Science of the Total Environment 826 (2022) 154161

Contents lists available at ScienceDirect

Science of the Total Environment

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

Review

Soil carbon sequestration, greenhouse gas emissions, and water pollution under different tillage practices

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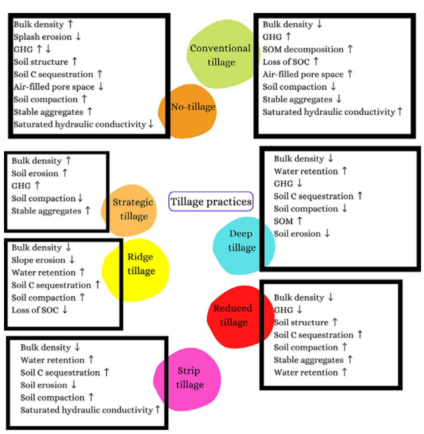
HIGHLIGHTS

- The soil carbon sequestration (SCS) potential of no-tillage (NT) is high compared to other tillage practices.
- Tillage induced erosion, which decrease the magnitude of SCS, is less for NT and RT compared to CT.
- The Eutrophication potential of no-tillage (NT) is higher than CT due to higher NO_3^- leaching.
- The SCS potential of NT is counteracted by substantial nitrous oxide (N_2O) emission.
- Nitrification inhibitors coupled with tillage practices can offset both N_2O emission and nitrate pollution.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 October 2021
Received in revised form 20 February 2022
Accepted 23 February 2022
Available online 26 February 2022

Editor: Fang Wang

Keywords:
Soil carbon sequestration
Soil health
Tillage systems
Eutrophication
Soi organic matter

ABSTRACT

Tillage is a common agricultural practice and a critical component of agricultural systems that is frequently employed worldwide in croplands to reduce climatic and soil restrictions while also sustaining various ecosystem services. Tillage can affect a variety of soil-mediated processes, e.g., soil carbon sequestration (SCS) or depletion, greenhouse gas (GHG) (CO_2, CH_4, and N_2O) emission, and water pollution. Several tillage practices are in vogue globally, and they exhibit varied impacts on these processes. Hence, there is a dire need to synthesize, collate and comprehensively present these interlinked phenomena to facilitate future researches. This study deals with the co-benefits and trade-offs produced by several tillage practices on SCS and related soil properties, GHG emissions, and water quality. We hypothesized that improved tillage practices could enable agriculture to contribute to SCS and mitigate GHG emissions and leaching of nutrients and pesticides. Based on our current understanding, we conclude that sustainable soil moisture level and soil temperature management is crucial under different tillage practices to offset leaching loss of soil stored nutrients/pesticides, GHG emissions and ensuring SCS. For instance, higher carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions from conventional tillage (CT) and no-tillage (NT) could be attributed to the fluctuations in soil

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http://dx.doi.org/10.1016/j.scitotenv.2022.154161

Water pollution
Environmental health
GHG emissions

moisture and temperature regimes. In addition, NT may enhance nitrate (NO_3^-) leaching over CT because of improved soil structure, infiltration capacity, and greater water flux, however, suggesting that the eutrophication potential of NT is high. Our study indicates that the evaluation of the eutrophication potential of different tillage practices is still overlooked. Our study suggests that improving tillage practices in terms of mitigation of N_2O emission and preventing NO_3^- pollution may be sustainable if nitrification inhibitors are applied.

Contents

1. Introduction

Current agricultural practices have enormously intensified by focusing on enhanced crop yield to feed the world's billions of people (Busari et al., 2015). Such agricultural intensification is putting additional pressure on natural resources, altering natural processes, and causing deterioration of soil, air, and water quality, by soil organic carbon (SOC) depletion, elevated greenhouse gases (GHG) emissions, soil nutrient imbalances, and fertilizer and pesticide export to aquatic bodies (Poeplau et al., 2011; Vitousek et al., 2009; Subbarao et al., 2017; Sun et al., 2012). However, these impacts and their magnitude vary with site properties and farming practices (van Groenigen et al., 2011). Tillage is an agricultural management practice that affects soil, air, and water quality by affecting the exchange (sequestration of losses) of greenhouse gases to air and the loss of nutrients and pesticides to water. For example, tillage generally decreases soil carbon sequestration (SCS) due to the decomposition of elevated carbon (C). In addition, it may enhance/lessen carbon dioxide (CO_2) emissions (Ogle et al., 2005; Abdalla et al., 2016). Reduced or no-tillage is thus seen as a means to enhance soil carbon sequestration (SCS) and reduce CO_2 emissions. This effect may be counteracted by enhanced emissions of nitrous oxide (N_2O), as shown in several studies (Mei et al., 2018; Van Kessel et al., 2013), while tillage also affects methane (CH_4) emissions. Reduced tillage is also advocated as a means to reduce losses of accumulated pesticides and nutrients through leaching or surface-runoff (Fig. 1) (Luo et al., 2010; Endale et al., 2017; Nevins et al., 2020; Aziz et al., 2013; Zhou et al., 2017; Raiesi and Kabiri, 2016; Haddaway et al., 2017; Çelik et al., 2021; Shang et al., 2021; Elias et al., 2018). Numerous statements regarding the adverse impacts of tillage and thus the benefits of no-tillage or reduced tillage, however, overlook differences among tillage practices, soil properties, and associated land management. Different kinds of tillage practices are being practiced globally (Porwollik et al., 2019), for instance, conventional tillage (CT), no-tillage (NT), reduced tillage (RT) or minimum tillage (MT), ridge Tillage (RiT), strip-tillage (ST), strategic tillage (STR), and deep tillage (DT) (see Section 2.1 for background on these practices). The effects of these tillage types on soil-air-water quality may vary across regions and are dependent on specific soil-climatic-management conditions (Chatterjee and Lal, 2009; Feng et al., 2020; Hussein et al., 2019; Powlson et al., 2014).

Below we summarize some impacts of soil-climatic-management conditions on (i) SCS and CO_2 exchange, (ii) N_2O and CH_4 emissions that may counteract the CO_2 emissions, and (iii) nutrient (N and P) and pesticide leaching and runoff.

Soil carbon sequestration (SCS) induced by agricultural practices is an important solution for decreasing the overall emissions to cause a net atmospheric C drawdown (Derpsch et al., 2014; Mehra et al., 2018; Zomer et al., 2017; Li et al., 2020). SCS potential of global agricultural soils accounts for 0.90–1.85 Pg C yr^{-1} (Zomer et al., 2017), exemplifying the potential of agricultural soil management (Lal, 2015) to mitigate CO_2 emissions (Krupenikov et al., 2011). SCS and GHG emissions within agricultural settings are associated with adopted tillage methods. (Wulanningtyas et al., 2021; Shakoor et al., 2021; Shang et al., 2021). Studies have shown that the effect of NT over CT on SCS might be confined to surface soils (0-10 cm) in developing countries (Bhattacharyya et al., 2021), which is also evident in Europe (Soane et al., 2012), China (Wang et al., 2021; Huang et al., 2016). Contrarily, NT may positively influence SCS in terms of whole soil profile compared to CT in Italy (Badagliacca et al., 2018), Mediterranean regions (Mazzoncini et al., 2016), and Japan (Wulanningtyas et al., 2021). These studies imply that the potential of tillage practices on SCS fluctuates widely (Chatterjee and Lal, 2009). These above-mentioned variations produced by NT may arise discrepancies (Wang et al., 2021) and must be considered to have a clear idea about future endeavors. Moreover, soil organic matter (SOM), SOC and its fractions, soil aggregates, soil microbial community, soil hydrological attributes (e.g., water retention, saturated hydraulic conductivity, etc.), and their inter- and intra- relationships define effective and sustainable SCS (Bhattacharyya et al., 2022). Several studies showed that intensive tillage operations could augment changes in the chemical composition of SOM, also on the quantity and quality of soil microbial populations, and lead to a reduction in structural stability, thus reducing the SOC

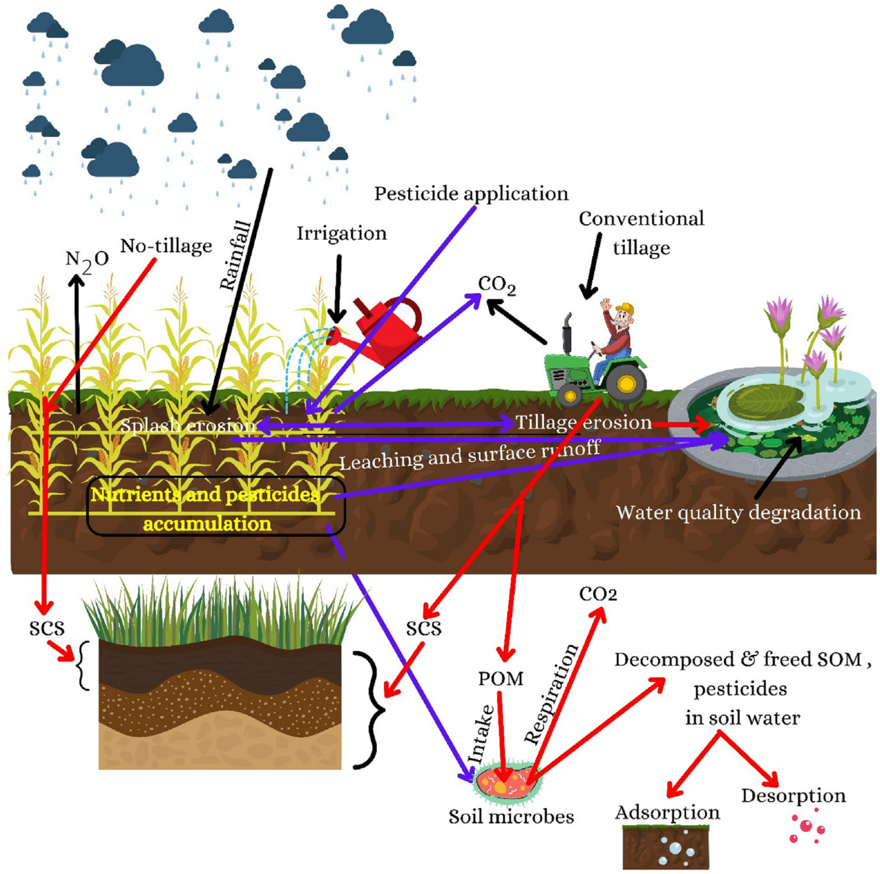

Fig. 1. Conceptual schematic diagram illustrating tillage practices (NT and CT) impact soil-air-water quality. Note: SCS- soil carbon sequestration, POM- particulate organic matter.

storage capacity of the soil (Acir et al., 2020; Assunção et al., 2019; Sithole et al., 2019; Tuzzin de Moraes et al., 2016; Kladivko, 2001).

Tillage practices also influence N_2O emissions by affecting nitrification and denitrification processes (Li et al., 2015) and CH_4 emission by affecting methanotrophs. N_2O and CH_4 are greenhouse gases with a global warming potential of about 300 and 30 times larger than CO_2. CH_4 and N_2O both can offset the positive benefits gained by SCS (Guenet et al., 2021; Hemes et al., 2018). Shakoor et al. (2021) observed a substantial amount of N_2O and CH_4 releases were associated with NT soils over CT globally. So, these tillage-induced trade-offs should be well-documented to fetch out future research directions.

Soil tillage affects SCS and GHG emissions and soil and water quality by erosion and runoff by affecting soil structure, reducing soil stability, and making it more prone to erosion. Melland et al. (2017) concluded that tillage, e.g., ST may increase the susceptibility of soils to erosion while resistance to erosion has been reported for CT/NT rotation (Zhang et al., 2018). In addition, although tillage may improve soil water storage capacity and saturated hydraulic conductivity (Schlüter et al., 2018; Zhang et al., 2018), tillage may also facilitate particulate nutrient loss (Melland et al., 2017), e.g., particulate organic C (POC) or particulate organic N (PON).

Several studies have revealed that tillage may also either increase (Elias et al., 2018), decrease (Klik and Rosner, 2020) or not affect (Okada et al., 2019) leaching or runoff of soil stored pesticides/fertilizers to aquatic bodies. When nitrogenous fertilizers are applied, soil immediately adsorbs and immobilizes NH_4^+ (Sørensen and Amato, 2002). In contrast, the negative charge of NO_3 produced by nitrification, is not easily adsorbed and immobilized by soil, resulting in NO_3^- loss through runoff or leaching (Li et al., 2015), tillage practice may influence these processes. Bertol et al. (2017) revealed that runoff is more prominent under NT than CT. However, NT prevents erosional loss, while Daryanto et al. (2017b) stated that NT failed to control erosion-induced phosphorus (P) loss to the water. In light of these findings, finding a way to resolve this detrimental phenomenon remain as an enormous challenge.

This study jointly presents the varied impact of tillage practices on soil quality, soil carbon sequestration (SCS), GHG emissions, leaching of C and N, and water pollution (Fig. 2). Previous reviews or meta-analyses considered only the effects of NT, CT, or DT on SCS or only their pathways (Bai et al., 2019; Haddaway et al., 2017; Bandyopadhyay, 2019) or only N_2O emissions (Huang et al., 2018; Feng et al., 2020) or only water pollution (Elias et al., 2018; Daryanto et al., 2017a). Optimizing tillage practices for agronomic and environmental benefits requires insights into the synergies and trade-offs of these practices. We hypothesized that improved tillage practices could enable agriculture to contribute to soil carbon sequestration (SCS) and mitigate GHG emissions and leaching of nutrients and pesticides. Our study provides in-depth global insights into the varied impacts of different tillage systems on soil carbon storage and air and water pollution.

2. Tillage practices and their impacts on soil carbon sequestration and related soil properties

2.1. Tillage practices

Conventional tillage (CT) is described as any tillage activity that utilizes cultivation such as ploughing and harrowing to prepare a seedbed, remove plant residues from the previous crops, or manage weeds. CT improves soil porosity, aeration, temperature and favors good root growth. No-tillage (NT)/zero tillage is the extreme form of conservation tillage practice where seeds are sown in a no-tilled soil without incorporating residues into soils from previous crops (Horowitz et al., 2012). Reduced tillage (RT) or minimum tillage (MT) is another conservation tillage technique that does not turn the soil over, thus avoiding changes in soil structure. In contrast, the soil surface is kept partly covered by 15% or 30% of crop

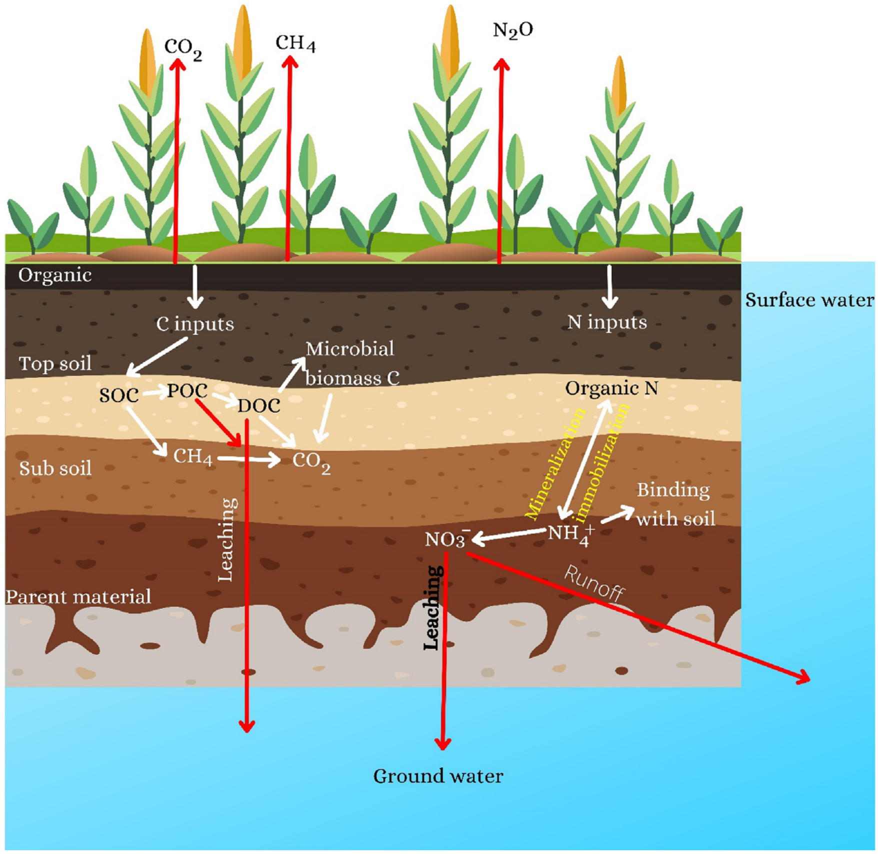

Fig. 2. Conceptualized schematic representation of the relationship between soil C and N pools, GHG emission, and leaching of C and N. Note: SOC- soil organic carbon, POC- particulate organic carbon, DOC- dissolved organic carbon.

residues from the previous crop. Compared to CT, NT/RT practices tend to increase soil moisture retention and improve water infiltration, but the soil remains prone to wind and water erosion. Ridge tillage (RiT) is a method of seedbed preparation where the topsoil is concentrated in a defined region to raise the seedbed above the natural topography. RiT is considered as a sustainable tillage practice in the black soils of China (Liu et al., 2018). Deep tillage (DT) involves mechanical modification of the soil profile such as subsoiling, deep ploughing, and mixing of soil profiles that can alleviate high subsoil compaction, and help deeper rooting of plants to reach water and nutrients from the subsoil (Tian et al., 2016; Scanlan and Davies, 2019; Schneider et al., 2017). This type of tillage may not be practical for sites without root-restricting soil layers and could even decrease the crop yields in that situation. It is only recommended for areas with a presence of root-restricting soil layers, especially in regions with continual aridity and erratic rainfall (Schneider et al., 2017). Strip-Tillage (ST) is a method of tillage where the soil is disturbed just in the seeding row while leaving the inter-row with residue cover, conserving soil moisture, decreasing penetration resistance, and creating an ideal seedbed for plant emergence and development (Licht and Al-Kaisi, 2005). Strategic tillage (STR) aims to achieve a balance between NT and CT, combining the benefits between both methods while minimizing the negative impacts of NT (Dang et al., 2015). The main objective of this kind of tillage is to manage herbicide-resistant weeds, diseases, and insects that have a below-ground pupal stage.

2.2. Impacts on soil carbon sequestration

Soil organic matter (SOM) is a mixture of materials, including organic particles, humus, coal, and living microbial biomass and the fine roots of plants (Stockmann et al., 2013). SOM improves soil chemical and biological characteristics, increases water and nutrient use efficiency, and promotes improved agricultural output and sustainability (Obalum et al., 2017; Sarker et al., 2018a, 2018b). It contains three-folds more C than any other source (Schmidt et al., 2011). SOM usually comprises almost half or more than half of soil organic carbon (SOC) of its total composition (Pribyl, 2010). This indicates the dependent dynamism (changes in SOM can induce change in SOC) of SOM on SOC. The SOM stabilization is attributed to the humification process, which favors the selective preservation of more recalcitrant organic structures, the physical protection of soil aggregates, and chemical bonds through organo-mineral complexes (Bottinelli et al., 2017; Sarker et al., 2018a, 2018b; Six et al., 2002).

However, SOC is prone to changes due to different tillage practices. For instance, CT increases O_2 availability and microorganisms' access to soil aggregates, speeding up SOM decomposition, stimulating oxidation of SOC to form CO_2 (Sithole et al., 2019; Six et al., 2000). Especially, CT with harrowing and ploughing makes the SOM more exposed to microorganisms and increases mineralization, which may trigger higher CO_2 emissions from soils (Galdos et al., 2019; Marafon et al., 2020). In addition, in a maize cultivation system, mixing crop residues in deeper soil layers through CT may encourage higher microbial activity, enhancing CO_2 emissions compared to RT (Rutkowska et al., 2018), which corroborates with the findings of Franco-Luesma et al. (2020). They concluded that apart from microbial activities, higher soil temperature and around 60% water-filled pore space (WFPS) may contribute to the higher CO_2 emissions from CT soils. In NT systems, soils are not disturbed, kept covered by crop residues, reduce splash erosion of the topsoil so that SOM may remain proportionally higher in the upper soil than in deeper layers (Corbeels et al., 2016; Lal, 2019). A 23 years study in Brazil revealed that NT increases the particulate organic carbon (POC), the mineral-associated organic matter (MAOM), and humin contents. This enhances the efficacy of SCS in diverse organic matter fractions (Ferreira et al., 2020). NT systems can increase SOC by increasing the mean residence time and decreasing turn-over (Rahmati et al., 2020).

Additionally, in a meta-analysis performed by Haddaway et al. (2017), 351 studies were systematically reviewed and found significantly higher in NT relative to forms of CT in the 0–15 cm soil layer. But CO_2 emission may be higher in NT soils. For instance, Li et al. (2010) compared CT and NT in Chinese-directed seeded paddy fields and found NT substantially augmented CO_2 than CT. CO_2 fluxes might be related to soil temperature (Almaraz et al., 2009; Li et al., 2010). STR may increase CO_2 releases two-folds (Melland et al., 2017). Negassa et al. (2015) observed that RiT emits substantial CO_2 instead of chisel tillage in various topographic areas. The root causes identified were high soil moisture and soil temperature. In ST, fuel consumption and working speed of the tractor remain as the determining factor for GHG emissions. For instance, Šarauskis et al. (2017) reported low working speed and working depth augmentation from 0 to 200 mm produced the highest CO_2 from the system. A long-term experiment conducted in Belgium showed higher CO_2 production from RT than CT. The underlying reason might be the uniform incorporation of residues throughout the soil profile, which improved SOM. Hence, greater microbial respiration led to the substantial production of CO_2 (Lognoul et al., 2017). Almaraz et al. (2009) reported tillage-derived CO_2 fluxes as season-dependent in soybean fields. For instance, during summer CO_2 emissions were 160 g m^{-2} d^{-1} and 68 g m^{-2} d^{-1} under CT and NT, respectively, while N_2O emissions remained significantly higher over CT owing to residue retention in soils. The reasons behind higher CO_2 fluxes may be higher soil temperature (21–28 °C) and WFPS (44–60%) in the summer (Horák et al., 2020).

Table 1 shows some studies that compared the SOC stock or SOC content in different tillage systems in different soils and regions of the world. It illustrates that a comparison of no tillage with conventual tillage are the most common studied tillage systems and the intercomparison shows that SOC stocks or contents are always higher in the no tillage (and also strip and ridge tillage) systems as compared to conventional tillage but the impacts of tillage on SCS is affected by soil-climatic conditions (Abdalla et al., 2013).

2.3. Impacts on soil structure

Soil tillage can have multiple impacts on soil structure (Table 2), and improved soil structure is vital for greater SCS (Guo et al., 2020). Good soil structure ensures preserving SOC for a longer time and prevents being respired as CO_2 in the atmosphere (Ewing et al., 2006). Studies have shown that tillage systems exhibit substantial influence on SOC dynamics, pools, stocks, and in SCS (Alvarez and Steinbach, 2009; He et al., 2011; Van Den Putte et al., 2010; Ramnarine et al., 2018; Jha et al., 2020; Awale et al., 2017; Mehra et al., 2018). Two major pools that regulate SOC dynamics are light fractions (LF) and heavy fractions (HF) (Christensen, 2020; Cerli et al., 2012). The constituents of HF include water-soluble and non-water-soluble elements. A long-term study conducted by Ramnarine et al. (2018) revealed NT exerted a substantial impact on HF, especially on the non-water-soluble fractions and sequestered C, which accounted for 28.9 Mg C ha^{-1}. The sequestered C was confined to 0-10 cm soil depth over CT with increasing soil depth. Thus, an insignificant difference exists between NT and CT in these components. Pinheiro et al. (2015) observed SOC stocking in HF around 12.3 g kg^{-1} soil under NT. Again, these fractions may vary with soil types. Azam et al. (2020) found HF maintains a strong relationship with TOC while LF does not. Therefore, HF regulates SOC dynamics, and undoubtedly, the SCS potential of HF is high. Again, a correlation can be drawn among SOC, soil aggregation, and tillage operations (Guo et al., 2020). Aggregate stability and macroaggregates formation are the prerequisites for effective SCS; aggregate collapse causes SOC loss. Theoretically, C is firstly captured by macroaggregates and then transferred to microaggregates, hence, macroaggregates enrichment is another important key to obtaining abundant SCS. High SOC content is often found in soils with more stable aggregates (Parvin et al., 2021). The stability of soil aggregates increases with microbial activity, which helps create glues such as glomalin, allowing this aggregation. Physical soil aggregates are formed when the soil matrix is disrupted through wetting and drying cycles (Rodríguez et al., 2021). Because soil aggregates contain nearly 90% of SOC, they are vital components of SOC protection. For instance, Kan et al. (2020) found that NT increases the proportions of macro-aggregates. Hati et al. (2019) reported better aggregate stabilization through enhanced activities of soil biota (more C enriched macroaggregates) in topsoil under conservative tillage in vertisols of India, although SOC and nutrient stratification was evident. Kravchenko et al. (2011) reported long-term CT affects soil porosity and aggregate formation in alfisols. Aggregates, in general, are vulnerable to tillage; disruption of macro-aggregates causes transformations of soil structure to microaggregates. Macro-aggregates are formed by adhesives that result from activities linked to microbial activity (Kan et al., 2020). Resins and glues produced by microbes in the soil help bind soil particles together to form water-stable aggregates. They function as the main reserves of SOC and could be a useful parameter to monitor SOC. Pinheiro et al. (2015) acknowledged the significant role of sand particles in SCS compared to silt and clay but affirmed these fractions mainly protect and store the sequestered C in soil. Again, tillage operations have a significant effect on soil particles. NT with residue retention increased silt plus clay associated C by 45% and 74% at 0–20 and 20–40 cm depth, respectively over CT (Kumar and Nath, 2019). Decreasing mechanical cultivation allows SOC to be protected by reducing macro-and micro-aggregates turnover. This helps minimize exposure of more stable SOC to microbial activities (Brewer and Gaudin, 2020). Overall, soil aggregates can shield SOC substantially from microbial spells (Schmidt et al., 2011). These studies suggest that microaggregates are another important regulator of SOC dynamics and can be used as a sustainable indicator to identify and calculate the SCS rate.

Apart from these, transition from CT to RT may lead to the formation of soil firmness, but remain unpaid, lacking higher actions by soil microorganisms (Schlüter et al., 2018). Moldboard plow appeared as the best option for conserving soil structure (0-20 cm depth) in a long-term experiment in Danish Sandy loam soils compared to RT. Residue retention can compensate for the adverse effects created by RT (Abdollahi and Munkholm, 2017). DT is utilized in arid regions with fine or medium-textured soil with high bulk density and soil compaction, while NT/DT rotation tillage benefits SOC sequestration levels (Feng et al., 2020). In a semi-arid area on the Huang-Huai-Hai Plain of China, DT reduced soil bulk density at 0–40 cm layer, favoring root growth and increased grain filling rate and maize grain yield (Zhai et al., 2017). With improved soybean yields, the contribution of DT was substantial in a dry silt loam soil having low SOM in Arkansas, USA compared to CT due to the breakage of the compact layer at 7 to 15 cm in the soil subsurface, which makes the soil more favorable for plant growth (Henry et al., 2018). and this practice has site-specific positive and negative effects on grain yield. Additionally, it is very dependent on environmental conditions and agronomic management factors (Feng et al., 2020).

2.4. Impacts on soil hydrological parameters

Tillage practices may influence soil hydrological parameters largely. Recent researches into the impact of NT activities found that, as opposed to other tillage schemes, NT may not facilitate water retention (Blanco-Canqui et al., 2017; Deuschle et al., 2019), while other authors exposed increased hydraulic parameters (e.g., greater saturated hydraulic conductivity) and water availability with improved infiltration in NT systems (Acharya et al., 2019; de Almeida et al., 2018). Again, Bertolino et al. (2010) revealed soils under CT remained saturated for a longer time after each shower event. In the case of torrents, it encouraged interflows while the NT system continued to drain. This phenomenon was identified as the determining factor for increased erosion rate under CT systems compared to NT.

RiT tends to reduce evapotranspiration and increase soil moisture in the upper soil profile, water availability, water use efficiency, and grain yield than CT, especially in the dry season (low rainfall and N) when the water is a limiting factor for crops (Li et al., 2018). Cross-ridge tillage can be

Table 1
Impact of different tillage systems on SOC storage under different soil types.

Reference (s)	Type of Tillage Practice(s)	Cropping systems	SOC/TOC ($g\ kg^{-1}$)	Total SOC Stock ($ton\ ha^{-1}$)	Soil classification	Region/ Country	Observation(s)
Nath et al., 2017	No-Tillage	Wheat- mungbean (*Vigna radiata* (L.) Wilczek)	–	12.5	Inceptisol, mahauli	New Delhi, India	No tillage with residue retention and nitrogen management increased SOC stock.
	Conventional Tillage		–	11.6			
Dimassi et al., 2014	No-Tillage	1st period: maize/winter wheat rotation; 2nd period: crop residues were removed; 3rd period: winter wheat/barley/sugarbeet/pea; 4th period: catch crop (oats/vetch) after wheat crop	8.25	45.1	Haplic Luvisol	Northern France	No difference between the tillage systems from the layer of 27.9 cm after 40 years with different crop systems.
	Shallow Tillage		8.5	44.5			
	Full inversion Tillage		11.0	44.2			
Rahmati et al., 2020	No-Tillage	Rotation of vetch and wheat (one crop per year)	9.8	–	Typic calcixerepts (clay loam texture	Maragheh, East Azerbaijan Province, Iran	Conservation tillage practices can increase SOC by increasing the mean residence time and decreasing turn-over.
	Reduced-Tillage		9.2	–			
	Conventional Tillage		7.3	–			
Jha et al., 2020	No-Tillage	Wheat	–	20.9	Vertisol or Ustic Pellustert	Queensland, Australia	The greatest increases in SOC occurred with no tillage at higher rates of N fertilization.
	Conventional Tillage		–	19.9			
Kumar and Nath, 2019	No-Tillage	Wheat/chickpea (winter) and mungbean (summer) after puddled transplanted rice in the rainy season	5.2	–	Inceptisol (Typic Ustochrept, sandy loam texture)	Uttar Pradesh, India	No tillage significantly differes from conventional tillage in the 0–20 cm layer.
	Conventional Tillage		3.7	–			
Pinheiro et al., 2015	No-Tillage	Rotation of vegetables: tomato, green pepper and beans	15.2	17.6	Dystrophic Red Latosol (Typic Haplortox)	Southeast Brazil	In tropical soils, no tillage is the main strategy for SOM accumulation, even when low input of vegetables crop residues occurs.
	Conventional Tillage		10.8	12.3			
Ramnarine et al., 2018	No-Tillage	Corn-soybean-wheat rotation	24.1	–	Typic Hapludalf (silt loam)	Southern Ontario, Canada	Significant differences observed in 0–10 cm layer, but no significant differences of TOC in 10–30 cm for both tillage treatments.
	Conventional Tillage		21.0	–			
Liu et al., 2018	Conventional Tillage	Maize-soybean rotation	17.2	–	Black soil/ Hapudoll (clay loam texture)	Northeast China	Ridge tillage generated a significantly higher SOC than conventional tillage in the 0–5 cm.
	Ridge-Tillage		26.10	–			
	No-Tillage		25.0	–			
Alcántara et al., 2016	Deep Tillage	Crop rotation: mayze, wheat, oilseed rape, potato,	–	142	Cambisols and Podzols	Northern and central Germany	Deep tillage has a high potential for increasing SCS through the incorporation of SOC-rich topsoil into the subsoil.
	Conventional Tillage		–	100			
Jaskulska and Jaskulski, 2020	Strip-Tillage	Winter wheat and barley	11.0	–	Cambisol	Central and Eastern Europe	The TOC in the 0–20 cm soil layer increased more than 1 $g\ kg^{-1}$ after 6 years of ST.
	Conventional Tillage		9.9	–			
Endale et al., 2017	Strip-Tillage	Cotton and peanut	86.00	–	Ultisols	Southeastern USA	TOC storage was greater for strip tillage than CT, due to reduced erosion and decreased runoff.
	Conventional Tillage		41.6	–			

used to replace downslope tillage on hilly regions to intercept the surface runoff volume, increase water infiltration and reduce loss of topsoil. This practice greatly reduces the sediment and N and P losses during heavy rainfall events in hilly regions from China. This is accomplished by shortening the slope length and retaining runoff (Guo et al., 2019). In humid Ethiopian Highlands, DT was found to break up the dense soil hardpan, thus, increasing infiltration rates and soil moisture throughout the soil profile, reducing the bulk density, penetration resistance, and soil loss, having high potential to improve degraded soils in that region. The objective of DT is to improve soil functions including water infiltration capacity and root penetration, optimizing conditions for crop growth (Hussein et al., 2019; Alcántara et al., 2016).

3. Impacts of tillage practices on soil erosion and water pollution

3.1. Impacts on soil erosion

SOC is a primary indicator of soil health (Krupenikov et al., 2011; Manlay et al., 2007), and highly sensitive to erosion losses as it remains concentrated in the proximity of soil surface. Soil hydrology, SCS, soil water content, and soil erosion are interlinked with each other, and tillage practices exhibit a significant impact on them (Bertolino et al., 2010; Moreno-Casasola et al., 2017). For instance, in China's calcareous soils, Ye et al. (2020) calculated that tillage-induced SOC loss might account for avg. 77% of total SOC loss during the initial tillage

Table 2
Role of some selected tillage practices in improving soil structure.

Tillage practices	Role (s)
No Tillage (NT)	1. The inclusion of plant residues and lack of disturbance to soil encourage NT to increase SOM, aggregate-induced SOC, stable aggregates, increased micropores, and smart connectivity, improving soil structural stability and resistance against rainfall events near the soil surface (Wang et al., 2019; Guo et al., 2020; Chenu et al., 2019). 2. NT may induce greater bulk density and bearing capacity of soil compared to CT and RT and alter water pathways beneficial for soil microorganisms (Soane et al., 2012).
Reduced Tillage (RT)	1. RT encourages lower bulk density, increased soil porosity, and air space, higher saturated hydraulic conductivity, higher macroporosity, and pore connectivity (Schlüter et al., 2018). 2. Contrarily, lack of soil disturbance may lead to decreased air pore space, increased bulk density, and penetration resistance in the topsoil (Abdollahi and Munkholm, 2017).
Deep Tillage (DT)	1. DT reduces higher bulk density and soil compaction, improves SOM and favors good root growth (Feng et al., 2020; Zhai et al., 2017; Henry et al., 2018), but might not be a good option for the soils with poor structure (Alcántara et al., 2016).
Strip Tillage (ST)	1. ST creates mechanical resistance, providing a good soil structure that is capable of withstanding mechanical stress (Pöhlitz et al., 2018). 2. It may reduce nutrient mineralization in soils (Laufer and Koch, 2017).
Strategic tillage (STR)	1. STR lowers bulk density, improves aggregate stability and penetration resistance induced by NT (Çelik et al., 2019).

period. A long-term comparative study of CT, NT, and RT revealed that depending on soil texture, annual erosion rates from CT, NT, and RT might be average 20.9, 2.45, and 4.45 t ha^{-1}, respectively (Klik and Rosner, 2020). SOC subjected to splash erosion may undergo the erosion-sedimentation process. Thus, SCS may be reduced by 0.6–1.5 Gt yr^{-1} (Lal, 2005). Klik and Rosner (2020) observed different potentials of runoff of N and P from CT, NT, and RT practices. They quantified total N losses ranged from 13.3–48.1, 1.6–9.4, and 4.5–18.7 Kg ha^{-1}, respectively, from CT, NT, and RT while total P losses were 6.7–29.4, 0.7–2.4 and 2.1–3.7 Kg ha^{-1}, respectively. Chowaniak et al. (2020) observed that NT soils might encourage 4% higher runoff over CT, whereas NT soils may have 67% lower soil loss. In addition, NT can reduce total organic C (TOC) loss and organic C loss through sediments by 46% and 53%, respectively, over CT. NT may reduce runoff volume and sediment losses by 50% and 50%–95%, respectively, in Fluvi-Calcaric Cambisol soils (Carretta et al., 2021). Over CT, RT and NT may decrease soil loss from silty clay loam soil by 38 and 65%, and from silt loam soil values remain 70–88% and 84–93%, respectively (Klik and Rosner, 2020). Olson et al. (2013) and colleagues reported substantial annual losses of C under different tillage practices in the USA during 24 years. They revealed that soils under NT lost less amounts (1.2 $Mgha^{-1}$) of C compared to chisel plow (9.9 $Mgha^{-1}$) and moldboard plow (8.2 Mg ha^{-1}). Novara et al. (2019) estimated that 9.5 ± 1.2 Mg C ha-1 may be lost annually due to tillage from a vineyard. Bogunovic et al. (2018) recorded typical yearly soil loss under NT (0.53 t ha^{-1}), DT (3.11 t ha^{-1}), and CT (13.11 t ha^{-1}) in Croatia. These losses might occur due to soil erosion plus tillage-induced erosion and notably, responsible for decreased SCS (Lal, 2005) and water pollution by sedimentation-erosion processes. Again, water erosion may cause the formation of labile C, increased mineralization-immobilization processes accompanied by elevated CH_4 and N_2, consequently water pollution and air pollution may occur simultaneously (Issaka and Ashraf, 2017). Intense tillage (e.g., CT) induced erosion may increase soil erosion (Lal, 2005; Chalise et al., 2019). These studies suggest that tillage practices may facilitate soil erosion and decrease SCS through SOC losses. Moreover, nutrient (N and P) loss through leaching surface/sub-surface runoff may cause water pollution or water quality degradation by causing eutrophication or hypertrophication.

3.2. Impacts on water pollution

3.2.1. Tillage can translocate accumulated nutrients on soil surface to aquatic bodies

Farming intensification has caused greater agricultural input materials, e.g., N and P fertilizers (Lu and Tian, 2017) and pesticides (Kremer, 2018). Unwarranted use of these materials may lead to net anthropogenic imbalances in soil systems, influencing leaching loss or surface runoff of nutrients/contaminants (Fowler et al., 2013). Tillage disturbs the stored soil contaminants/nutrients, causing them to be lost from the system and into surrounding bodies of water. There is a strong link between tillage practices and water contamination (Chalise et al., 2019). Nitrate (NO_3^-), for example, is primarily lost by leaching and is one of the most common causes of eutrophic or hypertrophic conditions (Lu and Tian, 2017; Reza et al., 2020; Hanrahan et al., 2019; Spiess et al., 2020; Syswerda et al., 2012). Studies have shown that different tillage practices can control the leachate volume and concentration of NO_3^- (Khan et al., 2017a, 2017b; Daryanto et al., 2017b). Additionally, Endale et al. (2019) showed higher sediment losses and nutrient runoff in ultisols under NT compared to CT. Residue retention and soil compaction may enhance runoff volume, increased macropores may contribute to leachate volume, and SOM may contribute to runoff and leachate concentration (Daryanto et al., 2017a, 2017b). These studies indicate that tillage systems can influence nutrient loss trails and contribute substantially to the deterioration of water quality and eutrophication.

Khan et al. (2017a, 2017b) demonstrated that soils under CT, RT and DT tend to show varying capacities regarding leaching loss of NO_3^-. For example, RT can significantly reduce NO_3^- concentration at 0–25 cm soil depth compared to CT and DT, but increased NO_3^- concentration 17.34% observed at 25–50 cm depth. That indicates CT and DT's potential to surface water contamination through NO_3^- elimination from the soil system, while the deeper movement of NO_3^- under NT may prevent ground water contamination. Spiess et al. (2020) revealed that NO_3^- leaching rates are regulated by the quantity of soil NO_3^- and they quantified leaching loss of 50 kg N ha^{-1} yr^{-1} under NT and mouldboard plow practices in a diverse crop rotation system.

Further, Hess et al. (2020) found that NT can create a buffer against leaching loss of N. Daryanto et al. (2017b) showed in a meta-analysis that although leachate NO_3^- load and runoff NO_3^- concentration from NT was determined by water flux, values were higher than CT. RiT has a greater leaching potential of NO_3^- in sandy soils, especially after rainfall (Waddell and Weil, 2006). Contrarily, RiT reduced surface runoff and leaching loss of N in paddy soils compared to CT (Qin et al., 2020). Ridge coupled with NT can slow down NH_4^+ oxidation, thereby reducing the leaching loss (Li et al., 2015). Under simulated rainfall conditions in wheat-soybean rotation, Daverede et al. (2003) found the concentration of PO_4^{2-} leachate was 0.40 and 0.24 mgL^{-1} under NT and chisel plow tillage systems. To find out why such a higher rate of leaching loss, Williams et al. (2018) observed that fertilization has a great impact under NT soils to induce higher leaching. They concluded that instead of broadcasting, injection or fertilizer placement through tillage could reduce the volume associated with water quality degradation. However, recent studies investigating the prevention of leaching and runoff from soils revealed that applying animal manures coupled with nitrapyrin could reduce both N and P leaching (Luo et al., 2017; Giacometti et al., 2020).

3.2.2. Tillage can release soil stored pesticides/herbicides to aquatic bodies

Several studies have shown that applied pesticides can cause malfunction of soil biota and decay of soil structure (Kremer, 2018; Yang et al., 2018), even accumulation of heavy metals in cultivated soils (Soane et al., 2012), and they are major agents of eco-degradation. Soils act as a reservoir for contaminants safeguarding them from leaching and entry to the aquatic systems, most importantly, translocation by plants (Düring et al., 2002). Many studies identified the persistent existence of several heavy metals in topsoils of rice (Abuzaid and Bassouny, 2020; Ali et al., 2018), maize, soybean, chihua squash (Dzul-Caamal et al., 2020), etc., even, sub-surface soils may also remain subjected to extreme, high and moderate levels of contamination

(Abuzaid and Bassouny, 2020). Additionally, several studies explicitly showed that SOM plays a leading role in the adsorption, binding, and storing of applied pesticides in soil (Stevenson, 1972; Hayes, 1970; Hance, 1974; Payá-Pérez et al., 1992). Under such context, it's critical to figure out how different tillage techniques affect surface/subsurface runoff processes, including leaching by altering SOM or other soil qualities, or how they affect pollutant transport to aquatic bodies. Mottes et al. (2020) reported that tillage might induce leaching loss of pesticides through i) SOM dilapidation, ii) altered water pathways within soil systems, and iii) amorphous phyllosilicate (e.g., allophane clay) corrosion. In a 13-year field trial, Babal et al. (2021) revealed that pendimethalin herbicide applied in an alluvial sandy loam soil under NT may be filtrated down to the subsoil compared to CT, although NT increased 69% higher SOC stock in 0–5 cm soil while the leaching rate was observed almost same between CT and NT. A study did not find any effect of NT on surface runoff of herbicides in a soybean-corn rotation. At the same time, CT impacted the loss of herbicide due to the wash off of the intercepted herbicides on the plant residue (Gonzalez, 2018). Contrarily, NT may increase glyphosate herbicide loss by surface runoff compared to CT, due to increased residue cover, reducing sorption (Shipitalo and Owens, 2011). Glyphosate may exhibit significant residual levels in soils under NT, which may adversely impact soil microbiome (da Silva et al., 2021). The herbicides atrazine and metolachlor are also lost in higher quantity through surface runoff from NT compared to mulch tillage (Ghidey et al., 2010). Residual herbicides bound to mineral and organic fractions in the soil can be leached out through surface runoff, producing water pollution and adversely impacting human health (Alletto et al., 2010). Compared to CT, a meta-analysis indicated that NT might have a modest effect in lowering pesticide load in the runoff. Still, it postulated that soil properties, such as acid soil pH, could modify pesticides' physicochemical properties (polarity, pKa) and affect their mobility to water bodies (Elias et al., 2018). In moderately fine and medium-textured soils with less than 2.3% SOM, NT may enhance pesticide concentration and loads in runoff (Elias et al., 2018). Potter et al. (2015) quantified 2.5 folds greater sub-surface loss of pesticide fluometuron under ST, although ST may reduce surface runoff of this pesticide by 10 times compared to CT. In addition, surface runoff volume under CT may be 2 times higher over ST.

Kaur et al. (2016) showed clay particles facilitate adsorption and the SOM handles the desorption of pesticides in soils as observed for the fate of pretilachlor in Punjab soils. The releasing capacity of different soils is variable. For instance, loamy sand soils favor more leaching loss of pesticides (Kaur et al., 2016). Apart from these, the role of soil aggregates cannot be overlooked. Soil aggregates play a pivotal role in capturing and accessibility of the accumulated heavy metal in cultivated soils (Huang et al., 2017). Huang et al. (2017) observed reduced action of metals in the greater soil depth, thus indicating the importance of maintaining CT or other tillage methods except NT because CT or other tillage practices tend to invert the soil profile. Similarly, observations of long-term tiling impact on Eutric Cambisol and Luvisol revealed soils under NT accumulated more pollutants compared to CT (Düring et al., 2002).

These studies indicate that waterbodies are at significant risk of pollution by tillage practices worldwide. NT although facilitates condensation of pollutants in surface soils, organic amendments can help to a great extent to reduce the leaching loss of pollutants from the surface soil. For example, chlordecone is considered a major soil contaminant and threat to human and crop health (Clostre et al., 2014; Mottes et al., 2020). Organic amendments can act as a potential sequestration tool in this context. Clostre et al. (2014) observed seven times decrease in leaching, and only 5% organic usage led to a substantial reduction of contaminant uptake by crops.

4. Tillage-induced synergies and trade-offs in greenhouse gas emissions

4.1. Tillage induced GHG emissions

Regulation of greenhouse gases (GHG) in the atmosphere is an important soil ecosystem service that is affected by tillage practices (Table 3) (Lal, 2019; Prado et al., 2016). Quantifying CO_2/ CH_4 output proportion is crucial because the net benefit from SCS could not be achieved due to the excess releases (Yu et al., 2008). But, contrasting research results make tillage's role in GHG emissions questionable (Table 4). For instance, decreases in GHG emissions in NT systems compared to CT were observed (Li et al., 2013; de Figueiredo et al., 2018; Fangueiro et al., 2017; Lu et al., 2016), while some reported no significant difference or increase on the GHG (Oorts et al., 2007; Plaza-Bonilla et al., 2014; Zhang et al., 2016a, 2016b). A global meta-analysis conducted by Shakoor et al. (2021) and colleagues revealed that NT augmented global CO_2, N_2O, and CH_4 emissions by 7.1%, 12%, 20.8%, respectively, compared to CT. More specifically, a substantial increase in N_2O and CH_4 discharges occurred globally in rainfed and irrigated agricultural areas. Another rigorous meta-analysis of 740 paired observations showed that NT has a considerable potential to minimize GHG and the global warming potential (GWP); however, net benefits require further understanding of the agroecological environment (Huang et al., 2018). Additionally, life-cycle assessment of tillage practices revealed that the impact order of GHG production is CT > NT > RT (Sørensen et al., 2014). The underlying cause was the higher mineralization rate in soils. NT with legumes as cover crops can boost N_2O emission, but the SCS rate and SOC deposition rate can dominantly mitigate the CO_2 amount of N_2O, and NT soils act as a potential sink for GHG (Bayer et al., 2016). NT may reduce GHG indirectly via reduced fossil fuel usage and reduced demand for synthetic fertilizers (Haddaway et al., 2017). A recent study in China suggests the combination of RiT and NT may act as a potential inhibitor of GHG compared to CT and NT (Li et al., 2021a, 2021b).

4.2. Tillage induced methane emissions

Studies have shown that soils can act as a net source or sink of CH_4 depending on soil temperature, moisture, N level, soil microbial community, air-filled porosity, spatial heterogeneity of soil profile, and so on (Gregorich et al., 2005; Bréchet et al., 2021; Díaz et al., 2018; Feng et al., 2021). Overall, drained agricultural soils are a small CH4 sink, while CH4 emissions occur in irrigated paddy-rice systems. For example, Shang et al. (2021) evaluated CT and RT in a Chinese double paddy cropping system. They found that CT and RT were responsible for a huge volume of CH_4, yet, CH_4 production was related to the SCS potential of the soils.

In drained agricultural soils, tillage can alter the mechanisms that govern the release or oxidation of CH_4 through its impact on the soil water regime (Feng et al., 2021). Moisture generally substantially influences CH_4 uptake rates (Liu et al., 2019). Hence, structural deterioration, more specifically compaction prevalent in extensively tilled soils, can negatively influence CH_4 consumption (Ball et al., 1999). For example, it was found that CH_4 uptake was less under STR over NT due to the decreased soil bulk density (Melland et al., 2017). In addition, enhanced residue retention associated with NT may also improve CH_4 consumption, as observed in a maize monoculture system in which NT combined with residue retention was around 3 and 1.5 times higher than CT and NT only, respectively (Franco-Luesma et al., 2020). It has been found NT and RT, reducing soil compaction, may increase two-fold CH_4 uptake compared to CT due to the greater soil shear strength, pore connectivity, and niche availability. These properties may also improve the functioning of soil methanotrophic population, which may increase CH_4 oxidation resulting in lower CH_4 emissions (Alskaf et al., 2021). In irrigated and/or flooded soils, the impact of tillage practices differs from drained soils Franco-Luesma et al. (2020) found that shortly after water application in flooded irrigation, no significant changes were observed in CH_4 fluxes in a maize monocropping system under NT and CT practices. Contrarily, Kim et al. (2016) observed that continuous NT in rice monocropping enhanced soil physical properties and reduced CH_4 emission during the early years of NT establishment but increased CH_4 emission over time. The cause is most likely due to increased labile SOC boosting methanogenic abundance. Overall, however, NT combined with residue retention on the soil surface likely lowers CH_4 emission from rice under different tillage practices. For instance, Zhang et al. (2013) showed that residue retention combined with NT enhanced soil porosity

Table 3
Overview of different tillage techniques on soil carbon sequestration and GHG emissions.

Source	Scale	Type of tillage practices	Duration	Impact on GHG emissions	Impact on SOC stock	Impact on SOC quantity (whole soil profile)	Impact order of tillage practices for SCS
Shakoor et al. (2021)	Global	NT and CT	-	NT = + + CT = −	NT = + + CT = +	NT = + CT = +	CT > NT
Wang et al. (2021)	Regional	NTS, RTS, CTS, CT	14 years	NTS = n.e. RTS = n.e. CTS = n.e. CT = n.e.	NTS = + + RTS = + + CTS = + CT = +	NTS = + RTS = + + CTS = + + CT = +	NTS ≈ RTS > CTS > CT
Badagliacca et al. (2018)	Regional	NT, CT	23 years	NT = + CT = −	NT = + CT = −	NT = − CT = +	NT > CT
Huang et al. (2016)	Regional	NT, CT	10 years	NT = n.e. CT = n.e.	NT = − CT = +	NT = − CT = +	CT > NT
Chatterjee and Lal (2009)	Regional	NT, PT	>4 years	NT = n.e. PT = n.e.	NT = + + PT = +	NT = + + PT = +	NT > PT
Chen et al. (2021)	Regional	NTS, RTS and CTS	09 years	NTS = + RTS = − CTS = −	NTS = + RTS = + CTS = +	NTS = + RTS = + CTS = −	NTS > RTS > CTS
Li et al. (2021a, 2021b)	Global	NT, RT, CT	44 years	NT = n.e CT = n.e RT = n.e	NT = + + RT = +	NT = + RT = +	NT > RT > CT
Olson et al. (2013)	Regional	NT, CP, MP	24 years	NT = n.e CP = n.e MP = n.e	NT = − CP = − MP = −	NT = − CP = − MP = −	NT > MP > CP
Wang et al. (2019)	Regional	NTS, RTS, CTS, CTO	9 years	NTS = n.e RTS = n.e CTS = n.e CTO = n.e	NTS = + RTS = + CTS = + CTO = -	NTS = + RTS = + CTS = + CTO = -	NTS > RTS > CTS > CTO
Modak et al. (2020)	Regional	NT, CT	9 years	NT = n.e CT = n.e	NT = + CT = −	NT = − CT = −	NT > CT
Du et al. (2017)	Regional	NT, CT	≥3 years	NT = n.e CT = n.e	NT = + CT = −	NT = + CT = −	NT > CT
Lembaid et al. (2021)	Regional	NT, CT	9 years	NT = n.e CT = n.e	NT = + CT = −	NT = + + CT = +	NT > CT
Wulanningtyas et al. (2021)	Regional	NT, MP, R	3 years	NT = n.e; MP = n.e; R = n.e	NT = + MP = − R = −	NT = + MP = − R = −	NT > MP > R
Gwenzi et al. (2009)	Regional	NT, RT, CT	6 years	NTS = n.e RTR = n.e CTR = n.e	NTS = + RTR + CTR = −	NTS = + RTR = + CTR = −	RTR > NTS > CTR
Yu et al. (2020)	Regional	NT, CT, RT	14 years	NT = + CT = − RT = +	NT = − CT = + RT = +	NT = − CT = + RT = +	RT > CT > NT
Mazzoncini et al. (2016)	Regional	NT, CT	28 years	NT = n.e CT = n.e	NT = + CT = −	NT = + CT = −	NT > CT

Indicators and Abbreviations: 0 = Neutral; + = High; + + = Extremely high; − = Low; −- = Extremely low; CT = Conventional Tillage; CTR = Conventional Tillage with residue retention; NT = No-tillage/Zero tillage; RT = Reduced/ Minimum Tillage; ST = Subsoiling tillage; SCS = Soil Carbon sequestration, R = Rotary tillage; NTS = No tillage with residue retention; RTS = Rotary Tillage with residue retention; RTR = Reduced Tillage with residue retention; CTS = Plow tillage with residue retention; CTO = Plow tillage with no residue retention; PT = Plow Tillage; CP = Chisel plow; MP = Moldboard plow; ASRT = All straw return tillage; SRT = Shallow rotary treatment; n.e. = Not evaluated.

and raised the oxidation layer. Hence, CH_4 emission appeared to be lower from a Chinese paddy field. Similarly, NT with residue retention increased CH_4 consumption around 3 and 1.5 times higher compared to CT and NT, respectively (Franco-Luesma et al., 2020). In a bioenergy cropping system, rotary tillage increased CH_4 emission compared to NT if combined with soil ameliorant or residue retention (Liu et al., 2015).

Table 4
Impacts of different forms of tillage practices on the direction (+ is increase, 0 is no effect and – is decrease) of GHG emissions from agricultural lands.

Tillage practice(s)	Type of study	Scale	Studied crop(s)/cropping systems	Soil type(s)	CO_2	N_2O	CH_4	Reference(s)
STR compared to NT	Primary research	Regional	Controlled-traffic farming regimes	Vertosol, and Sodosol	+	–	–	Melland et al. (2017)
NT compared to CT	Meta-analysis	Global	–	–	+	+	+	Shakoor et al. (2021)
NT compared to CT	Meta-analysis	Global	–	–	–	+	–	Huang et al. (2018)
RT compared to CT	Primary research	Regional	Maize	Cutanic Luvisol	+	+	n.e.	Lognoul et al. (2017)
CT compared to NT	Primary research	Regional	Rice	Hydromorphic paddy soil (silty clay loam)	0	+	+	Ahmad et al. (2009)
RiT compared to CT	Primary research	Regional	Rice	Haplic lixisol	0	0	0	Nyamadzawo et al. (2013)
DT compared to CA	Primary research	Regional	Maize and wheat rotation	Haplic Phaeozem	0	0	0	Dendooven et al. (2012)
ST compared to NT and CT	Primary research	Regional	Corn–soybean rotation	Typic Haplaquolls and Typic Hapludolls	–	n.e.	n.e.	Al-Kaisi and Yin (2005)

Abbreviations: NT = no tillage, CT = conventional tillage; RT = reduced tillage, RiT = ridge tillage, DT = deep tillage, ST = strip tillage, CA = conservation agriculture.

4.3. Tillage induced nitrous oxide emissions and mitigation

Nitrous oxide (N_2O) emissions from agricultural lands have become a major concern since i) the global warming potential of N_2O is around 300 times higher than CO_2 thus, playing a direct role in global climate change, and (ii) it is currently the primary driver of stratospheric ozone layer depletion (Ravishankara et al., 2009; Li et al., 2014). Li et al. (2005) acknowledged that 75–100% obvious benefit from SCS could be balanced from the upsurge in N_2O concentrations (Mei et al., 2018; Guenet et al., 2021). Nitrification and denitrification predominantly are the main routes of N_2O releases from cultivated fields (Braker and Conrad, 2011). Nitrification is the aerobic biological oxidation of ammonium (NH_4^+) to form nitrite (NO_2^-), nitrate (NO_3^-) as the main products, and N_2O as a byproduct accomplished by the activities of auto and heterotrophic bacteria. Denitrification is the anaerobic reduction of NO_3^- to NO_2^-, NO, N_2O, and finally N_2 (Butterbach-Bahl et al., 2013; Braker and Conrad, 2011; Lognoul et al., 2017). Both of these processes are dependent on soil microbial metabolic activities (Butterbach-Bahl et al., 2013; Congreves et al., 2017).

Tillage systems exhibit a role in N_2O emission either by favoring or reducing nitrification and/or denitrification and thus, soil N_2O emissions due to impacts on several factors, including soil texture, soil temperature, water-filed pore space (WFPS), soil mineral nitrogen (NH_4^+-N, NO_3^-N) concentration, and C:N ratio (Davidson and Swank, 1986; Abalos et al., 2014; Liu et al., 2017; Chen et al., 2013).

Empirical evidence thus shows that the introduction of no-till practices on N_2O emissions can cause both increases and decreases in N_2O emissions (van Kessel et al., 2013), since it affects the biophysical factors that influence N_2O emissions in contrasting manners (Snyder et al., 2009). There is generally an increase in soil moisture under NT, which is caused by higher water infiltration rates and reduced soil evaporation. In addition, no-till practices tend to increase bulk density and thus higher relative soil moisture contents affecting nitrification and denitrification rates and, therefore N_2O emissions (van Kessel et al., 2013). In wet regions, as in the tropical and humid areas, nitrification is thus mostly reduced by no-till practices, whereas it increases in dryer regions. Furthermore, no-till can lower soil temperature exchange between soil and atmosphere through the presence of litter residues, which can reduce N_2O emissions (Enrique et al., 1999). However, we lack a complete insight into the impacts of different tillage systems on the emission of N_2O in dependence on on-site properties (Congreves et al., 2017). Studies showed that CT might release 1.4–6.3 folds higher N_2O over NT in cold soils (Congreves et al., 2017). Zhang et al. (2013) showed rotary tillage had the highest potential of N_2O emissions over CT and NT. Regina and Alakukku (2010) reported in various Northern European Boreal soils that there is indeed a chance of elevated N2O over the first years of NT compared to CT, which may remain almost consistent in both types. Shakoor et al. (2021) demonstrated in a meta-analysis that NT is responsible for higher N_2O over CT. N_2O releases were higher in irrigated sub-tropical rice-wheat wheat-maize systems under NT over CT (Pandey et al., 2012; Niu et al., 2019). These studies indicate that when tillage intensity is reduced, there remains a chance of higher N_2O emissions. As per our discussion in Section 2.0, it can be concluded that higher N_2O discharges in NT systems might be linked up with increased SOM, NH_4^+ plus NO_3^- contents, and WFPS. Moreover, a robust meta-analysis comprising 323 observations concluded that activity and number of denitrifiers and the abundance of denitrifying genes were proportionally higher in response to NT, however, thus enhancing N2O production as compared to CT (Wang and Zou, 2020). Badagliacca et al. (2018) found almost similar results in the Mediterranean region. They stated that a substantial amount of N_2O was associated with an abundance of denitrifying genes, bacterial activities, greater bulk density, and WFPS. These studies indicate that soil structure and soil biota also control N_2O releases largely. Contrarily, Plaza-Bonilla et al. (2018) reported that soils under NT had 2.8–3.3 times lower N_2O emitting potential in the rainfed Mediterranean region compared to CT. This was because the unaccounted nitrifying and non-denitrifying populations lacking nitrous oxide reductase might be a potential storage for the produced soil N_2O (Hallin et al., 2018; Philippot et al., 2011; Jones et al., 2013). These studies suggest that benefits from NT should be evaluated in terms of N_2O production since the global areas under NT are increasing. Apart from CT and NT, STR reduces N_2O emissions in dermosols and sodosols (Melland et al., 2017). RiT has almost similar trend of N_2O emissions in paddy fields compared to CT, and even the differences were not statistically significant for paddy soils (Qin et al., 2020). Ridge combined with NT can substantially lower N_2O emissions than CT in paddy soils (Li et al., 2015).

Besides, studies showed that nitrification is responsible for most N_2O emissions in well-aerated soil with less than 60% WFPS, while denitrification is the major agent of N_2O emissions when soil moisture surpasses 70% WFPS (Pihlatie et al., 2004; Bateman and Baggs, 2005). In a meta-analysis, Chen et al. (2013) showed that crop residue retention might be favorable for SCS (Abalos et al., 2013), but it provides a congenial microenvironment to denitrifiers if WFPS remains 60–90%. Consequently, a substantial volume of N_20 releases occur. But at >90% WFPS, it may act as a denitrification inhibitor. Abalos et al. (2013) found 105% increases in N_2O emissions in Mediterranean burley fields when crop residues are retained, but removal greatly cut off the N_2O level.

Nitrification inhibitors (Liu et al., 2017) such as dicyandiamide (DCD), nitrapyrin, pronitradine, etc., are proven to be the most promising means of abating N_2O pollution from agricultural soils. For example, when nitrogenous fertilizers are broadcasted, nitrapyrin can reduce N_2O emissions from cold semiarid climatic soils by 41% and 32%, respectively, as found in maize crop fields under both CT and RT practices (Borzouei et al., 2021). Additionally, nitrapyrin addition can significantly slow down NH_4^+ oxidation (Hayden et al., 2021; Giacometti et al., 2020). Liu et al. (2017) reported nitrapyrin plus urea addition in calcareous drip fertigated cotton soils might significantly stabilize soil NH_4^+-N content and decrease N_2O emissions, but dependent on WFPS percentage. Combined application of nitrapyrin and DMPSA (3,4-dimethylpyrazole succinic acid) substantially reduced N_2O emissions in both gray Luvisol 60% and 56% at 60% and 80% WFPS, respectively (Lin and Hernandez-Ramirez, 2020). Meng et al. (2020) found DCD, nitrapyrin, and N- (n-butyl) thiophosphoric triamide (NBPT) as the potential N_2 fixer in paddy soils. These studies indicate that soil water content has a prominent role in both nitrification and denitrification processes also on the effectiveness of nitrification inhibitors. These substances can improve benefits from SCS by abating soil N_2O releases by increasing the use efficiency of nitrogenous fertilizers under different tillage systems.

5. Overall conclusions and perspectives

This review compares and contrasts the co-benefits and trade-offs produced from the impact of different tillage practices. We also highlighted several important soil ecosystem services (soil carbon sequestration, GHG regulation, water, and air quality) and their inter-and intra- relationships with different tillage practices. We confirm our hypothesis that improved tillage practices can enable agriculture to contribute to soil carbon sequestration (SCS) and mitigate GHG emissions and loss of accumulated nutrients and pesticides. Our significant findings are:

a) SOM is very prone to different tillage practices. Therefore, SOM protection is crucial for maximized SCS. Although NT practices tend to enrich SOM in the upper surface of soils, our study indicated that its impact on the whole soil profile is still dubious. Therefore, DT is a good option for improving continuous NT soils and mixing up the SOM across the entire soil profile since NT promotes greater bulk density.
b) CT emits more CO_2 than NT because of higher mineralization rates, microbial activity, and soil temperature and moisture. Although NT and RT have a greater SCS than other tillage techniques, higher soil temperatures may cause sequestered carbon to be lost. Higher N_2O emission under NT is related to soil moisture, increased denitrifier activity, and higher NO_3^- levels in soils. Therefore, soil moisture management is crucial to prevent N_2O emissions from NT soils.
c) The volume and magnitude of leaching loss of pesticides and nutrients

are relatively low in the case of CT and DT compared to NT, as they can bury them deep inside of soils. For example, we observed that NT enhances NO_3^- leaching over CT because of improved soil structure, infiltration capacity, and greater water flux.

d) Tillage erosion coupled with splash/wind erosion remains a significant problem. These processes may decrease the rate of SCS and increase the magnitude of nutrient pollution (eutrophication) in water bodies.
e) Nitrification inhibitors such as nitrapyrin or DCD coupled with nitrogenous fertilizers can potentially reduce N_2O emissions from soils. The advantages of nitrapyrin should be evaluated more in field settings (Luo et al., 2017). Future research on how to improve the effectiveness of nitrapyrin should be expanded. Despite preventing N_2O emissions, these substances are also quite capable of avoiding leaching loss of nutrients (N and P). Our study suggests that improvement of tillage practices in terms of mitigation of N_2O emission and preventing NO_3^- pollution may be achievable if these inhibitors are applied.

Apart from these, we also demonstrated that the accumulation of SOC and associated SCS is highly correlated with adopted tillage systems. All of the tillage practices have the potential to improve SCS, nevertheless, the role of NT over other practices on SCS is still unclear (Chatterjee and Lal, 2009), and also full potential is confined to certain pedo-climatic-regional conditions. Based on our current understanding, it can be concluded that if soil-climatic needs are not taken seriously, then it may produce erroneous estimates. The confounding factor that triggers the uncertainties and variations in data might be heterogeneity in the adopted outlook regarding NT (Meurer et al., 2018). Derpsch et al. (2014) proposed to develop a systematic procedure based on spatio-temporal variations to avoid existing doubts regarding the SCS potential of NT.

Additionally, Xiao et al. (2020) and Blanco-Canqui et al. (2021) identified the depth factor as the main reason for fueling debate regarding NT. Moreover, CT can improve SOC contents, ultimately reallocating C content in the whole soil profile. NT/RT practices improve soil moisture, water infiltration, stable aggregates, increased micropores, POC, MAOM, humin contents, TSN, MBC, TOC, etc. RT soils have a lower bulk density over NT, higher macropore, and improved aeration. RiT is associated with decreased evapotranspiration loss, improved water use efficiency, and greater SCS than CT and NT. Reduced erosion and reduced runoff from ST system yield in improved SCS, TOC, and TON. STR improves aggregate stability, bulk density, soil compactions, and a smart quantity of sequestered C. DT effectively raises SOM contents and improves SCS. We found a dearth of research in finding out the GHG emissions caused by STR, ST, and RiT. It's critical to find a sustainable solution for limiting C losses under high soil temperature using various tillage techniques. In addition, evaluation of eutrophication potential of different tillage practices (e.g., NT) should be taken into consideration. Current research is much focused on CT and NT, their SCS potential evaluation, and GHG producing capabilities. Future research on other forms of tillage practices needs to be undertaken to have a clear insight into other practices.

CRediT authorship contribution statement

Siddhartha Shankar Bhattacharyya: Conceptualization, Data Analysis, Tables, Figures, Writing-Original Draft, Reviewing and Editing. **Fernanda Figueiredo Granja Dorilêo Leite:** Data Analysis, Tables, Writing-Original Draft. **Casey L. France:** Tables, Writing-Original Draft. **Adetomi O. Adekoya:** Tables, Writing-Original Draft. **Gerard H. Ros:** Figures, Tables, Writing-Original Draft. **Wim de Vries:** Data Analysis, Figures, Tables, Writing-Original Draft. **Elda M. Melchor-Martínez:** Data Analysis, Figures, Tables, Writing-Original Draft. **Hafiz M.N. Iqbal:** Conceptualization, Data Analysis, Figures, Tables, Writing-Original Draft, Reviewing and Editing, Supervision. **Roberto Parra-Saldívar:** Conceptualization, Data Analysis, Figures, Tables, Writing-Original Draft, Reviewing and Editing, Supervision.

Declaration of competing interest

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

Acknowledgements

Consejo Nacional de Ciencia y Tecnología (CONACYT) Mexico is thankfully acknowledged for partially supporting this work under Sistema Nacional de Investigadores (SNI) program awarded to Elda M. Melchor-Martínez (CVU: 230784), Hafiz M.N. Iqbal (CVU: 735340) and Roberto Parra-Saldívar (CVU: 35753). S. S. Bhattacharyya thankfully acknowledges the Department of Agronomy, Bangladesh Agricultural University, Mymensingh, Bangladesh, for literature facilities. The authors would like to express their admiration to the four anonymous reviewers for their insightful and critical remarks and suggestions, which helped to improve a previous version of the paper.

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