay, S., Chowdhuri, I., Das, N., Pal, S.C., Mandal, S., 2023. The effects of no-tillage and conventional tillage on greenhouse gas emissions from paddy fields with various rice varieties. Soil Tillage Res. 232, 105772.
Garbout, A., Munkholm, L.J., Hansen, S.B., 2013. Tillage effects on topsoil structural quality assessed using X-ray CT, soil cores and visual soil evaluation. Soil Tillage Res. 128, 104–109.
García-Marco, S., Abalos, D., Espejo, R., Vallejo, A., Mariscal-Sancho, I., 2016. No tillage and liming reduce greenhouse gas emissions from poorly drained agricultural soils in Mediterranean regions. Sci. Total Environ. 566, 512–520.
Gathala, M.K., Timsina, J., Islam, M.S., Rahman, M.M., Hossain, M.I., Harun-Ar-Rashid, M., Ghosh, A.K., Krupnik, T.J., Tiwari, T.P., McDonald, A., 2015. Conservation agriculture-based tillage and crop establishment options can maintain farmers' yields and increase profits in South Asia's rice–maize systems: evidence from Bangladesh. Field Crop Res 172, 85–98.
Ghaley, B., Porter, J., Sandhu, H.S., 2014. Soil-based ecosystem services: a synthesis of nutrient cycling and carbon sequestration assessment methods. Int. J. Biodivers. Sci. Ecosyst. Serv. Manag. 10, 177–186.
Ghaley, B.B., Rusu, T., Sandén, T., Spiegel, H., Menta, C., Visioli, G., O'Sullivan, L., Gattin, I.T., Delgado, A., Liebig, M.A., Vrebos, D., 2018. Assessment of benefits of conservation agriculture on soil functions in arable production Systems in Europe. Sustainability 10, 794. https://doi.org/10.3390/su10030794.
Ghidey, F., Alberts, E.E., 1998. Runoff and soil losses as affected by corn and soybean tillage systems. J. Soil Water Conserv. 53, 64–70.
Ghosh, B.N., Dogra, P., Sharma, N.K., Bhattacharyya, R., Mishra, P.K., 2015. Conservation agriculture impact for soil conservation in maize–wheat cropping system in the Indian sub-Himalayas. Inter. Soil Water Cons. Res. 3 (2), 112–118.
Ghoul, M., Mitri, S., 2016. The ecology and evolution of microbial competition. Trends Microbiol. 24, 833–845. https://doi.org/10.1016/j.tim.2016.06.011.
Giambalvo, D., Amato, G., Badagliacca, G., Ingraffia, R., Di Miceli, G., Frenda, A.S., Plaia, A., Venezia, G., Ruisi, P., 2018. Switching from conventional tillage to no-tillage: soil N availability, N uptake, 15N fertilizer recovery, and grain yield of durum wheat. Field Crop Res 218, 171–181. https://doi.org/10.1016/j.fcr.2018.01.18.
Gianfreda, L., Ruggiero, P., 2006. Enzyme activities in soil. In: Nannipieri, P., Smalla, K. (Eds.), Nucleic Acids and Proteins in Soil. Springer, Heidelberg, pp. 257–311.
Giller, K.E., Witter, E., Corbeels, M., Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crop Res 114, 23–34.
Goddard, T., Zoebisch, M., Gan, Y., Eillis, W., Watson, A., Sombatpanit, S., 2008. No-till farming systems. (Special Publication No. 3. by The World Association of Soil and Water Conservation (WASWC), Bangkok, p. 544).
Gómez-Muñoz, B., Jensen, L.S., Munkholm, L., Olesen, J.E., Møller Hansen, E., Bruun, S., 2021. Long-term effect of tillage and straw retention in conservation agriculture systems on soil carbon storage. Soil Sci. Soc. Am. J. 85 (5), 1465–1478. https://doi.org/10.1002/saj2.20312.
Gomiero, T., 2018. Large-scale biofuels production: a possible threat to soil conservation and environmental services. Appl. Soil Ecol. 123, 729–736. https://doi.org/10.1016/j.apsoil.2017.09.028.

Govaerts, B., Mezzalama, M., Unno, Y., Sayre, K.D., Luna-Guido, M., Vanherck, K., Dendooven, L., Deckers, J., 2007. Influence of tillage, residue management, and crop rotation on soil microbial biomass and catabolic diversity. Appl. Soil Ecol. 37, 18–30.

Govaerts, B., Verhulst, N., Castellanos-Navarrete, A., Sayre, K.D., Dixon, J., Dendooven, L., 2009. Conservation agriculture and soil carbon sequestration; between myth and farmer reality. Crit. Rev. Plant Sci. 28 (3), 97–122.

Grandy, A.S., Loecke, T.D., Parr, S., Robertson, G.P., 2006a. Long-term trends on nitrous oxide emissions, soil nitrogen, and crop yields of till and no-till cropping systems. J. Environ. Qual. 35, 1487–1495.

Grandy, A.S., Robertson, G.P., Thelen, K.D., 2006b. Do productivity and environmental trade-offs justify periodically cultivating no-till cropping systems? Agron. J. 98, 1377–1383.

Grzesiak, S., Grzesiak, M.T., Hura, T., Marcinska, I., Rzepka, A., 2012. Changes in root system structure, leaf matric potential and gas exchange of maize and triticale seedlings affected by soil compaction. Environ. Exp. Bot. 88, 2–10. https://doi.org/10.1016/j.envexpbot.2012.01.010.

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta-analysis. Glob. Chang. Biol. 8, 345–360. https://doi.org/10.1046/j.1354-1013.2002.00486.x.

Gupta, D.K., Bhatia, A., Das, T.K., Jain, N., Tomer, R., Malyan, S.K., Fagodiya, R.K., Dubey, R., Pathak, H., 2016. Mitigation of greenhouse gas emission from rice-wheat system of the indo-Gangetic plains: through tillage, irrigation and fertilizer management. Agric. Ecosyst. Environ. 230, 1–9.

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil Tillage Res. 82, 121–145. https://doi.org/10.1016/j.still.2004.08.009.

Hangen, E., Buczko, U., Bens, O., Brunotte, J., Hüttl, R.F., 2002. Infiltration patterns into two soils under conventional and conservation tillage: influence of the spatial distribution of plant root structures and soil animal activity. Soil Tillage Res. 63, 181–186.

Hao, X., Chang, C., Carefoot, J.M., Janzen, H.H., Ellert, B.H., 2001. Nitrous oxide emissions from an irrigated soil as affected by fertilizer and straw management. Nutr. Cycl. Agroecosyst. 60, 1–8.

Harrold, L.L., Edwards, W.M., 1974. No-tillage system reduces erosion from continuous corn watersheds. Trans. ASAE 17 (3), 414–416.

Hartzler, R.G., Owen, M.D., 1997. Weed Management in Conservation Tillage System. Iowa State University, Ames (Available online: www.extension.edu/Publications/PM1176. pdf).

Haruna, S.I., Anderson, S.H., 2023. Carbon storage and dynamics under sustainable soil management: lessons learned from long-term experiments. In: Jayaraman, S., et al. (Eds.), Sustainable Soil Management: Beyond Food Production, p. 50.

Hassan, W., Saba, T., Jabbi, F., Wang, B., Cai, A., Wu, J., 2022. Improved and sustainable agroecosystem, food security and environmental resilience through zero tillage with emphasis on soils of temperate and subtropical climate regions: a review. Inter. Soil Water Cons. Res. 10 (3), 530–545.

Hassen, T.B., El Bilali, H., 2022. Impacts of the Russia-Ukraine war on global food security: towards more sustainable and resilient food systems? Foods 11 (15), 2301.

Hati, K.M., Jha, P., Dalal, R.C., Jayaraman, S., Dang, Y.P., Kopittke, P.M., Kirchhof, G., Menzies, N.W., 2021. 50 years of continuous no-tillage, stubble retention and nitrogen fertilization enhanced macro-aggregate formation and stabilisation in a vertisol. Soil Tillage Res. 214, 105163.

He, J., Wang, Q., Li, H., Tullberg, J.N., McHugh, A.D., Bai, Y., Zhang, X., McLaughlin, N., Gao, H., 2009. Soil physical properties and infiltration after long-term no-tillage and ploughing on the Chinese loess plateau. New Zealand J. Crop Horti. Sci. 37 (3), 157–166.

He, J., Li, H., Rasaily, R., et al., 2011. Soil properties and crop yields after 11 years of no tillage farming in wheat–maize cropping system in North China plain. Soil Tillage Res. 113, 48–54.
He, C., Chen, Z., Qiu, K.Y., Chen, J.S., Bohoussou, Y.N.D., Dang, Y.P., Zhang, H.L., 2023. Effects of conservation agriculture on carbon mineralization: a global meta-analysis. Soil Tillage Res. 229, 105685.
Henry, B., Dalal, R.C., Harrison, M.T., Keating, B., 2023. Creating Frameworks to Foster Soil Carbon Sequestration. Burleigh Dodds Science Publishing, Cambridge, https://doi.org/10.19103/AS.2022.0106.25.
Hobbs, P.R., 2007. Conservation agriculture: what is it and why is it important for future sustainable food production? J. Agric. Sci. 145, 127–137. https://doi.org/10.1017/S002185960 7006892.
Hou, X.Q., Li, R., Jia, Z.K., Han, Q.F., 2013. Effect of rational tillage on soil aggregates, organic carbon and nitrogen in the loess plateau area of China. Pedosphere 23 (4), 542–548.
Hou, D., Bolan, N.S., Tsang, D.C., Kirkham, M.B., O'Connor, D., 2020. Sustainable soil use and management: an interdisciplinary and systematic approach. Sci. Total Environ. 729, 138961.
Houx III, J.H., Wiebold, W.J., Fritschi, F.B., 2011. Long-term tillage and crop rotation determines the mineral nutrient distributions of some elements in a Vertic Epiaqualf. Soil Tillage Res. 112 (1), 27–35.
Howard, D.D., Essington, E.E., Tyler, D.D., 1999. Vertical phosphorus and potassium stratification in no-till cotton soil. Agron. J. 91, 266–269.
Huang, Y., Ren, W., Wang, L., Hui, D., Grove, J.H., Yang, X., Tao, B., Goff, B., 2018. Greenhouse gas emissions and crop yield in no-tillage systems: a meta-analysis. Agric. Ecosyst. Environ. 268, 144–153.
Huang, X., Terrer, C., Dijkstra, F.A., Hungate, B.A., Zhang, W., van Groenigen, K.J., 2020. New soil carbon sequestration with nitrogen enrichment: a meta-analysis. Plant Soil 454, 299–310. https://doi.org/10.1007/s11104-020-04617-x.
Hubert, F., Hallaire, V., Sardini, P., Caner, L., Heddadj, D., 2007. Pore morphology changes under tillage and no-tillage practices. Geoderma 142, 226–236.
Hurni, H., Giger, M., Liniger, H., Studer, R.M., Messerli, P., Portner, B., Schwilch, G., Wolfgramm, B., Breu, T., 2015. Soils, agriculture and food security: the interplay between ecosystem functioning and human well-being. Curr. Opin. Environ. Sustain. 15, 25–34.
Hussain, S., Hussain, S., Guo, R., Sarwar, M., Ren, X., Krstic, D., Aslam, Z., Zulifqar, U., Rauf, A., Hano, C., El-Esawi, M.A., 2021. Carbon sequestration to avoid soil degradation: a review on the role of conservation tillage. Plan. Theory 10 (10), 2001.
Hydbom, S., Olsson, P.A., 2021. Biochemical signatures reveal positive effects of conservation tillage on arbuscular mycorrhizal fungi but not on saprotrophic fungi and bacteria. Appl. Soil Ecol. 157, 103765. https://doi.org/10.1016/j.apsoil.2020.103765.
INRA, IRD, CIRAD, 2016. "4 Per Thousand", Carbon Sequestration in Soils. Ministeré De L'Agriculture De L' Enseignement Superieur Et de la Recherche. Paris, France.
IPCC, 2022. Summary for policymakers. In: Shukla, P.R., Skea, J., Reisinger, A., Slade, R., Fradera, R., Pathak, M., Vyas, P. (Eds.), Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, https://doi.org/10.1017/9781009157926.00.
Iqbal, A., Khan, A., Green, S.J., Ali, I., He, L., Zeeshan, M., Luo, Y., Wu, X., Wei, S., Jiang, L., 2021. Long-term straw mulching in a no-till field improves soil functionality and rice yield by increasing soil enzymatic activity and chemical properties in paddy soils. J. Plant Nutr. Soil Sci. 184 (6), 622–634. https://doi.org/10.1002/jpln.202100089.

Islam, R., Reeder, R., 2014. No-till and conservation agriculture in the United States: An example from the David Brandt farm, Carroll, Ohio. Int. Soil Water Cons. Res. 2 (1), 97–107.

Ismail, L., Blevins, R.L., Frye, W.W., 1994. Long-term no-tillage effects on soil properties and continuous corn yields. Soil Sci. Soc. Am. J. 54, 193–198.

Jacinthe, P.A., Lal, R., 2005. Labile carbon and methane uptake as affected by tillage intensity in a Mollisol. Soil Tillage Res. 80 (1–2), 35–45.

Janzen, H.H., Campbell, C.A., Gregorich, E.G., Ellert, B.H., 1997. Soil carbon dynamics in Canadian agroecosystems. In: Lal, R., Kimble, J., Follett, R., Stewart, E.A. (Eds.), Soil Processes and the Carbon Cycle. CRC Press, Boca Raton, FL, pp. 57–80.

Jarecki, M.K., Lal, R., 2005. Soil organic carbon sequestration rates in two long-term no-till experiments in Ohio. Soil Sci. 170 (4), 280–291.

Jarecki, M.K., Lal, R., 2006. Compost and mulch effects on gaseous flux from an alfisol in Ohio. Soil Sci. 171, 249–260.

Jastrow, J.D., Amonette, J.E., Bailey, V.L., 2007. Mechanisms controlling soil carbon turnover and their potential application for enhancing carbon sequestration. Clim. Change 80, 5–23.

Jat, R.A., Wani, S.P., Sahrawat, K.L., 2012. Conservation agriculture in the semi-arid tropics: prospects and problems. Adv. Agron. 117, 191–273.

Jat, M.L., Chakraborty, D., Ladha, J.K., Rana, D.S., Gathala, M.K., McDonald, A., Gerard, B., 2020. Conservation agriculture for sustainable intensification in South Asia. Nat. Sustain. 3 (4), 336–343.

Jayaraman, S., Dalal, R.C., 2022. No-till farming: prospects, challenges–productivity, soil health, and ecosystem services. Soil Res. 60 (6), 435–441.

Jayaraman, S., Reeves, S., Wang, W., Heenan, M., Dalal, R.C., 2017. Impact of 47 years of no-tillage and stubble retention on soil aggregation and carbon distribution in a vertisol. Land Degrad. Develop. 28, 1589–1602. https://doi.org/10.1002/ldr.2689.

Jayaraman, S., Sinha, N.K., Dalal, R.C., Lal, R., Mohanty, M., Naorem, A.K., Hati, K.M., Chaudhary, R.S., Biswas, A.K., Patra, A.K., Chaudhari, S.K., 2020. No-till farming and conservation agriculture in South Asia–issues, challenges, prospects and benefits. Crit. Rev. Plant Sci. 39 (3), 236–279.

Jayaraman, S., Dang, Y.P., Naorem, A., Page, K.L., Dalal, R.C., 2021a. Conservation agriculture as a system to enhance ecosystem services. Agri 11 (8), 718.

Jayaraman, S., Sinha, N.K., Mohanty, M., Hati, K.M., Chaudhary, R.S., Shukla, A.K., Shirale, A.O., Neenu, S., Naorem, A.K., Rashmi, I., et al., 2021b. Conservation tillage, residue management, and crop rotation effects on soil major and micro-nutrients in semi-arid Vertisols of India. J. Soil Sci. Plant Nutr. 21, 523–535.

Jayaraman, S., Naorem, A.K., Lal, R., Dalal, R.C., Sinha, N.K., Patra, A.K., Chaudhari, S.K., 2021c. Disease-suppressive soils—beyond food production: a critical review. J. Soil Sci. Plant Nutr. 21, 1437–1465.

Jayaraman, S., Sahu, M., Sinha, N.K., Mohanty, M., Chaudhary, R.S., Yadav, B., Srivastava, L.K., Hati, K.M., Patra, A.K., Dalal, R.C., 2022. Conservation agricultural practices impact on soil organic carbon, soil aggregation and greenhouse gas emission in a vertisol. Agriculture 12 (7), 1004.

Jayaraman, S., Dalal, R.C., Lal, R., 2023a. Conclusions: perspectives on sustainable soil management. In: Jayamanan, S., et al. (Eds.), Sustainable Soil Management: Beyond Food Production. Cambridge Scholar Publishing, pp. 322–335.

Jayaraman, S., Dalal, R.C., Patra, A.K., Lal, R., 2023b. Sustainable soil management: challenges, prospects and benefits. In: Jayaraman, S., et al. (Eds.), Sustainable Soil Management: Beyond Food Production, pp. 1–30.

Jenkinson, D.S., Hart, P.B.S., Rayner, J.H., Parry, L.C., 1987. Modelling the turnover of organic matter in long-term experiments at Rothamsted. Intecol Bull. 15, 1–8.

Joergensen, R.G., Emmerling, C., 2006. Methods for evaluating human impact on soil microorganisms based on their activity, biomass, and diversity in agricultural soils. J. Plant Nutr. Soil Sci. 169, 295–309.
Johnson, A.M., Hoyt, G.D., 1999. Changes to the soil environment under conservation tillage. Hort Technology. 9, 380–393.
Johnson, M.D., Wyse, D.L., Lueschen, W.E., 1989. The influence of herbicide formulation on weed control in four tillage systems. Weed Sci. 37, 239–249.
Jones, C., Chen, C., Allison, E., Neill, K., 2007. Tillage effects on phosphorus availability. In: Proceedings of the Western Nutrient Management Conference, Salt Lake City, UT, USA, 8–9 March 2007; Vol 7, p. 13.
Kakaei, H., Nourmoradi, H., Bakhtiyari, S., Jalilian, M., Mirzaei, A., 2022. Effect of COVID-19 on food security, hunger, and food crisis. In: COVID-19 and the Sustainable Development Goals. Elsevier, pp. 3–29.
Kan, Z.R., Liu, W.X., Liu, W.S., Lal, R., Dang, Y.P., Zhao, X., Zhang, H.L., 2022. Mechanisms of soil organic carbon stability and its response to no-till: a global synthesis and perspective. Glob. Chang. Biol. 28 (3), 693–710.
Kandeler, E., Tscherko, D., Spiegel, H., 1999. Long-term monitoring of microbial biomass, N mineralisation and enzyme activities of a Chernozem under different tillage management. Biol. Fertil. Soils 28, 343–351.
Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.B., Eash, N.S., Jordahl, J.L., 1994. Long-term tillage effects on soil quality. Soil Tillage Res. 32 (4), 313–327. https://doi.org/10.1016/0167-1987(94)00427-g.
Kaschuk, G., Alberton, O., Hungria, M., 2010. Three decades of soil microbial biomass studies in Brazilian ecosystems: lessons learned about soil quality and indications for improving sustainability. Soil Biol. Biochem. 42, 1–13.
Kassam, A., Friedrich, T., Derpsch, R., 2019. Global spread of conservation agriculture. Intern. J. Environ. Stud. 76, 29–51. https://doi.org/10.1080/00207233.2018.1494927.
Ke, S., Yang, J., Xue, Y., Lv, W., Zheng, X., Pan, J., 2016. Influence of tillage practices and straw incorporation on soil aggregates, organic carbon, and crop yields in a rice-wheat rotation system. Sci. Rep. 6, 36602.
Kennedy, A., Kremer, R., 1996. Microorganisms in weed control strategies. J. Prod. Agric. 9, 480–485.
Kertész, A., Madarász, B., 2014. Conservation agriculture in Europe. Int. Soil Water Cons. Res. 2, 91–96.
Kessavalou, A., Doran, J.W., Mosier, A.R., Drijber, R.A., 1998. Greenhouse gas fluxes following tillage and wetting in a wheat—fallow cropping system. J. Environ. Qual. 27, 1105–1116.
Kettler, T.A., Lyon, D.J., Doran, J.W., Powers, W.L., Stroup, W.W., 2000. Soil quality assessment after weed-control tillage in a no-till wheat fallow cropping system. Soil Sci. Soc. Am. J. 64, 339–346.
Khaledian, M.R., Mailhol, J.C., Ruelle, P., Mubarak, I., Perret, S., 2010. The impacts of direct seeding into mulch on the energy balance of crop production system in the SE of France. Soil Tillage Res. 106, 218–226.
Khanh, T., Xuan, T., Chung, I., 2007. Rice allelopathy and the possibility for weed management. Ann. Appl. Biol. 151, 325–339.
Kienzler, K., Lamers, J., McDonald, A., Mirzabaev, A., Ibragimov, N., Egamberdiev, O., Ruzibaev, E., Akramkhanov, A., 2012. Conservation agriculture in Central Asia—what do we know and where do we go from here? Field Crop Res 132, 95–105.
Kim, S.Y., Gutierrez, J., Kim, P.J., 2016. Unexpected stimulation of CH_4 emissions under continuous no-tillage system in mono-rice paddy soils during cultivation. Geoderma 267, 34–40.
Kimber, R., 1973. Phytotoxicity from plant residues II. The effect of time of rotting of straw from some grasses and legumes on the growth of wheat seedlings. Plant Soil 38, 347–361.

Kisic, I., Basic, F., Nestroy, O., Mesic, M., Butorac, A., 2002. Soil erosion under different tillage methods in Central Croatia. Bodenkult.-Wien Mun. 53 (4), 199–206.
Kladivko, E.J., 2001. Tillage systems and soil ecology. Soil Tillage Res. 61, 61–76.
Klein, T., Holzkämper, A., Calanca, P., Fuhrer, J., 2013. Adaptation options under climate change for multifunctional agriculture: a simulation stud for western Switzerland. Reg. Environ. Change 14 (1), 167–184.
Koeller, K., 1989. Machinery requirements and possible energy savings by reduced tillage. In: Baumer, K., Ehlers, W. (Eds.), Agriculture. Energy Saving by Reduced Soil Tillage.
Kopittke, P.M., Menzies, N.W., Dalal, R.C., McKenna, B.A., Husted, S., Wang, P., Lombi, E., 2021. The role of soil in defining planetary boundaries and the safe operating space for humanity. Environ. Int. 146, 106245. https://doi.org/10.1016/j.envint.2020.106245.
Kumar, S., Kadono, A., Lal, R., Dick, W., 2012. Long-term tillage and crop rotations for 47–49 years influences hydrological properties of two soils in Ohio. Soil Sci. Soc. Am. J. 76 (6), 2195–2207.
Kurothe, R.S., Kumar, G., Singh, R., Singh, H.B., Tiwari, S.P., Vishwakarma, A.K., Sena, D.R., Pande, V.C., 2014. Effect of tillage and cropping systems on runoff, soil loss and crop yields under semiarid rainfed agriculture in India. Soil Tillage Res. 140, 126–134.
Kushwah, S.S., Damodar Reddy, D., Somasundaram, J., Srivastava, S., Khamparia, S.A., 2016. Crop residue retention and nutrient management practices on stratification of phosphorus and soil organic carbon under soybean-wheat system in vertisols of Central India. Commun. Soil Sci. Plant Anal. 47, 2387–2395. https://doi.org/10.1080/00103624.2016.1243703.
La Scala, N., Bolonhezi, D., Pereira, G.T., 2006. Short-term soil CO_2 emission after conventional and reduced tillage of a no-till sugar cane area in southern Brazil. Soil Tillage Res. 91, 244–248.
Laine, M., Rütting, T., Alakukku, L., Palojarvi, A., Strommer, R., 2017. Process rates of nitrogen cycle in uppermost topsoil after harvesting in no-tilled and ploughed agricultural clay soil. Nutr. Cycl. Agroecosyst. 110, 39–49. https://doi.org/10.1007/s10705-017-9825-2.
Lal, R., 1997. Soil degradative effects of slope length and tillage methods on Alfisols in western Nigeria. I. Runoff, erosion and crop response. Land Degrad. Dev. 8, 201–219.
Lal, R., 2003. Soil erosion and the global carbon budget. Environ. Int. 29, 437–450. https://doi.org/10.1016/S0160-4120(02)00192-7.
Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623–1627.
Lal, R., 2009. Soil degradation as a reason for inadequate human nutrition. Food Sec. 1, 45–57. https://doi.org/10.1007/s12571-009-0009-z.
Lal, R., 2015a. A system approach to conservation agriculture. J. Soil Water Conserv. 70, 82A–88A. https://doi.org/10.2489/jswc.70.4.82A.
Lal, R., 2015b. Sequestering carbon and increasing productivity by conservation agriculture. J. Soil Water Conserv. 70, 55A–62A. https://doi.org/10.2489/jswc.70.3.55A.
Lal, R., 2015c. Cover cropping and the "4 per thousand" proposal. J. Soil Water Conserv. 70, 141A. https://doi.org/10.2489/jswc.70.6.141A.
Lal, R., 2016. Beyond COP 21: potential and challenges of the "4 per thousand" initiative. J. Soil Water Conserv. 71, 20A–25A.
Lal, R., 2020a. The Soil-Human Health-Nexus. CRC Press, pp. 1–350.
Lal, R., 2020b. Managing soil quality for humanity and the planet. Front. Agric. Sci. Engg. 7 (3), 251–253. https://doi.org/10.15302/J-FASE-2020329.
Lal, R., 2023. Farming systems to return land for nature: It's all about soil health and re-carbonization of the terrestrial biosphere. Farming Syst. 1 (1), 100002.

Lal, R., Follett, R.F., Kimble, J.M., 2003. Achieving soil carbon sequestration in the United States: a challenge to policy makers. Soil Sci. 168, 827–845. https://doi.org/10.1097/01.ss.0000106407.84926.6b.

Lal, R., Reicosky, D.C., Hanson, J.D., 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil Tillage Res. 93, 1–12. https://doi.org/10.1016/j.still.2006.11.004.

Lal, R., Bouma, J., Brevik, E., Dawson, L., Field, D.J., Glaser, B., Hatano, R., et al., 2021. Soils and sustainable development goals of the United Nations: an International Union of Soil Sciences perspective. Geoderma Reg. 25, e00398.

Larsen, E., Grossman, J., Edgell, J., Hoyt, G., Osmond, D., Hu, S.J., 2014. Soil biological properties, soil losses and corn yield in long-term organic and conventional farming systems. Soil Tillage Res. 139, 37–45.

Lembaid, I., Moussadek, R., Mrabet, R., Douaik, A., Bouhaouss, A., 2021. Modeling the effects of farming management practices on soil organic carbon stock under two tillage practices in a semi-arid region, Morocco. Heliyon 7 (1), e05889.

Lemke, R.L., Izaurralde, R.C., Nyborg, M., Solberg, E.D., 1999. Tillage and N source influence soil-emitted nitrous oxide in the Alberta parkland region. Can. J. Soil Sci. 79, 15–24.

Li, C., 1996. The DNDC model. In: Evaluation of Soil Organic Matter Models: Using Existing Long-Term Datasets. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 263–267.

Li, C., Folkring, S., Harriss, R., 1994. Modelling carbon biogeochemistry in agricultural soils. Global Biogeochem. Cycles 8, 237–254.

Li, C., Salas, W., DeAngelo, B., Rose, S., 2006. Assessing alternatives for mitigating net greenhouse gas emissions and increasing yields from rice production in China over the next twenty years. J. Environ. Qual. 35 (4), 1554–1565.

Li, F., Chen, L., Zhang, J., Yin, J., Huang, S., 2017. Bacterial community structure after long-term organic and inorganic fertilization reveals important associations between soil nutrients and specific taxa involved in nutrient transformations. Front. Microbiol. 8, 187. https://doi.org/10.3389/fmicb.2017.00187.

Li, L., Guan, J., Chen, S., Zhang, X., 2022. Intermittent deep tillage on improving soil physical properties and crop performance in an intensive cropping system. Agron. 12, 688. https://doi.org/10.3390/agronomy12030688.

Liebenberg, A., van der Nest, J.R., Hardie, A.G., Labuschagne, J., Swanepoel, P.A., 2020. Extent of soil acidity in no-tillage Systems in the Western Cape Province of South Africa. Land 9, 361. https://doi.org/10.3390/land9100361.

Linn, D.M., Doran, J.W., 1984. Effect of water filled pore space on carbon dioxide and nitrous oxide production in tilled and non-tilled soils. Soil Sci. Soc. Am. J. 48, 1267–1272.

Littrell, J., Xu, S., Omondi, E., Saha, D., Lee, J., Jagadamma, S., 2021. Long-term organic management combined with conservation tillage enhanced soil organic carbon accumulation and aggregation. Soil Sci. Soc. Am. J. 85 (5), 1741–1754. https://doi.org/10.1002/saj2.20259.

Liu, X.J., Mosier, A.R., Halvorson, A.D., Zhang, F.S., 2006. The impact of nitrogen placement on NO, N_2O, CH_4 and CO_2 fluxes from non-tilled soil compared with conventional-tilled soil. Plant and Soil 280, 177–188.

Locker, C.R., Torkamani, S., Laurenzi, I.J., Jin, V.L., Schmer, M.R., Karlen, D.L., 2019. Field-to-farm gate greenhouse gas emissions from corn Stover production in the Midwestern U.S. J. Clean. Prod. 226, 1116–1127.

Lopez-Garrido, R., Diaz-Espejo, A., Madejon, E., Murillo, J.M., Moreno, F., 2009. Carbon losses by tillage under semi-arid mediterranean rainfed agriculture (SW Spain). Span. J. Agric. Res. 7, 706–716.

Lu, X., Lu, X., Tanveer, S., Wen, X., Liao, Y., 2016. Effects of tillage management on soil CO_2 emission and wheat yield under rain-fed conditions. Arid. Soil Res. Rehabil. 54, 38–48.
Luo, Z., Wang, E., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric. Ecosyst. Environ. 139 (1–2), 224–231.
Luo, Y., Iqbal, A., He, L., Zhao, Q., Wei, S., Ali, I., Ullah, S., Yan, B., Jiang, L., 2020. Long-term no-tillage and straw retention management enhances soil bacterial community diversity and soil properties in southern China. Agron. 10 (9), 1233.
Lutz, F., Herzfeld, T., Heinke, J., Rolinski, S., Schaphoff, S., Von Bloh, W., et al., 2019. Simulating the effect of tillage practices with the global ecosystem model LPJmL (version 5.0-tillage). Geosci. Model Dev. 12 (6), 2419–2440.
Ma, Y., Sun, L., Zhang, X., et al., 2013. Mitigation of nitrous oxide emissions from paddy soil under conventional and no-till practices using nitrification inhibitors during the winter wheat-growing season. Biol. Fertil. Soils 49, 627–635.
Macdonald, C.A., Delgado-Baquerizo, M., Reay, D.S., Hicks, L.C., Singh, B.K., 2018. Soil nutrients and soil carbon storage: modulators and mechanisms. Soil Carbon Storage Modul. Mech. Model. 2018, 167–205. https://doi.org/10.1016/B978-0-12-812766-7.00006-8.
MacKenzie, A.F., Fan, M.X., Cadrin, F., 1997. Nitrous oxide emission as affected by tillage, corn–soybean–alfalfa rotations and nitrogen fertilization. Can. J. Soil Sci. 77, 145–152.
Mahajan, G., Brar, L.S., Sardana, V., 1999. Effect of tillage and time of sowing on the efficacy of herbicides against *Phalaris minor* in wheat. In: The Proceeding of 17th Asian Pacific Weed Science Society Conference, Bangkok, Thailand, pp. 193–198.
Malecka, I., Blecharczyk, A., Sawinska, Z., Dobrzeniecki, T., 2012. The effect of various long-term tillage systems on soil properties and spring barley yield. Turk. J. Agric. Fores. 36 (2), 217–226.
Malo, D.D., Schumacher, T.E., Doolittle, J.J., 2005. Long-term cultivation impacts on selected soil properties in the northern Great Plains. Soil Tillage Res. 81 (2), 277–291.
Martens, D.A., 2001. Nitrogen cycling under different soil management systems. Adv. Agron. 70, 143–192.
Martínez, E., Fuentes, J.P., Silva, P., Valle, S., Acevedo, E., 2008. Soil physical properties and wheat root growth as affected by no tillage and conventional tillage systems in a Mediterranean environment of Chile. Soil Tillage Res. 99, 232–244.
Matula, S., 2003. The influence of tillage treatments on water infiltration into soil profile. Plant, Soil Environ. 49, 298–306.
Maucieri, C., Tolomio, M., McDaniel, M.D., Zhang, Y., Robatjazi, J., Borin, M., 2021. No-tillage effects on soil CH_4 fluxes: a meta-analysis. Soil Tillage Res. 212, 105042. https://doi.org/10.1016/j.still.2021.10504.
Mbuthia, L.W., Acosta-Martínez, V., DeBruyn, J., Schaeffer, S., Tyler, D., Odoi, E., Eash, N., 2015. Long term tillage, cover crop, and fertilization effects on microbial community structure, activity: implications for soil quality. Soil Biol. Biochem. 89, 24–34. https://doi.org/10.1016/j.soilbio.2015.06.016.
Medeiros, J.C., Da Silva, A.P., Cerri, C.E.P., Giarola, N.F.B., Figueiredo, G.C., Fracetto, F.J.C., 2011. Linking physical quality and CO_2 emissions under long-term no-till and conventional-till in a subtropical soil in Brazil. Plant Soil 338, 5–15.
Melero, S.L., Rosa, G., Jose, M.M., Fe, L.M., 2009. Conservation tillage: short- and long-term effects on soil carbon fractions and enzymatic activities under Mediterranean conditions. Soil Tillage Res. 104, 292–298.
Mengel, D., Nelson, D., Huber, D., 1982. Placement of nitrogen fertilizers for no-till and conventional till corn. Agron. J. 74 (3), 515–518.

Mohler, C.L., 1993. A model of the effects of tillage on emergence of weed seedlings. Ecol. Appl. 3, 53–73.

Molina, J.A.E., Clapp, C.E., Shaffer, M.J., Chichester, F.W., Larson, W.E., 1983. NCSOIL, a model of nitrogen and carbon transformations in soil: description, calibration, and behavior. Soil Sci. Soc. Am. J. 47 (1), 85–91.

Mondal, S., Chakraborty, D., Paul, R.K., Mondal, A., Ladha, J.K., 2023. No-till is more of sustaining the soil than a climate change mitigation option. Agric. Ecosyst. Environ. 352, 108498.

Montgomery, D.R., 2007. Soil erosion and agricultural sustainability. Proc. Natl. Acad. Sci. U. S. A. 104, 13268–13272. https://doi.org/10.1073/pnas.0611508104.

Moraes, M.T., Debiasi, H., Carlesso, R., Franchini, J.C., Silva, V.R., 2014. Critical limits of soil penetrations resistance in a Rhodic Eutrudox. R. Bras. Ci. Solo. 38, 288–298.

Mosier, A.R., Halvorson, A.D., Reule, C.A., Liu, X.J., 2006. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. J. Environ. Qual. 35, 1584–1598.

Moussadek, R., Mrabet, R., Dahan, R., Douaik, A., Verdoodt, A., Van Ranst, E., Corbeels, M., 2011. Effect of tillage practices on the soil carbon dioxide flux during fall and spring seasons in a Mediterranean vertisol. J. Soil Sci. Environ. Manage. 2, 362–369.

Moyer, J., Roman, E., Lindwall, C., Blackshaw, R., 1994. Weed management in conservation tillage systems for wheat production in north and South America. Crop Prot. 13, 243–259.

Mueller, T., Jensen, L.S., Hansen, S., Nielsen, N.E., 1996. Simulating soil carbon and nitrogen dynamics with the soil-plant-atmosphere system model DAISY. In: Evaluation of Soil Organic Matter Models: Using Existing Long-Term Datasets. Springer, Berlin Heidelberg, pp. 275–281.

Mueller, L., Kay, B.D., Deen, B., Hu, C., Zhang, Y., Wolff, M., Eulenstein, F., Schindler, U., 2009. Visual assessment of soil structure: part II. Implications of tillage, rotation and traffic on sites in Canada, China and Germany. Soil Till. Res. 103, 188–196.

Mummey, D.L., Smith, J.L., Bluhm, G., 1998. Assessment of alternative soil management practices on N_2O emissions from US agriculture. Agric. Ecosyst. Environ. 70, 79–87.

Murphy, S.D., Clements, D.R., Belaoussoff, S., Kevan, P.G., Swanton, C.J., 2006. Promotion of weed species diversity and reduction of weed seed banks with conservation tillage and crop rotation. Weed Sci. 54, 69–77.

Naorem, A., Jayaraman, S., Sinha, N.K., Mohanty, M., Chaudhary, R.S., Hati, K.M., Mandal, A., Thakur, J.K., Patra, A.K., Srinivasarao, C., Chaudhari, S.K., Dalal, R.C., Lal, R., 2023. Eight-year impacts of conservation agriculture on soil quality, carbon storage, and carbon emission footprint. Soil Tillage Res. 232, 105748.

Nelson, P.J., 1997. To hold the land: soil erosion, agricultural scientists, and the development of conservation tillage techniques. Agric. Hist. 71, 71–90.

O'Dell, D., Sauer, T.J., Hicks, B.B., Thierfelder, C., Lambert, D.M., Logan, J., et al., 2015. A short-term assessment of carbon dioxide fluxes under contrasting agricultural and soil management practices in Zimbabwe. J. Agric. Sci. 7 (3), 32–48.

Ofori, F., Stern, W.R., 1987. Cereal-legume intercropping systems. Adv. Agron. 41, 41–90.

Ogle, S., Breidt, F., Paustian, K., 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochem. 72 (1), 87–121.

Ogle, S.M., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F.J., McConkey, B., Regina, K., Vazquez-Amabile, G.G., 2019. Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. Sci. Rep. 9, 11665.

Omara, P., Aula, L., Eickhoff, E.M., Dhillon, J.S., Lynch, T., Wehmeyer, G.B., Raun, W., 2019. Influence of no-tillage on soil organic carbon, total soil nitrogen, and winter wheat (*Triticum aestivum* L.) grain yield. Inter. J. Agron. 2019, 1–9.

Omonode, R.A., Vyn, T.J., Smith, D.R., Hegymegi, P., Gál, A., 2007. Soil carbon dioxide and methane fluxes from long-term tillage systems in continuous corn and corn–soybean rotations. Soil Tillage Res. 95, 182–195.

Oorts, K., Merckx, R., Grehan, E., Labreuche, J., Nicolardot, B., 2007. Determinants of annual fluxes of CO_2 and N_2O in long-term no-tillage and conventional tillage systems in northern France. Soil Tillage Res. 95, 133–148.

Pacala, S., Socolow, R., 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science 305, 968–972. https://doi.org/10.1126/science.1100103.

Page, K.L., Dang, Y.P., Dalal, R.C., Reeves, S., Thomas, G., Wang, W., Thompson, J.P., 2019. Changes in soil water storage with no-tillage and crop residue retention on a vertisol: impact on productivity and profitability over a 50 year period. Soil Tillage Res. 194, 104319.

Page, K.L., Dalal, R.C., Reeves, S.H., Wang, W.J., Jayaraman, S., Dang, Y.P., 2020. Changes in soil organic carbon and nitrogen after 47 years with different tillage, stubble and fertiliser management in a vertisol of North-Eastern Australia. Soil Res. 58 (4), 346–355.

Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L., Grace, P., 2014. Conservation agriculture and ecosystem services: an overview. Agric. Ecosyst. Environ. 187, 87–105.

Parton, W.J., 1996. The CENTURY model. In: Evaluation of Soil Organic Matter Models: Using Existing Long-Term Datasets. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 283–291.

Pasricha, N.S., 2017. Conservation agriculture effects on dynamics of soil C and N under climate change scenario. Adv. Agron. 145, 269–312.

Passianoto, C.C., Ahrens, T., Feigle, B.J., Steudler, P.A., do Carmo, J.B., Melillo, J.M., 2003. Emissions of CO_2, N_2O and NO in conventional and no-till management practices in Rondonia, Brazil. Biol. Fertil. Soil. 38, 200–208.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532, 49–57.

Peigné, J., Ball, B.C., Roger-Estrade, J., David, C.J.S.U., 2007. Is conservation tillage suitable for organic farming? A review. Soil Use Manage. 23 (2), 129–144. https://doi.org/10.1111/j.1475-2743.2006.00082.x.

Peigné, J., Vian, J.-F., Cannavacciuolo, M., Lefevre, V., Gautronneau, Y., Boizard, H., 2013. Assessment of soil structure in the transition layer between topsoil and subsoil using the profil cultural method. Soil Tillage Res. 127, 13–25.

Phillips, E.R., Phillips, S.H., 1984. No- Tillage Agriculture, Principles and Practices. Van Nostrand Reinhold Co., New York, pp. 1–306.

Piron, D., Boizard, H., Heddadj, D., Pérès, G., Hallaire, V., Cluzeau, D., 2017. Indicators of earthworm bioturbation to improve visual assessment of soil structure. Soil Tillage Res. 173, 53–63.

Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015. Productivity limits and potentials of the principles of conservation agric. Nature 517, 365–368. https://doi.org/10.1038/nature13809.

Plaza-Bonilla, D., Álvaro-Fuentes, J., Arrúe, J., Cantero-Martínez, C., 2014. Tillage and nitrogen fertilization effects on nitrous oxide yield-scaled emissions in a rainfed Mediterranean area. Agric. Ecosyst. Environ. 189, 43–52.

Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops–a meta-analysis. Agric. Ecosyst. Environ. 200, 33–41.

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of notill agriculture for climate change mitigation. Natu. Cli. Chan. 4 (8), 678–683. https://doi.org/10.1038/nclimate2292.

Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jat, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agric. Ecosyst. Environ. 220, 164–174.

Prommer, J., Walker, T.W.N., Wanek, W., Braun, J., Zezula, D., Hu, Y., Hofhansl, F., Richter, A., 2020. Increased microbial growth, biomass, and turnover drive soil organic carbon accumulation at higher plant diversity. Glob. Chang. Biol. 26, 669–681. https://doi.org/10.1111/gcb.14777.

Quincke, J.A., Wortmann, C.S., Mamo, M., Franti, T., Drijber, R.A., 2007. Occasional tillage of no-till systems: carbon dioxide flux and changes in total and labile soil organic carbon. Agron. J. 99, 1158–1168.

Quinton, J.N., Catt, J.A., 2004. The effects of minimal tillage and contour cultivation on surface runoff, soil loss and crop yield in the long-term Woburn erosion reference experiment on sandy soil at Woburn, England. Soil Use Manage. 20 (3), 343–349.

Raczkowski, C.W., Reyes, M.R., Reddy, G.B., Busscher, W.J., Bauer, P.J., 2009. Comparison of conventional and no-tillage corn and soybean production on runoff and erosion in the southeastern US Piedmont. J. Soil Water Conserv. 64 (1), 53–60.

Rahman, M.H., Okubo, A., Sugiyama, S., Mayland, H.F., 2008. Physical, chemical and microbiological properties of an Andisol as related to land use and tillage practice. Soil Tillage Res. 101, 10–19.

Rao, K.K., Samal, S.K., Poonia, S.P., Kumar, R., Mishra, J.S., Bhatt, B.P., Dwivedi, S.K., Mondal, S., Choubey, A.K., Kumar, S., Kumar, M., 2022. Conservation agriculture improves soil physical properties and crop productivity: a long-term study in middle Indo-Gangetic Plains of India. Soil Res. 60 (6), 442–454.

Regina, K., Alakukku, L., 2010. Greenhouse gas fluxes in varying soils types under conventional and no tillage practices. Soil Tillage Res. 109, 144–152.

Reicosky, D.C., Reeves, D.W., Prior, S.A., Runion, G.B., Rogers, H.H., Raper, R.L., 1999. Effects of residue management and controlled traffic on carbon dioxide and water loss. Soil Tillage Res. 52, 153–165.

Reicosky, D.C., Gesch, R.W., Wagner, S.W., Gilbert, R.A., Wente, C.D., Morris, D.R., 2008. Tillage and wind effects on soil CO_2 concentrations in muck soils. Soil Tillage Res. 99, 221–231.

Richter, D.D., Hofmockel, M., Callaham, M.A., Powlson, D.S., Smith, P., 2007. Long-term soil experiments: keys to managing Earth's rapidly changing ecosystems. Soil Sci. Soc. Am. J. 71 (2), 266–279.

Rimal, B.K., Lal, R., 2009. Soil and carbon losses from five different land management areas under simulated rainfall. Soil Tillage Res. 106 (1), 62–70.

Rochette, P., 2008. No-till only increases N_2O emissions in poorly-aerated soils. Soil Till. Res. 101 (1–2), 97–100.

Romaneckas, K., Romaneckiene, R., Sarauskis, E., Pilipavicius, V., Sakalauskas, A., 2009. The effect of conservation primary and zero tillage on soil bulk density, water content, sugar beet growth and weed infestation. Agron. Res. 7, 73–86.

Roth, C.M., Shroyer, J.P., Paulsen, G.M., 2000. Allelopathy of sorghum on wheat under several tillage systems. Agron. J. 92, 855–860.

Ruis, S.J., Blanco-Canqui, H., Jasa, P.J., Jin, V.L., 2022. No-till farming and greenhouse gas fluxes: insights from literature and experimental data. Soil Tillage Res. 220, 105359.

Ryan, M.R., Mirsky, S.B., Mortensen, D.A., Teasdale, J.R., Curran, W.S., 2011. Potential synergistic effects of cereal rye biomass and soybean planting density on weed suppression. Weed Sci. 59, 238–246. https://doi.org/10.1614/WS-D-10-00110.1.

Sa, J.C.M., Tivet, F., Lal, R., Briedis, C., Hartman, D.C., dos Santos, J.Z., dos Santos, J.B., 2014. Long-term tillage systems impact on soil C dynamics, soil resilience and agronomic productivity of a Brazilian Oxisol. Soil Tillage Res. 136, 38–50.

Sainju, U.M., Jabro, J.D., Stevens, W.B., 2008. Soil carbon dioxide emission and carbon content as affected by irrigation, tillage, cropping system, and nitrogen fertilization. J. Environ. Qual. 37 (1), 98–106.
Salem, H.M., Constantino Valero, M.A.M., GilRodríguez, M., Silva, L.L., 2015. Short-term effects of four tillage practices on soil physical properties, soil water potential, and maize yield. Geoderma 237-238, 60–70.
Sanchez, M.L., Ozores, M.I., Colle, R., Lopez, M.J., De Torre, B., Garcia, M.A., Perez, I., 2002. Soil CO_2 fluxes in cereal land use of the Spanish plateau: influence of conventional and reduced tillage practices. Chemosphere 47, 837–844.
Sanchez, M.L., Ozores, M.I., Lopez, M.J., Colle, R., De Torre, B., Garcia, M.A., Perez, I., 2003. Soil CO_2 fluxes beneath barley on the central Spanish plateau. Agric. For. Meteorol. 118, 85–95.
Sanderman, J., Farquharson, R., Baldock, J., 2010. Soil Carbon Sequestration Potential: A Review for Australian Agriculture. Department of Climate Change and Energy Efficiency, Aust. Gover, p. 81.
Sanderman, J., Hengl, T., Fiske, G.J., 2017. Soil carbon debt of 12,000 years of human land use. Proc. Natl. Acad. Sci. U. S. A. 114 (36), 9575–9580.
Sapkota, T.B., Jat, M.L., Aryal, J.P., Jat, R.K., Khatri-Chhetri, A., 2015. Climate change adaptation, greenhouse gas mitigation and economic profitability of conservation agriculture: Some examples from cereal systems of indo-Gangetic Plains. J. Integr. Agric. 14 (8), 1524–1533.
Sarker, J.R., Singh, B.P., Cowie, A.L., Fang, Y., Collins, D., Badgery, W., Dalal, R.C., 2018. Agricultural management practices impacted carbon and nutrient concentrations in soil aggregates, with minimal influence on aggregate stability and total carbon and nutrient stocks in contrasting soils. Soil Tillage Res. 178, 209–223.
Schimel, J.P., Schaeffer, S.M., 2012. Microbial control over carbon cycling in soil. Front. Microbiol. 3, 348. https://doi.org/10.3389/fmicb.2012.00348.
Schjønning, P., Jensen, J.L., Bruun, S., Jensen, L.S., Christensen, B.T., Munkholm, L.J., Oelofse, M., Baby, S., Knudsen, L., 2018. The role of soil organic matter for maintaining crop yields: evidence for a renewed conceptual basis. Adv. Agron. 150, 35–79. https://doi.org/10.1016/bs.agron.2018.03.001.
Schneider, F., Don, A., Hennings, I., Schmittmann, O., Seidel, S.J., 2017. The effect of deep tillage on crop yield—what do we really know. Soil Tillage Res. 174, 193–204.
Schroder, J.L., Zhang, H., Girma, K., Raun, W.R., Penn, C.J., Payton, M.E., 2011. Soil acidification from Long-term use of nitrogen fertilizer on winter wheat. Soil Sci. Soc. Am. J. 75, 957–964.
Seitz, S., Goebes, P., Puerta, V.L., Pereira, E.I.P., Wittwer, R., Six, J., van Der Heijden, M.G., Scholten, T., 2019. Conservation tillage and organic farming reduce soil erosion. Agron. Sustain. Dev. 39, 1–10.
Selles, F., Kochhann, R.A., Denardin, J.E., Zenter, R.P., Faganello, A., 1997. Distribution of phosphorus fractions in a Brazilian Oxisol under different tillage systems. Soil Tillage Res. 44, 23–34. https://doi.org/10.1016/S0167-1987(97)00026-3.
Shakoor, A., Shahbaz, M., Farooq, T.H., Sahar, N.E., Shahzad, S.M., Altaf, M.M., Ashraf, M., 2021. A global meta-analysis of greenhouse gases emission and crop yield under no-tillage as compared to conventional tillage. Sci. Total Environ. 750, 142299.
Sheehy, J., Six, J., Alakukku, L., Regina, K., 2013. Fluxes of nitrous oxide in tilled and no-tilled boreal arable soils. Agric. Ecosyst. Environ. 164, 190–199.
Sheehy, J., Regina, K., Alakukku, L., Six, J., 2015. Impact of no-till and reduced tillage on aggregation and aggregate-associated carbon in northern European agroecosystems. Soil Tillage Res. 150, 107–113. https://doi.org/10.1016/j.still.2015.01.015.
Sheley, R., Manoukian, M., Marks, G., 2002. Preventing Noxious Weed Invasion Extension Bulletin. Montana State University.

Shrestha, A., Knezevic, S.Z., Roy, R.C., Ball-Coelho, B.R., Swanton, C.J., 2002. Effect of tillage, cover crop and crop rotation on the composition of weed flora in a sandy soil. Weed Res. 42, 76–87.

Singh, S., Kirkwood, R.C., Marshall, G., 1999. A review of the biology and control of Phalaris minor Retz. (*littleseed canarygrass*) in cereals. Crop Prot. 18, 1e16.

Singh, G., Bhattacharyya, R., Das, T.K., Sharma, A.R., Ghosh, A., Das, S., Jha, P., 2018. Crop rotation and residue management effects on soil enzyme activities, glomalin and aggregate stability under zero tillage in the indo-Gangetic Plains. Soil Tillage Res. 184, 291–300.

Singh, R., Rai, A.K., Kumari, R., Sharma, D.K., Kumar, S., Joshi, P.K., et al., 2019. Long term effect of crop residue and tillage on carbon sequestration, soil aggregation and crop productivity in rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system under partially reclaimed sodic soils. Ind. J. Agron. 64 (1), 11–17.

Sisti, C.P.J., Dos Santos, H.P., Kohhann, R., Alves, B.J.R., Urquiaga, S., Boddey, R.M., 2004. Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. Soil Tillage Res. 76, 39–58.

Six, J., Paustian, K., 2014. Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. Soil Biol. Biochem. 68, A4–A9.

Six, J., Feller, C., Denef, K., Ogle, S.M., de Morales Sa, J.C., Albrecht, A., 2002. Soil organic matter, biota and aggregation in temperate and tropical soils—effects of no-tillage. Agron. 22, 755–775.

Six, J., Ogle, S.M., Breidt, F.J., Conant, R.T., Mosier, A.R., Paustian, K., 2004. The potential to mitigate global warming with no-tillage management is only realized when practiced in the long term. Glob. Chang. Biol. 10, 155–160.

Six, J., Frey, S.D., Thiet, R.K., Batten, K.M., 2006. Bacterial and fungal contribution to carbon sequestration in agroecosystems. Soil Sci. Soc. Am. J. 70, 555–569.

Smith, P., 2005. An overview of the permanence of soil organic carbon stocks: influence of direct human-induced, indirect and natural effects. Eur. J. Soil Sci. 56 (5), 673–680.

Smith, P., Powlson, D.S., Glendining, M.J., 1996. Establishing a European soil organic matter network (SOMNET). In: Powlson, P.S., Smith, J.U. (Eds.), Evaluation of Soil Organic Matter Models Using Existing Long-Term Datasets. NATO ASI Series I, Volume 38. Springer-Verlag, Heidelberg, pp. 81–98.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., 2008. Agriculture. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, pp. 497–540.

Smith, J., Gottschalk, P., Bellarby, J., Chapman, S., Lilly, A., Towers, W., Bell, J., Coleman, K., Nayak, D., Richards, M., Hillier, J., 2010. Estimating changes in Scottish soil carbon stocks using ECOSSE. I. Model description and uncertainties. Climate Res. 45, 179–192.

Smith, P., Adams, J., Beerling, D.J., Beringer, T., Calvin, K.V., Fuss, S., Griscom, B., Hagemann, N., Kammann, C., Kraxner, F., Minx, J., Popp, A., Renforth, P., Vicente Vicente, J.L., 2020. Land-management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals. Annu. Rev. Env. Resour. 45, 345–386.

Snyder, C.S., Bruulsema, T.W., Jensen, T.L., Fixen, P.E., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric. Ecosyst. Environ. 133, 247–266.

Soane, B.D., Ball, B.C., Arvidsson, J., Basch, G., Moreno, F., Roger-Estrade, J., 2012. No-till in northern, western and South-Western Europe: a review of problems and opportunities for crop production and the environment. Soil Tillage Res. 118, 66–87. https://doi.org/10.1016/j.still.2011.10.015.

Sosnoskie, L.M., Herms, C.P., Cardina, J., 2006. Weed seed bank community composition in a 35-year-old tillage and rotation experiment. Weed Sci. 54, 263–273.

Srinivasarao, C., Kundu, R.S., Thakur, P.B., 2015. Conservation agriculture and soil carbon sequestration. In: Farooq, M., Siddique, K.H.M. (Eds.), Conservation Agriculture. Springer, Cham, pp. 479–524.

Stocking, M.A., 2003. Tropical soils and food security: the next 50 years. Science 302 (5649), 1356–1359.

Strudley, M.W., Green, T.R., Ascough II, J.C., 2008. Tillage effects on soil hydraulic properties in space and time: state of the science. Soil Tillage Res. 99, 4–48.

Sun, R., Li, W., Dong, W., Tian, Y., Hu, C., Liu, B., 2018. Tillage changes vertical distribution of soil bacterial and fungal communities. Front. Microbiol. 9, 1–13. https://doi.org/10.3389/fmicb.2018.00699.

Sun, W., Canadell, J.G., Yu, L., Yu, L., Zhang, W., Smith, P., Fischer, T., Huang, Y., 2020. Climate drives global soil carbon sequestration and crop yield changes under conservation agriculture. Glob. Chang. Biol. 26, 3325–3335. https://doi.org/10.1111/gcb.15001.

Swanton, C.J., Clements, D.R., Derksen, D.A., 1993. Weed succession under conservation tillage: a hierarchical framework for research and management. Weed Technol. 7, 286–297.

Swanton, C.J., Shrestha, A., Roy, R.C., Ball-Coelho, B.R., Knezevic, S.Z., 1999. Effect of tillage systems, N, and cover crop on the composition of weed flora. Weed Sci. 47, 454–461.

Swanton, C.J., Shrestha, A., Knezevic, S.Z., Ro, R.C., Ball-Coelho, B.R., 2000. Influence of tillage type on vertical weed seedbank distribution in a sandy soil. Can. J. Plant Sci. 80, 455–457.

Tang, H., Xiao, X., Li, C., Tang, W., Cheng, K., Pan, X., Wang, K., Li, W., 2019. Effects of different soil tillage systems on soil carbon management index under double-cropping rice field in southern China. Agron. J. 111 (1), 440–447.

Teasdale, J.R., Mohler, C.L., 1993. Light transmittance, soil- temperature, and soil-moisture under residue of hairy vetch and rye. Agron. J. 85, 673–680.

Tebrugge, F., 2001. No-tillage visions—protection of soil, water and climate and influence on management and farm income. In: Garcia-Torres, L., Benites, J., Martinez-Vilela, A. (Eds.), Conservation Agriculture—A Worldwide Challenge. World Congress on Conservation Agriculture (WCCA), vol. 1, pp. 303–316.

Tebrugge, F., Bohrnsen, A., 1997. Crop yields and economic aspects of no-tillage compared to plough tillage: results of long-term soil tillage field experiments in Germany. In: Tebrugge, F., Bohrnsen, A. (Eds.), Experience with the Applicability of No-tillage Crop Production in the West-European Countries. Proc. EC Workshop-IV, WissenschaftlicherFachverlag, 35428 Langg¨ons, German, pp. 25–43.

Thurston, H.D., Smith, M., Abawi, G., Kearl, S., 1994. Los sistemas de siembra con cobertura. CIFAD, Cornell Univ.

Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33, 141–163.

Tiwari, R., Naresh, R.K., Vivek, L.J., Purushattom, S., Singh, A., 2018. Soil aggregation and aggregate associated organic carbon fractions and microbial activities as affected by tillage and straw management in a rice-wheat rotation: a review. J. Pharm. Phytochem. 7, 2865–2893.

Todorovic, G.R., Rampazzo, N., Mentler, A., Blum, W.E.H., Eder, A., Strauss, P., 2014. Influence of soil tillage and erosion on the dispersion of glyphosate and aminomethylphosphonic acid in agricultural soils. Int. Agrophys. 28, 93–100.

Triplett, G.B., Dick, W.A., 2008. No-tillage crop production: a revolution in agriculture. Agron. J. 100, 153. https://doi.org/10.2134/agronj2007.0005c.

Tubiello, F.N., Conchedda, G., 2021. Emissions due to agriculture. Global, regional and country trends 1990–2018. FAO Food Nutr. Pap. 1 (18).
Urbanek, E., Horn, R., Smucker, A.J.M., 2014. Tensile and erosive strength of soil macro-aggregates from soils under different management system. J. Hydrol. Hydromech. 62, 324.
USDA 1975, Minimum tillage: A preliminary technology assessment, Office of Planning and Evaluation. USDA, 1985, Conservation tillage: Things to consider, Agriculture Information Bulletin No. 46.
Ussiri, D.A., Lal, R., Jarecki, M.K., 2009. Nitrous oxide and methane emissions from long-term tillage under a continuous corn cropping system in Ohio. Soil Tillage Res. 104, 247–255.
Valkama, E., Kunypiyaeva, G., Zhapayev, R., Karabayev, M., Zhusupbekov, E., Perego, A., et al., 2020. Can conservation agriculture increase soil carbon sequestration? A modelling approach. Geoder. 369, 114298.
van Capelle, C., Schrader, S., Brunotte, J., 2012. Tillage-induced changes in the functional diversity of soil biota e a review with a focus on German data. Eur. J. Soil Biol. 50, 165–181.
Van Gaelen, N., Verschoren, V., Clymans, W., Poesen, J., Govers, G., Vanderborght, J., Diels, J., 2014. Controls on dissolved organic carbon export through surface runoff from loamy agricultural soils. Geoderma 226–227, 387–396.
Van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M.A., Linquist, B., van Groenigen, K.J., 2013. Climate, duration, and N placement determine N_2O emissions in reduced tillage: a meta-analysis. Glob. Chang. Biol. 19 (1), 33–44.
VandenBygaart, A.J., 2016. Agriculture & Agri-Food Canada. Eastern Cereal and Oilseed Research Centre, Ottawa, ON, Canada. KW Neatby Building, 960 Carling Avenue,.
Varvel, G.E., 2006. Soil organic carbon changes in diversified rotations of the western corn belt. Soil Sci. Soc. Am. J. 70, 426–433.
Venterea, R.T., Stanenas, A.J., 2008. Profile analysis and modeling of reduced tillage effects on soil nitrous oxide flux. J. Environ. Qual. 37 (4), 1360–1367.
Venterea, R.T., Baker, J.M., Dolan, M.S., Spokas, K.A., 2006. Carbon and nitrogen storage are greater under biennial tillage in a Minnesota corn-soybean rotation. Soil Sci. Soc. Am. J. 70, 1752–1762. https://doi.org/10.2136/sssaj2006.001.
Verhulst, N., Govaerts, B., Verachtert, E., Castellanos-Navarrete, A., Mezzalama, M., Wall, P., Deckers, J., Sayre, K.D., 2010. Conservation agriculture, improving soil quality for sustainable production systems. In: Lai, R., Stewart, B.A. (Eds.), Advances in Soil Science: Food Security and Soil Quality. CRC Press, Boca Raton, Florida, pp. 137–208.
Vogel, E., Deumlich, D., Kaupenjohann, M., 2016. Bioenergy maize and soil erosion—risk assessment and erosion control concepts. Geoderma 261, 80–92.
von Bloh, W., Schaphoff, S., Müller, C., Rolinski, S., Waha, K., Zaehle, S., 2018. Implementing the nitrogen cycle into the dynamic global vegetation, hydrology, and crop growth model LPJmL (version 5.0). Geosci. Model Dev. 11, 2789–2812. https://doi.org/10.5194/gmd-11-2789-2018.
Wacker, T.S., Jensen, L.S., Thorup-Kristensen, K., 2022. Conservation agriculture affects soil organic matter distribution, microbial metabolic capacity and nitrogen turnover under Danish field conditions. Soil Tillage Res. 224, 105508. https://doi.org/10.1016/j.still.2022.105508.
Wang, W.J., Dalal, R.C., 2015. Nitrogen management is the key for low-emission wheat production in Australia: a life cycle perspective. Eur. J. Agron. 66, 74–82.
Wang, L.F., Shangguan, Z.P., 2015. Water-use efficiency of dry land wheat in response to mulching and tillage practices on the loess plateau. Sci. Rep. 5, 12225. https://doi.org/10.1038/srep12225.

Wang, W., Dalal, R.C., Reeves, S.H., Butterbach-Bahl, K., Kiese, R., 2011. Greenhouse gas fluxes from an Australian subtropical cropland under long-term contrasting management regimes. Glob. Chang. Biol. 17, 3089–3101.
Wang, Y., Li, C., Tu, C., Hoyt, G.D., DeForest, J.L., Hu, S., 2017. Long-term no-tillage and organic input management enhanced the diversity and stability of soil microbial community. Sci. Total Environ. 609, 341–347.
Wang, X., Qi, J.Y., Zhang, X.Z., Li, S.S., Virk, A.L., Zhao, X., Xiao, X.P., Zhang, H.L., 2019. Effects of tillage and residue management on soil aggregates and associated carbon storage in a double paddy cropping system. Soil Tillage Res. 194, 104339.
Wang, X., He, C., Liu, B., Zhao, X., Liu, Y., Wang, Q., Zhang, H., 2020a. Effects of residue returning on soil organic carbon storage and sequestration rate in China's croplands: a meta-analysis. Agronomy 10 (5), 691.
Wang, H., Wang, S., Yu, Q., Zhang, Y., Wang, R., Li, J., Wang, X., 2020b. No tillage increases soil organic carbon storage and decreases carbon dioxide emission in the crop residue-returned farming system. J. Environ. Manage. 261, 110261.
West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci. Soc. Am. J. 66, 1930–1946.
Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützow, M., Marin-Spiotta, E., van Wesemael, B., Rabot, E., Ließ, M., Garcia-Franco, N., Wollschlager, U., Vogel, H.J., Kogel-Knabner, I., 2019. Soil organic carbon storage as a key function of soils—a review of drivers and indicators at various scales. Geoderma 333, 149–162. https://doi.org/10.1016/j.geoderma.2018.07.026.
Williams, J.D., Gollany, H.T., Siemens, M.C., Wuest, S.B., Long, D.S., 2009. Comparison of runoff, soil erosion, and winter wheat yields from no-till and inversion tillage production systems in northeastern Oregon. J. Soil Water Conserv. 64 (1), 43–52.
Wright, A.L., Hons, F.M., Lemon, R.G., McFarland, M.L., Nichols, R.L., 2007. Stratification of nutrients in soil for different tillage regimes and cotton rotations. Soil Tillage Res. 96, 19–27.
Wrucke, M.A., Arnold, W.E., 1985. Weed species distribution as influenced by tillage and herbicides. Weed Sci. 33, 853–856.
Wu, H., Pratley, J., Lemerle, D., Haig, T., 2001. Allelopathy in wheat (Triticum aestivum). Ann. Appl. Biol. 139, 1–9.
Wulf, S., Lehmann, J., Zech, W., 1999. Emissions of nitrous oxide from runoff-irrigated and rainfed soils in semiarid north-West Kenya. Agric. Ecosyst. Environ. 72 (2), 201–205.
Yadav, G.S., Das, A., Lal, R., Babu, S., Datta, M., Meena, R.S., et al., 2019. Impact of no-till and mulching on soil carbon sequestration under rice (*Oryza sativa* L.)-rapeseed *(Brassica campestris* L. var. rapeseed) cropping system in hilly agro-ecosystem of the eastern Himalayas, India. Agric. Ecosys. Environ. 275, 81–92.
Yamulki, S., Jarvis, S., 2002. Short-term effects of tillage and compaction on nitrous oxide, nitric oxide, nitrogen dioxide, methane and carbon dioxide fluxes from grassland. Biol. Fertil. Soils 36, 224–231.
Yang, Q., Wang, X., Shen, Y., Philp, J., 2013. Functional diversity of soil microbial communities in response to tillage and crop residue retention in an eroded loess soil. Soil Sci. Plant Nutr. 59, 311–321.
Young, K.R., Cousens, R.D., 1999. Factors affecting the germination and emergence of wild radish (*Raphanus raphanistrum*) and their effect on management options. In: Bishop, A.C., et al. (Eds.), Proceedings of 12th Australian Weeds Conference. Tasmanian Weed Society, Tasmania, Hobart, pp. 179–182.
Zhang, J., Zhang, F., 2020. Highlights of the special issue on "health soil for healthy food". Front. Agric. Sci. Engg. 7 (3), 233–255. https://doi.org/10.15302/J-FASE-2020345.
Zhang, S.X., Chen, X.W., Jia, S.X., Liang, A.Z., Zhang, X.P., Yang, X.M., Wei, S.C., Sun, B.J., Huang, D.D., Zhou, G.Y., 2015. The potential mechanism of long-term

conservation tillage effects on maize yield in the black soil of Northeast China. Soil Tillage Res. 154, 84–90.
Zhang, C., Liu, G., Xue, S., Wang, G., 2016. Soil bacterial community dynamics reflect changes in plant community and soil properties during the secondary succession of abandoned farmland in the loess plateau. Soil Biol. Biochem. 97, 40–49. https://doi.org/10.1016/j.soilbio.2016.02.013.
Zhang, Y.J., Wang, R., Wang, S.L., Wang, H., Xu, Z.G., Jia, G.C., Wang, X.L., Li, J., 2017. Effects of different sub-soiling frequencies incorporated into no-tillage systems on soil properties and crop yield in dry land wheat-maize rotation system. Field Crop Res 209, 151–158.
Zhang, Y.J., Wang, S.L., Wang, H., Ning, F., Zhang, Y.H., Dong, Z.Y., Wen, P.F., Wang, R., Wang, X.L., Li, J., 2018. The effects of rotating conservation tillage with conventional tillage on soil properties and grain yields in winter wheat- spring maize rotations. Agric. For. Meteorol. 263, 107–117.
Zhang, Y., Dalal, R.C., Bhattacharyya, R., Meyer, G., Wang, P., Menzies, N.W., Kopittke, P.M., 2021a. Effect of long-term no-tillage and nitrogen fertilization on phosphorus distribution in bulk soil and aggregates of a vertisol. Soil Tillage Res. 205, 104760.
Zhang, Y., Tan, C., Wang, R., Li, J., Wang, X., 2021b. Conservation tillage rotation enhanced soil structure and soil nutrients in long-term dry land agriculture. Eur. J. Agron. 131, 126379. https://doi.org/10.1016/j.eja.2021.126379.
Zhang, X., Wang, J., Feng, X., Yang, H., Li, Y., Yakov, K., Liu, S., Li, F.M., 2023a. Effects of tillage on soil organic carbon and crop yield under straw return. Agric. Ecosyst. Environ. 354, 108543.
Zhang, Y., Bhattacharyya, R., Finn, D., Birt, H.W.G., Dennis, P.G., Dalal, R.C., Jones, A.R., Meyer, G., Dayananda, B., Wang, P., Menzies, N.W., Kopittke, P.M., 2023b. Soil carbon, nitrogen, and biotic properties after long-term no-till and nitrogen fertilization in a subtropical vertisol. Soil Tillage Res. 227, 105614. https://doi.org/10.1016/j.still.2022.105614.
Zhao, X., Liu, S.L., Pu, C., Zhang, X.Q., Xue, J.F., Zhang, R., Wang, Y.Q., Lal, R., Zhang, H.L., Chen, F., 2016. Methane and nitrous oxide emissions under no-till farming in China: a meta-analysis. Glob. Chang. Biol. 22, 1372–1384.
Zheng, H., Yang, T., Bao, Y., He, P., Yang, K., Mei, X., Wei, Z., Xu, Y., Shen, Q., Banerjee, S., 2021. Network analysis and subsequent culturing reveal keystone taxa involved in microbial litter decomposition dynamics. Soil Biol. Biochem. 157, 108230. https://doi.org/10.1016/j.soilbio.2021.108230.
Zheng, F., Wu, X., Zhang, M., Liu, X., Song, X., Lu, J., Wang, B., Jan van Groenigen, K., Li, S., 2022. Linking soil microbial community traits and organic carbon accumulation rate under long-term conservation tillage practices. Soil Tillage Res. 220, 105360. https://doi.org/10.1016/j.still.2022.105360.
Zhou, H., Gao, Y., Jia, X., Wang, M., Ding, J., Cheng, L., 2020. Network analysis reveals the strengthening of microbial interaction in biological soil crust development in the Mu Us Sandy Land. Soil Biol. Biochem. 144. https://doi.org/10.1016/j.soilbio.2020.107782.
Zhou, Z., Li, Z., Chen, K., Chen, Z., Zeng, X., Yu, H., Guo, S., Shangguan, Y., Chen, Q., Fan, H., Tu, S., He, M., Qin, Y., 2021. Changes in soil physicochemical properties and bacterial communities at different soil depths after long-term straw mulching under a no-till syst. Soil 7 (2), 595–609. https://doi.org/10.5194/soil-7-595-2021.
Zobeck, T.M., Halvorson, A.D., Wienhold, B., Acosta-Martinez, V., Karlen, D.L., 2008. Comparison of two soil quality indexes to evaluate cropping systems in northern Colorado. J. Soil Water Conserv. 63 (5), 329–338. https://doi.org/10.2489/jswc.63.5.32.
Zuber, S.M., Villamil, M.B., 2016. Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities. Soil Biol. Biochem. 97, 176–187. https://doi.org/10.1016/j.soilbio.2016.03.11.

Zulu, S.G., Magwaza, L.S., Motsa, N.M., Sithole, N.J., Ncama, K., 2022. Long-term no-till conservation agriculture and nitrogen fertilization on soil micronutrients in a semi-arid region of South Africa. Agron. 12, 1411. https://doi.org/10.3390/agronomy12061411.

Further reading

Hurisso, T., Norton, U., Norton, J.B., Odhiambo, J., Del Gross, S.J., Hergert, G.W., Lyon, D.J., 2016. Dryland soil greenhouse gases and yield-scaled emissions in no-till and organic winter wheat–fallow systems. Soil Sci. Soc. Am. J. 80, 178–192.
Lal, R., 2021a. Feeding the world and returning half of the agricultural land back to nature. J. Soil Water Conserv. 76 (4), 75A–78A.
Lal, R., 2021b. Negative emission farming. J. Soil Water Conserv. 76 (3), 61A–64A.
Li, C., Frolking, S., Crocker, G.J., Grace, P.R., Klír, J., Körchens, M., d Poulton, P.R., 1997. Simulating trends in soil organic carbon in long-term experiments using the DNDC model. Geoderma 81 (1–2), 45–60.
Parton, W.J., Hartman, M., Ojima, D., Schimel, D., 1998. DAYCENT and its land surface submodel: description and testing. Global Planet. Change 19, 35–48.
Reicosky, D.C., Kemper, W.D., Langdale, G.W., Douglas Jr., C.L., Rasmussen, P.E., 1995. Soil organic matter changes resulting from tillage and biomass production. J. Soil Water Conserv. 50, 253–261.
Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A., Folke, C., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347 (6223), 1259855.
Vereecken, H., Schnepf, A., Hopmans, J.W., Javaux, M., Or, D., Roose, T., Vanderborght, J., Young, M.H., Amelung, W., Aitkenhead, M., Allison, S.D., 2016. Modeling soil processes: review, key challenges, and new perspectives. Vadose Zone J. 15 (5).