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Conservation Tillage and Residue Management towards Low Greenhouse Gas Emission; Storage and Turnover of Natural Organic Matter in Soil under Sub-tropical Ecosystems: A Review

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A B S T R A C T

Soil organic carbon (SOC) dynamics in croplands is a crucial component of global carbon (C) cycle. Depending on local environmental conditions and management practices, typical C input is generally required to reduce or reverse C loss in agricultural soils. Changes in the soil organic carbon (SOC) stock are determined by the balance between the carbon input from organic materials and the output from the decomposition of soil C. The fate of SOC in cropland soils plays a significant role in both sustainable agricultural production and climate change mitigation. Tillage systems can influence C sequestration by changing aggregate formation and C distribution within the aggregate. Results showed that the soil organic carbon (SOC) stock in bulk soil was 40.2-51.1% higher in the 0.00-0.05 m layer and 11.3-17.0% lower in the 0.05-0.20 m layer in NT system no-tillage without straw (NT-S) and with straw (NT+S), compared to the MP system moldboard plow without straw (MP-S) and with straw (MP+S), respectively. Residue incorporation caused a significant increment of 15.65% in total water stable aggregates in surface soil (0–15 cm) and 7.53% in sub-surface soil (15–30 cm). In surface soil, the maximum (19.2%) and minimum (8.9%) proportion of total aggregated carbon was retained with >2 mm and 0.1–0.05 mm size fractions, respectively. DSR combined with zero tillage in wheat along with residue retention (T_6) had the highest capability to hold the organic carbon in surface (11.57 g kg^{-1} soil with the highest stratification ratio of SOC (1.5). A considerable proportion of the total SOC was found to be captured by the macro-aggregates (>2–0.25 mm) under both surface (67.1%) and sub-surface layers (66.7%) leaving rest amount in micro-aggregates and 'silt + clay' sized particles. Soil tillage practices have a profound influence on the greenhouse gas (GHG) balance. However there have been very few integrated studies on the emission of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) and soil biophysical and chemical characteristics under different soil management systems. Tillage played a significant role in the flux of CO_2 and CH_4. In contrast, N_2O flux was determined mainly by microbial biomass carbon and soil moisture content. Compared with other treatments, NT significantly reduced CH_4 emission among the rice growing seasons. However, much higher variations in N_2O emission were observed across the rice growing seasons due to the vulnerability of N_2O to external influences. The amount of CH_4 emission in paddy fields was much higher relative to N_2O emission. Conversion of CT to NT significantly reduced the cumulative CH_4 emission for both rice seasons compared with other treatments. The mixing of residues/surface retention into the soil increases SOM mineralisation due to greater exposure to microbial decomposers and optimal moisture and temperature regimes. Soil disturbance by tillage leads to destruction of the protective soil aggregate. This in turn exposes the labile C occluded in these aggregates to microbial breakdown. The present study found that SOC change was significantly influenced by the crop residue retention rate and the edaphic variable of initial SOC content.

Introduction

Agriculture accounts for approximately 40-50 % of the earth's surface is managed for agricultural purposes and contributes 10-12 % of global greenhouse gas (GHG) emissions, around 5.1-6.1 Pg CO_2 -eq yr^{-1} in 2005 (Smith *et al.*, 2007a). This is made up of 3.3 Pg CO2 -eq yr^{-1} from methane (CH_4) and 2.8Pg CO_2-eq yr^{-1} from nitrous oxide (N_2O) emissions. Although there are large exchanges of carbon dioxide (CO_2) between the atmosphere and agricultural ecosystems, emissions are thought to be roughly balanced by uptake, giving a net flux of only around 0.04 Pg CO_2 yr^{-1}, less than 1 % of global anthropogenic CO_2 emissions (Smith *et al.*, 2007a). Land use change is accounted for separately, but change to cultivated land is thought to contribute a further 5.9 ± 2.9PgCO_2-eq yr^{-1}, 6-17 % of total global GHG emissions (Bellarby *et al.*, 2008). If indirect emissions from agrochemical production and distribution and on-farm operations, including irrigation, are also included, an extra 0.4-1.6 Pg CO_2-eq yr^{-1} (0.8-3.2 %) can be attributed to agriculture, meaning that, in total, direct and indirect emissions from agricultural activity and land use change to agricultural use could contribute as much as 32.2 % of all GHG emissions (Bellarby *et al.*, 2008). Agriculture is the main source of global non CO_2 GHG emissions, contributing around 47 % of anthropogenic CH_4 emissions and 58 % of N_2O, although there is a large degree of uncertainty around estimates for both agricultural contribution and total anthropogenic emissions. The main sources, N_2O from soils and CH_4 from enteric fermentation, make up around 70 % of non-CO_2 emissions from the sector, with biomass burning, rice cultivation, and manure management, accounting for the remainder (Smith *et al.*, 2007a). Conservation tillage is one among many different mitigation options suggested to reduce GHG emissions from agriculture. Conservation tillage practices such as reduced/minimum/zero tillage, direct drilling and strip cropping are also widely recommended to protect soil against erosion and degradation of structure (Petersen *et al.*, 2011), create greater aggregate stability (Fernandez *et al.*, 2010; Zotarelli *et al.*, 2007) increase soil organic matter content, enhance sequestration of carbon (Six *et al.*, 2000) mitigate GHG emissions (Kong *et al.*, 2009) and improve biological activity (Helgason *et al.*, 2010).

Minimum tillage practices have been reported to reduce GHG emissions through decreased use of fossil fuels in field preparation and by increasing carbon sequestration in soil (Petersen *et al.*, 2008). The crop residues accumulated on the soil surface under reduced tilled conditions may result in carbon being lost to the atmosphere upon decomposition (Petersen *et al.*, 2008). Furthermore, climate change mitigation benefits such as reduced CO_2 emissions, by virtue of increased sequestration of carbon and increased CH_4 uptake under reduced tillage, could be offset by increased emissions of N_2O, a greenhouse gas with higher warming potential than both CO_2 and CH_4 (Hermle *et al.*, 2008; Chatskikh and Olesen, 2007). Increased N_2O emissions have been linked to increased denitrification under reduced tillage due to the formation of micro-aggregates within macro-aggregates that create anaerobic micro sites (Hermle *et al.*, 2008) with increased microbial activity leading to greater competition for oxygen (West and Marland, 2002).

Reduction of tillage can also create increased soil densification and a subsequent decrease in the volume of macro-pores (Schjønning and Rasmussen, 2000) leading to reduction in gaseous exchange. Soil aggregation and the resultant geometry of the pore structure are vitally important characteristics affected by tillage practices which impact on the physicochemical and hydro-thermal regime in soil, and ultimately crop yield. Additionally, the effect of tillage on the environment varies across farms geographically since the impacts of cultivation on soil organic matter and net greenhouse balance depends on soil type, climatic variables and management (Chatskikh and Olesen, 2007).

Natural organic matter in soils is the largest carbon reservoir in rapid exchange with atmospheric CO_2, and is thus important as a potential source and sink of greenhouse gases over time scales of human concern (Fischlin and Gyalistras, 1997). SOM is also an important human resource under active management in agricultural and range lands worldwide. Questions driving present research on the soil C cycle include: Are soils now acting as a net source or sink of carbon to the atmosphere? What role will soils play as a natural modulator or amplifier of climatic warming? How is C stabilized and sequestered, and what are effective management techniques to foster these processes? Answering these questions will require a mechanistic understanding of how and where C is stored in soils. SOM quantity and composition reflect the long-term balance between plant carbon inputs and microbial decomposition. The processes underlying soil carbon storage and turnover are complex and dynamic, involving influences from global to molecular scales. At the broadest level, SOM cycling is influenced by factors such as climate and parent material, which affect plant productivity and soil development. At a more proximate level, factors such as plant species and soil mineralogy affect decomposition pathways and stabilization processes. The molecular characteristics of SOM play a fundamental role in all processes of its storage and stability.

Historical global estimates for the top meter of soil vary from 800 Pg C to 2,400 Pg C, converging on the range of 1,300–1,600 Pg C to 1 m. Batjes (1996) estimated that an additional 900 Pg C is stored between 1 and 2 m depth, and Jobbágy and Jackson (2000) revised that estimate to 500 Pg between 1 and 2 m and another 350 Pg between 2 and 3 m depth. Global organic carbon stocks to 3 m are currently estimated at 2,300 Pg, with an additional 1,000 Pg contained in permafrost and peat lands (Jobbagy and Jackson, 2000; Zimov *et al.*, 2006). In this review paper we sought to evaluate the impact of conservation tillage on storage and turnover of natural organic matter in soil and GHG emissions. We hypothesized that conservation tillage improves storage and turnover of natural organic matter in soil and reduces GHG emissions compared with conventional tillage through the enhanced development of the soil carbon associated with less anthropogenic disturbance.

Reicosky and Archer (2007) reported that the CO_2 released immediately following tillage increased with ploughing depth and in every case was substantially greater than that from the no-tillage treatment. Intensive soil cultivation breaks down soil organic matter (SOM), producing CO_2, and consequently reduces the total C content. There are many reports suggesting that soil tillage accelerates organic C oxidation, releasing large amounts of CO_2 to the atmosphere over a few weeks (La Scala *et al.*, 2008). Conservation tillage has been shown to result in a greater percentage of soil present in macro-aggregates and a larger proportion of carbon associated with micro-aggregates compared to that in conventional ploughing (He *et al.*, 2011). Under conventional ploughing, macro-aggregates are readily broken down prior to micro-aggregate formation. This leads to a reduction in the proportion of C that is more protected in micro-aggregates and thus to the loss of recalcitrant SOC (Chivenge *et al.*, 2007). Li *et al.*, (2011) investigated methane emission patterns in a double-rice cropping system under conventional tillage and no-tillage in south-east China, where no-tillage reduced seasonal methane fluxes by 29% and 68% for the early and late rice, respectively. Ahmad *et al.,* (2009) also found that no-tillage significantly reduced methane emissions from paddy fields compared to conventional tillage (Fig. 1, 2 and 3).

Sarkhot *et al.,* (2012) reported that the prepared nutrient enriched bio-char by shaking the bio-char with dairy manure effluent for 24 h, which increased the C and N content of the bio-char by 9.3% and 8.3, respectively. When the untreated bio-cha and N enriched bio-char were added to a soil in eight week incubation, the reduction in availableNH_4^+-N and NO_3^{-}—N content was observed, suggesting the possibility of N immobilization. Still, N enriched bio-char could be used as a slow release N fertilizer. The net N nitrification rates in the CK, 1% BC and 3% BC treatments also peaked at day 25, then dramatically decreased and stayed at a very low level (0.35–0.42mg/(kg d)) at the end of incubation.

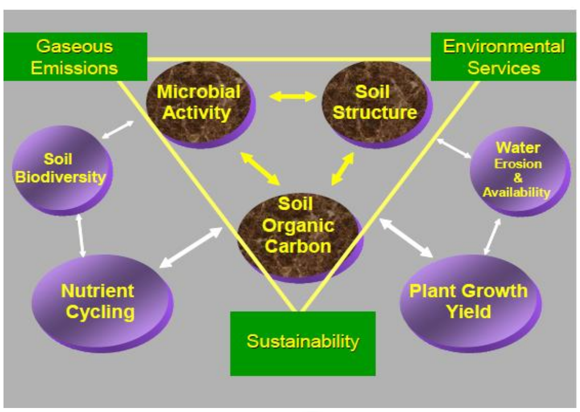
Sander *et al.,* (2014) reported that incorporation of rice residues immediately after harvest and subsequent aerobic decomposition of the residues before soil flooding for the next crop reduced CH_4 emissions by 2.5–5 times and also improved nutrient cycling in paddy field. It was also reported that residue incorporation accelerated CH_4 and N_2O emissions from irrigated rice field compared to residues left on the soil surface. The open burning of crop residues emits CO_2, CH_4, and N_2O. Mangalassery *et al.,* (2014) also found that neither ammonium (NH_4-N) nor nitrate (NO_3-N) content in soil was affected by tillage. Soil from the upper 10 cm contained significantly higher NH_4-N than the 10–20 cm layer. Nitrate (NO_3-N) followed a similar trend to NH_4-N. Tillage type and duration did not influence the NO_3-N content. Soil depth significantly influenced NO_3-N content with highest amount in the surface layer (0–10 cm) under both zero tillage and conventional tillage. Considering the GHGs together, tilled soil produced 20% greater net global warming than zero tilled soil indicating a potential for zero tillage system to mitigate climate change after only 5 to 10 years since conversion. Del Grosso *et al.,* (2005) also reported a 33% reduction in global warming potential under zero tillage (0.29 $MgCha^{-1}yr^{-1}$) compared with tilled soil (0.43 Mg C ha^{-1} yr^{-1}) for major non-rice cropping systems. Also in sub-tropical conditions, zero tillage has been found to reduce GWP by c. 20% (Pivea *et al.,* 2012).

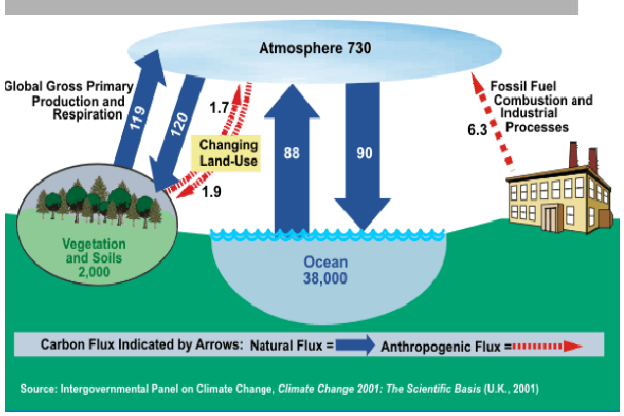
Residues management and crop rotations can affect N_2O emissions by altering the availability of NO_3^- in the soil, the decomposability of C substrates (Firestone and Davidson, 1989). The reduction of N_2O to N_2 is inhibited when NO_3^- and labile C concentrations are high (Senbayram *et al.,* 2012). The retention of crop residues and higher soil C in surface soils with CA play major roles in these processes. Under anaerobic conditions associated with soil water saturation, high contents of soluble carbon or readily decomposable organic matter can significantly boost de-nitrification (Dalal *et al.,* 2003) with the production of N_2O favoured with high quality C inputs (Bremner, 1997). The quantity and quality of residues or cover crops of CA systems can also affect N_2O emissions. Legume residues can result in higher N_2O–N losses (Millar *et al.,* 2004) than those from non-legume, low N residues (Aulakh *et al.,* 2001). Crop residues may affect CH_4 oxidation in upland soils and emission patterns in flooded soils differently depending on their C/N ratio; residues with a high C/N ratio have little effect on oxidation while residues with a narrow C/N ratio seem to inhibit oxidation (Hiitsch, 2011). Grace *et* *al.,* (2012) estimated an average of 29.3 Mg ha^{-1} of GHGs emitted over 20 years in conventional rice-wheat systems across the IGP; this decreased by only 3% with the widespread implementation of CA.

Agricultural practices such as tillage and fertilization have to be considered. Food systems alone – everything from growing plants to the disposal of biomass – contribute to 19–29% of global anthropogenic GHG emissions. Of this, 80–86% relate to agricultural production (including indirect emissions associated with land-cover change), albeit with significant regional variation (Vermeulen *et al.,* 2012). On agricultural sites, N_2O emissions from legume-N were significantly lower than fertilizer-N derived N_2O emissions (Schwenke *et al.,* 2015). Gupta *et al.,* (2016) revealed that the GWP (CH_4 + N_2O) of wheat–rice systems varied from 944 to 1891 kg CO_2 eq. ha^{-1} and 1167–2233 kg CO_2 eq. ha^{-1} in the first and second years of wheat–rice cropping respectively. The combination of ZTW followed by DSR showed significantly low GWP than other combination of wheat and rice treatments. These combinations led to about 44–47% reductions in GWP over the conventional CTW-TPR system in both the years. The order of GWP among the different combination of treatments was as follows: (ZTW + RR) - DSR < ZTW-DSR < ZTW-IWD < ZTW + NOCUTPR + NOCU < CTWTPR < ZTW-TPR in both the years. The share of rice in total GWP was 72–81% in those combinations in which TPR was a treatment while it varied from 56 to 65% where DSR was a treatment. These results indicate that adoption of ZTW followed by DSR in the IGP in place of conventional CTW-TPR can be an efficient low carbon emitting option. With the development of new drills, which are able to cut through crop residue, for zero-tillage crop planting, burning of straw can be avoided, which amounts to as much as 10 tons per hectare, potentially reducing release of some 13–14 tons of carbon dioxide (Gupta *et al.,* 2004). Elimination of burning on just 5 million hectares would reduce the huge flux of yearly CO_2 emissions by 43.3 million tons (including 0.8 million ton CO_2 produced upon burning of fossil fuel in tillage). Zero-tillage on an average saves about 60 l of fuel per hectare thus reducing emission of CO_2 by 156 kg per hectare per year (Grace *et al.,* 2003; Gupta *et al.,* 2004). Sah *et al.,* (2014) revealed that the CO_2 emissions conventionally tilled (CT) wheat emitted the highest amount of CO_2 (224 kg ha^{-1}) followed by PRB (146 kg ha^{-1}) and the lowest from ZT (126 kg ha^{-1}). The highest CO_2 emission through CT attributed to higher tractor usage on land preparation and more pumping time on irrigation. However, ZT and PBP wheat emitted lower CO_2 to the atmosphere by 43.7 % and 34.9 %, respectively, as compared to CT.

Conservation tillage practices decreased the exposure of un-mineralized organic substances to the microbial processes, thus reducing SOM decomposition and CO_2 emission. Apart from C, other greenhouse gases (GHGs) notably, nitrous oxide (N_2O) and methane (NH_4), have been reported to be influenced by tillage regimes (Steinbach and Alvarez, 2006). About 38% of the emissions to the atmosphere can be ascribed to nitrous oxide from soils (Bellarby *et al.,* 2008) while methane is considered as the most potential greenhouse gas after carbon dioxide (IPCC, 2001). Significantly higher N_2O emissions from ploughed than no-tilled sites has been reported by Kessavalou *et al.,* (1998). The higher aeration in tilled soil increases oxygen availability, possibly resulting in increased aerobic turnover in the soil and thus an increased potential for gaseous emissions (Skiba *et al.,* 2002). Seidel *et al.,* (2015) compared the ratio between greenhouse gas emissions from inputs and crop output across organic and conventional cropping systems and suggests that a legume tilled management exhibited the best ratio (59%) followed by manure tilled (63%), manure no till (65%), legume no till (84%) and conventional till (90%) as a per-cent of the GHG emissions from conventional no till management.

Several of the agricultural and forestry GHG mitigation options provide ancillary co-benefits to the agricultural sector and to society, making them somewhat unique in their ability to address climate change simultaneously with other pressing social and environmental issues. This has earned these reductions the title of "charismatic carbon credits." Increasing soil C also increases available plant nutrients; considering the nutrient supplying capacity of just N, P, S, a1% increase in soil organic matter content (equivalent to 21 Tons of CO_2) would translate to 75 lb N, 8 lb P and 8 lb of S per acre (Rice *et al.,* 2007).





CO_2 in the atmosphere is in a constant state of flux among its repositories, or "sinks"; this is called the Carbon Cycle. The movement, or "flux," of carbon between the atmosphere and the land and oceans sinks is dominated by natural processes, such as plant photosynthesis. While these natural processes can absorb some of the net 6.3 billion metric tons of human-produced CO_2 emissions emitted each year (about 2 billion metric tons are absorbed by the ocean and 1 billion by terrestrial systems, including soils), that leaves an estimated 3.2 billion metric tons that are added to the atmosphere annually. The Earth's positive imbalance between emissions and absorption of GHG has resulted in the increased concentration of greenhouse gases in the atmosphere. This causes global climate change.

Turnover time and dynamics of soil organic matter

Cambardella and Elliott, (1994) reported that the turnover time of POC ranged from 5 to 20 years in cultivated grassland soils. The reason might be that after cultivation of virgin black soils, soybean (C_3 crop) residues provided an extra source of organic matter input in addition to corn-derived C (C_4 crop). It might also be due to a certain amount of black C in POC (Knicker *et al.,* 2005). The mean turnover time indicated faster turnover of SOC in coarse fraction than that in fine fraction. We suggested that short-term NT did not significantly affect the turnover time of SOC. The turnover time of SOC was even longer in MP plots because of the incorporation of returned crop residues into soils. Thus, the short-term impact of no tillage was firstly shown in the coarse-size fractions (POC). The distribution of C_3–C mainly in fine particles (silt plus clay) indicated that the turnover of SOC in coarse-size fraction was faster under tillage practices. Regardless of residue type, mineralization of SOM increased up to from 50 to 90% due to addition of low and high levels, respectively, whereas residue addition was increased 3.6 times. Therefore, the amount of primed CO_2 decreased per unit of applied residue. This was also reported by Guenet *et al.*, (2010) and Xiao *et al.*, (2015).

Zhu *et al.*, (2015) revealed that the soil total organic C (TOC) and labile organic C fraction contents were higher under the straw return treatments compared to the no straw return treatment (0% S) at a 0–21 soil depth. The 50% annual straw return rate (50% S) had significantly higher soil TOC, dissolved organic C(DOC), easily oxidizable C (EOC), and microbial biomass C (MBC) contents than the 0% S treatment at a 0–21 cm depth. All of the straw return treatments had a significantly higher DOC content than the 0%S treatment at a 0–21 cm depth, except for the 100% only rice straw return treatment (100% RS). Wang *et al.*, (2015) also found that in the early paddy field, the average values of the total SOC, LFOC, DOC and MBC concentration in the top 40cm soil were significantly higher in the straw application plots than in the controls, by 7.2% 8.8%, 15.6%, and 128.6%, respectively. Wright *et al.*, (2007) reported that in the 0-5 cm soil depth, no-tillage increased macro-aggregate-associated OC as compared to conventional tillage. Macro-aggregates accounted for 38-64, 48-66, and 54-71% of the total soil mass in the 0-5, 5-10, and 10-20 cm soil depths, respectively. The corresponding proportions of the silt+clay fraction were 3-7, 2-6, and 1-5%, respectively. Proportions of macro-aggregates were increased with reduction of soil tillage frequency. For the 0-5 cm soil depth, treatments NT and 4T had significantly higher mass proportions of macro-aggregates (36 and 23%, respectively) than that of treatment. With additions of crop residues, the amount of macro-aggregates increased in all tillage treatments. Conservation tillage significantly increased SOC concentration of bulk soil in the 0−5 cm soil layer. This increase in SOC concentration can be attributed to a combination of less soil disturbance and more residues returned to the soil surface under conservation tillage (Du *et al.*, 2010; Dikgwatlhe *et al.*, 2014). Alvarez *et al.*, (2009) also found that NT increases SOC and total N concentrations in the first centimetres of the soil profile because NT maintains surface residues. Vanden Bygaart *et al.*, (2003) observe that non-inversion tillage physically protects part of the organic matter in the top layer from mineralization by inclusion within macro-aggregates. With conventional inversion tillage on the other hand, aggregates will be more thoroughly disrupted, assisting loss of organic matter. Mangalassery *et al.*, (2014) revealed that zero tilled soils contained significantly more soil organic matter (SOM) than tilled soils. Soil from the 0–10 cm layer contained more SOM than soils from the 10–20 cm layers in both zero tilled (7.8 and 7.4% at 0–10 cm and 10–20 cm respectively) and tilled soils (6.6% at 0–10 cm and 6.2% at 10–20 cm).

Temporal scales of soil C dynamics

Wang *et al.*, (2016) also found that higher amounts of C input can lead to higher soil C sink capacities. On a global average, the total amounts of C input to soils are 1.7, 2.7 and3.7 MgC ha^{-1} under the crop residue retention rates of 30, 60 and 90 %, respectively. Lal, (2004) reported that the rates of SOC sequestration in croplands range from 0.02 to 0.76 MgC ha^{-1} yr^{-1} when improved systems of crop management are adopted. However, it should be noted that the increased SOC sequestration rate that is contributed to by the increased C input can be limited at longer periods, as the SOC would eventually reach a relatively stable threshold (Stewart *et al.*, 2007). On a global scale, the estimated efficiency of the conversion of C input to

SOC is 14 %, which falls within the 10–18 % range estimated by Campbell *et al.,* (2000). It should be noted that the conversion efficiency varies across space and is highly dependent on the local climatic and edaphic conditions (Yu *et al.,* 2012). Mangalassery *et al.,* (2014) observed that zero tilled soils contained significantly more microbial biomass carbon than tilled soils. The mean microbial biomass carbon under zero tilled soil was 517.0 mg kg^{-1} soil compared with 418.7 mg kg^{-1} soil in tilled soils. Microbial biomass carbon was significantly higher in the 0–10 cm layer (517 mg kg^{-1} soil) than the 10–20 cm layer (419 mg kg^{-1} soil) under zero tillage and conventional tillage. Moreover, tillage and soil depth significantly influenced soil microbial biomass nitrogen. Zero tilled soils contained higher microbial biomass nitrogen (91.1 mg kg^{-1} soil) than tilled soil (70.0 mg kg^{-1} soil). Surface layers (0–10 cm) maintained more microbial biomass nitrogen than sub surface layers (10–20 cm) under both zero tilled soils and tilled soils.

Fortuna *et al.,* (2003a) found that addition of organic nutrient sources like compost to the soil for more than 6 years has the potential to increase the pools of slow (10% increase) and resistant (30% increase) C and the potential pool of potentially mineralizable N. West and Post (2002) calculated that converting from mouldboard plough to no-till sequestered an additional 0.57±0.14 Mg $Cha^{-1}yr^{-1}$ of C and complex crop rotations had the potential to sequester an additional 20±12 $gCm^{-2}yr^{-1}$ of C. Seventeen ±15% of C applied in animal amendments such as poultry manure becomes part of soil organic matter (SOM) (Johnson *et al.,* 2009). Key management practices that retain or return residues to the soil have been shown to insulate and elevate soil temperatures reducing the extremity and frequency of freeze-thaw cycles leading to a reduction in N_2O emissions. Soil C and N dynamics are influenced to a greater degree by quantity rather than quality of plant residues. Gentile *et al.,* (2011) reported that the quality of crop residues effects short term nutrient dynamics and has a less of an impact on C sequestration. Jha *et al.,* (2012) suggested that the addition of FYM to soil increased the active C pool to a greater extent as compared to the slow and resistant C pools. Powlson *et al.,* (2012) also found the effect of reduced tillage and addition of different organic materials on soil C stocks and N_2O emissions. They found that reduced tillage practices increased the annual C stocks compared to conventional tillage. However, this was compensated for increased N_2O emissions under reduced tillage management. Dendooven *et al.,* (2012) revealed that no till with crop residue removal and conventional tillage with residue retention or removal were net sources of CO_2, with a positive net GWP ranging from 1.288 to 1.885 Mg CO_2 $ha^{-1}yr^{-1}$. Hence, no till when practiced with residue retention had higher N_2O emissions but also increased the C storage to an extent that the systems had net negative GWP. Gattinger *et al.,* (2012) concluded that the SOC stocks and C sequestration rates were significantly higher in the zero net input organic farming systems as compared to non-organic cropping systems by 1.98 ±1.50 $MgCha^{-1}$ and 0.07±0.08 $MgCha^{-1}yr^{-1}$(mean ± 85% confidence interval) respectively. Palm *et al.,* (2014) reported that the combined effect of types of crops, intensity of cropping, duration of the cropping systems, the amount of inputs added to the systems in the form of residues and the tillage intensity along with soil properties like soil texture, temperature and moisture determines the overall soil C and N turnover and storage. Thomazini *et al.,* (2015) reported that organic no till with leguminous intercropping and pre-plant compost application had the potential to immobilize C in microorganisms thereby promoting a positive C balance in the soil leading to a C sink and improved soil health.

Zhao *et al.,* (2016) indicated that returning corn straw to the soil along with mixing it reduced the CO_2 emissions and increased the soil organic carbon content thereby improving the composition of micro-aggregate better than straw mulching. Zhang *et al.,* (2016) indicated that the application of chemical fertilizers plus manure could be a suitable management for ensuring crop yield and sustaining soil fertility but the ratio of chemical fertilizers to manure should be optimized to reduce C and N losses to the environment.

Tillage system influence on soil organic carbon storage

Wang *et al.,* (2018) reported that tillage system change influenced SOC content, NT, ST, and BT showed higher values of SOC content and increased 8.34, 7.83, and 1.64 $Mg{\cdot}C{\cdot}ha^{-1}$, respectively, compared with CT. Among the 3 changed tillage systems, NT and ST showed a 12.5% and 11.6% increase in SOC content then BT, respectively. Tillage system change influenced SOC stratification ratio values, with higher value observed in BT and NT compared CT but ST. Therefore, in loess soil, changing tillage system can significantly improve SOC storage and change profile distribution. Naresh *et al.,* (2018) reported that conservation tillage practices significantly influenced the total soil carbon (TC), Total inorganic carbon (TIC), total soil organic carbon (SOC) and oxidizable organic carbon (OC) content of the surface (0–15 cm) soil. Wide raised beds transplanted rice and zero till wheat with 100% (T_9) or with 50% residue management (T_8) showed significantly higher TC, SOC content of 11.93 and 10.73 g kg^{-1},respectively in T_9 and 10.98 and 9.38 g kg^{-1}, respectively in T_8 as compared to the other treatments. Irrespective of residue incorporation/ retention, wide raised beds with zero till wheat enhanced 53.6%, 33.3%, 38.7% and 41.9% of TC, TIC, SOC and OC, respectively, in surface soil as compared to conventional tillage with transplanted rice cultivation. Simultaneously, residue retention caused an increment of 6.4%, 7.4%, 8.7% and 10.6% in TC, TIC, SOC and OC, respectively over the treatments without residue management.

Concerning the organic carbon storage, SOCs varied between 31.9 $Mg{\cdot}ha^{-1}$ and 25.8 $Mg{\cdot}ha^{-1}$ under NT, while, in tilled treatments, SOCs ranged between 28.8 $Mg{\cdot}ha^{-1}$ and 24.8 $Mg{\cdot}ha^{-1}$. These values were lower than those observed by Fernández-Ugalde *et al.,* (2009) who found, in silty clay soil, a SOCs at 0–30 cm of 50.9 $Mg{\cdot}ha^{-1}$ after 7 years of no tillage, which was significantly higher than the 44.1 $Mg{\cdot}ha^{-1}$ under CT under wheat-barley cropping system in semiarid area. Hernanz *et al.,* (2009) also found, after 11 years under NT, a SOCs of 37 $Mg{\cdot}ha^{-1}$ which was higher than 33.5 $Mg{\cdot}ha^{-1}$ under CT, using a wheat-vetch (*Vectoria sativa* L.) rotation in silty soil. The lower SOCs values we observed can be explained by the fact that more time is needed before achieving the peak sequestration rate under NT. Xu *et al.,* (2013) observed that the SOC stocks in the 0–80 cm layer under NT was as high as 129.32 Mg C ha^{-1},significantly higher than those under PT and RT. The order of SOC stocks in the 0–80 cm soil layer was NT > PT > RT, and the same order was observed for SCB; however, in the 0–20 cm soil layer, the RT treatment had a higher SOC stock than the PT treatment. Alemayehu *et al.,* (2016) also found that the carbon storage per hectare for the four soil textures at 0 to 15 cm depth were 68.4, 63.7, 38.1 and 31.3 tha^{-1} for sandy loam, silt loam, loam and clay loam; respectively. Sand and silt loams had nearly twice the organic carbon content than loam and clay loam soil. The soil organic carbon content for tillage type at 0 to 15 cm was 8.6, 10.6, 11.8 and 19.8 g kg^{-1} for deep tillage, minimum tillage, shallow tillage, and zero tillage; respectively. Among tillage types soil organic carbon storage could be increased by using the minimum and shallow tillage. SOC storage decreased with soil depth, with a significant accumulation at 0-20cm depth. Zheng *et al.,* (2018) reported that across treatments, aggregate-associated C at a depth of 0–10cm was higher in the NT and ST treatments than in the MP and CT treatments. The advantage of the NT treatment weakened with soil depth, while the amount of aggregate-associated C remained higher for the ST treatment. There were more macro-aggregates in the ST and NT treatments than in the MP and CT treatments, while the MP and CT treatments had more micro-aggregates. The sum of macro-aggregate contributing rates for soil organic C (SOC) was significantly superior to that of the micro-aggregates. Mahajan *et al.*, (2019) reported that the increased SOC stock in the surface 50 kg m^{-2} under ZT and PRB was compensated by greater SOC stocks in the 50-200 and 200-400 kg m^{-2} interval under residue retained, but SOC stocks under CT were consistently lower in the surface 400 kg m^{-2}.Soil organic carbon fractions (SOC), microbial biomasses and enzyme activities in the macro-aggregates are more sensitive to conservation tillage (CT) than in the micro-aggregates. Responses of macro-aggregates to straw return showed positively linear with increasing SOC concentration. Straw-C input rate and clay content significantly affected the response of SOC.

Soil organic carbon and sequestration

SOM is a complex mixture which contributes positively to soil fertility, soil tilth, crop production, and overall soil sustainability. It minimizes negative environmental impacts, and thus improves soil quality (Farquharson *et al.*, 2003) (Fig. 4a). Loveland and Webb (2003) suggested that a major threshold is 2% SOC (ca. 3.4% SOM) in temperate regions, below which potentially serious decline in soil quality will occur. Storage of SOC is a balance between C additions from non-harvested portions of crops and organic amendments, and C losses, primarily through organic matter decomposition and release of respired CO_2 to the atmosphere. Organic matter returned to the soil, directly from crop residues or indirectly as manure, consists of many different organic compounds. Some of these are digested quickly by soil microorganisms. The result of this is a rapid formation of microbial compounds and body structures, important in holding particles together to provide soil structure and to limit soil erosion, and the release of carbon dioxide back to the atmosphere through microbial respiration (Kladivko 2001). Paustian *et al.*, (1998) compared tillage systems, ranging in duration from 5 to 20 years, and estimated that NT resulted in an average soil C increase of 285 g/m^2, compared to conventional tillage (CT). Liu *et al.*, (2003) showed a significant decline of total SOC that occurred in the first 5 years of cultivation where the average SOC loss per year was about 2300 kg/ha for the 0–17 cm horizon. The average annual SOC loss between 5- and 14-year cultivation was 950 kg/ha and between 14- and 50-year cultivation it was 290 kg/ha. These data clearly showed a rapid reduction of SOC for the initial soil disturbance by cultivation and a relatively gradual loss later. Compared with organic matter in the uncultivated soil, Liu *et al.*, (2003) also indicated that the total SOC loss was 17%, 28%, and 55% in the 5-, 14- and 50-year cultivation periods, respectively. The latter would correspond to the release of approximately 380 ton CO_2/ha to the atmosphere.

Within the surface 7.5 cm, the no-till system possessed significantly more SOC (by 7.28 Mg/ha), particulate organic matter C (by4.98 Mg/ha), potentially mineralizable N (by 32.4

kg/ha), and microbial biomass C (by 586 kg/ha), as well as greater aggregate stability (by 33.4%) and faster infiltration rates (by 55.6 cm/h) relative to the conventional tillage (Liebig *et al.,* 2004). Balota *et al.,* (2003) showed that no-tillage increased microbial biomass C, N, and P, and higher levels of more labile C existed in no-tillage systems than in conventional systems. Majumder *et al.,* (2008) reported 67.9% of C stabilization from FYM applied in a rice–wheat system in the lower Indo-Gangetic plains. Naresh *et al.,* (2015) reported that average SOC concentration of the control treatment was 0.54%, which increased to 0.65% in the RDF treatment and 0.82% in the RDF+ FYM treatment. Compared to F_1 control treatment the RDF+FYM treatment sequestered 0.33 Mg C ha^{-1} yr^{-1} whereas the NPK treatment sequestered 0.16 Mg C ha^{-1} yr^{-1}. Naresh *et al.,* (2018) revealed that the quantities of SOC at the 0-400 kg of soil m^{-2} interval decreased under T_1, T_4 and T_7 treatments evaluated. Stocks of SOC in the top 400 kg of soil m^{-2} decreased from 7.46 to 7.15 kg of C m^{-2} represented a change of - 0.31 ±0.03 kg of C m^{-2} in T_1, 8.81 to 8.75 kg of Cm^{-2} represented a change of -0.06 ±0.05 kg of C m^{-2} in T_4, and 5.92 to 5.22 of C m^{-2} represented a change of -0.70 ±0.09 kg of C m^{-2} in T_7 between 2000 and 2018. Soil C content in the 400-800 and 800-1200 kg of soil m^{-2} intervals performed similar change after 18 years. Changes over the length of the study averaged over tillage crop residue practices were -0.07±0.09 and -0.05±0.02 kg C m^{-2} in the 400-800 and 800-1200 kg of soil m^{-2} intervals. This is equivalent to an average yearly change rate of -5.5 and -3.9 g C m^{-2} yr^{-1} for each mentioned soil mass interval.

Kumar *et al.,* (2018) also found that the ZTR (zero till with residue retention) (T_1) and RTR (Reduced till with residue retention) (T_3) showed significantly higher BC, WSOC, SOC and OC content of 24.5%, 21.9%,19.37 and 18.34 gkg^{-1}, respectively as compared to the other treatments. Irrespective of residue retention, wheat sown in zero till plots enhanced 22.7%, 15.7%, 36.9% and 28.8% of BC, WSOC, SOC and OC, respectively, in surface soil as compared to conventional tillage. Simultaneously, residue retention in zero tillage caused an increment of 22.3%, 14.0%, 24.1% and 19.4% in BC, WSOC, SOC and OC, respectively over the treatments with no residue management. Similar increasing trends of conservation practices on different forms of carbon under sub-surface (15–30 cm) soil were observed however, the magnitude was relatively lower. Zhu *et al.,* (2011) compared to conventional tillage (CT) and zero-tillage (ZT) could significantly improve the SOC content in cropland. Frequent tillage under CT easily exacerbate C-rich macro-aggregates in soils broken down due to the increase of tillage intensity, then forming a large number of small aggregates with relatively low organic carbon content and free organic matter particles. Free organic matter particles have poor stability and are easy to degradation, thereby causing the loss of SOC Song *et al.,* (2011). Chen *et al.,* (2009) also found that single effect of residue application was not significant but its significance became apparent after its interaction with tillage system.

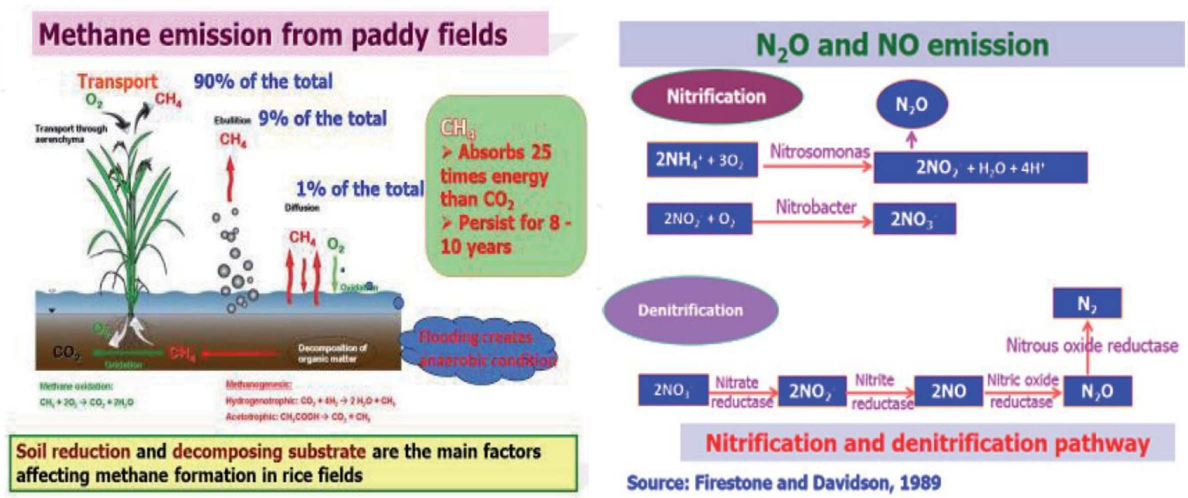
Naresh *et al.,* (2016) also found significantly higher POC content was probably also due to higher biomass C. Results on PON content after 3-year showed that in 0-5 cm soil layer of CT system, T_1, and T_5 treatments increased PON content from 35.8 $mgkg^{-1}$ in CT (T_9) to 47.3 and 67.7 $mg{\cdot}kg^{-1}$ without CR, and to 78.3, 92.4 and 103.8 $mgkg^{-1}$ with CR @ 2, 4 and 6 tha^{-1}, respectively. The corresponding increase of PON content under CA system was from 35.9$mgkg^{-1}$ in CT system to 49 and 69.6 $mgkg^{-1}$ without CR and 79.3, 93.0 and 104.3$mgkg^{-1}$ with CR @ 2,4 and 6tha^{-1}, respectively.

Table.1 Estimates of potential carbon sequestration of agricultural practices

Agricultural practice	Tons C/acre/yr	MT CO_2/acre/yr	MT C/hectare/year
No-till	0.15-0.30	0.45-1.05	0.30-0.70
Summer fallow elimination	0.05-0.15	0.15-0.5	0.10-0.35
Use of cover crops	0.05-0.15	0.15-0.5	0.10-0.35
Grazing land management	0.015-0.03	0.06-0.1	0.03-0.07

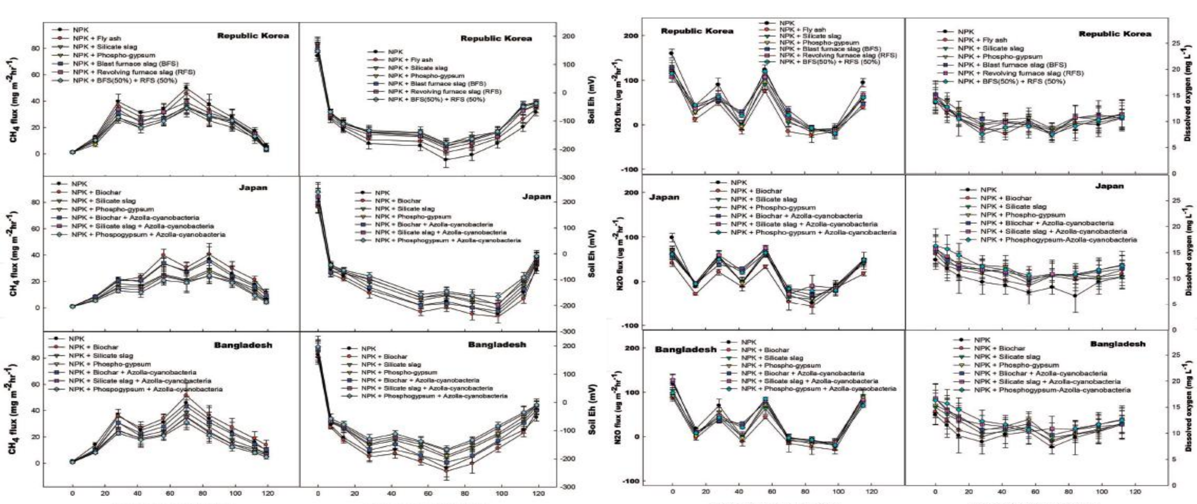
Co-benefits of Soil Carbon Sequestration: "Charismatic Carbon"

Fig.1 (a) Schematic diagram of methane production, oxidation, and emission from rice paddy field and (b) schematic diagram of N_2O, NO, and N_2 emissions from rice paddy field.



(a) (b)

Fig.2a&b Trends of CH_4 flux and soil Eh with different soil amendments during rice cultivation in Bangladesh, Japan, and Korea [Source: Ali *et al.*, 2015] and Trends of N_2O flux and DO concentrations under different soil amendments during rice cultivation in Bangladesh, Japan, and Korea [Source: Ali *et al.*, 2015].



(a) **(b)**

Fig.3 Key drivers of GHG emissions from soils

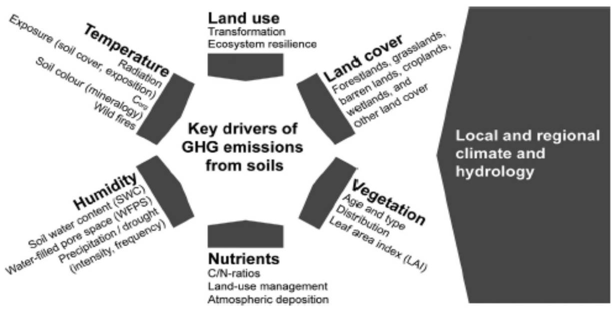
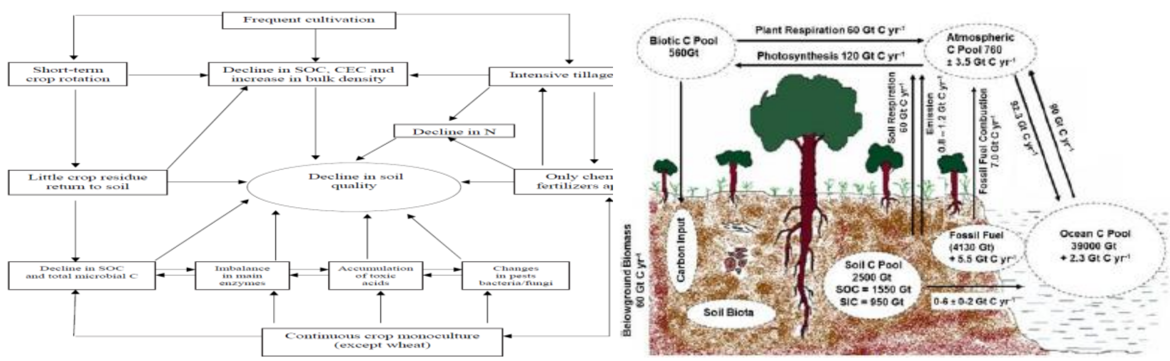


Fig.4a&b Diagram of interactions and negative impacts of agricultural management on soil quality and Sources and sinks of carbon from different pools under terrestrial and aquatic ecosystems



(a) **(b)**

Small improvement in PON content was observed after 4 years of the experiment. Singh *et al.,* (2018) found that carbon stock of 18.75, 19.84 and 23.83Mg ha^{-1} in the surface 0.4 m soil depth observed under CT was increased to 22.32, 26.73 and 33.07Mg ha^{-1} in 15 years of ZT in sandy loam, loam and clay loam soil. This increase was highest in clay loam (38.8%) followed by loam (34.7%) and sandy loam (19.0%) soil. The carbon sequestration rate was found to be 0.24, 0.46 and 0.62 Mg ha^{-1} yr^{-1} in sandy loam, loam and clay loam soil under ZT over CT (Table 1). Thus, fine textured soils have more potential for storing carbon and ZT practice enhances carbon sequestration rate in soils by providing better conditions in terms of moisture and temperature for higher biomass production and reduced oxidation (Gonzalez-Sanchez *et al.,* 2012). Bhattacharya *et al.,* (2013) reported that tillage-induced changes in POM C were distinguishable only in the 0- to 5-cm soil layer; the differences were insignificant in the 5- to 15-cm soil layer. Plots under ZT had about 14% higher POM C than CT plots (3.61 g kg^{-1} bulk soil) in the surface soil layer. Aulakh *et al.,* (2013) showed that PMN content after 2 years of the experiment in 0-5 cm soil layer of CT system, T_2, T_3 and T_4 treatments increased PMN content from 2.7 mgkg^{-1} 7d^{-1} in control (T_1) to 2.9, 3.9 and 5.1 mgkg^{-1} 7d^{-1} without CR, and to 6.9, 8.4 and 9.7 mg kg^{-1} 7d^{-1} with CR (T_6, T_7 and T_8), respectively. The corresponding increase of PMN content under CA system was from 3.6 mgkg^{-1} 7d^{-1} in control to 3.9, 5.1 and 6.5 mgkg^{-1} 7d^{-1} without CR and to 8.9, 10.3 and 12.1 mgkg^{-1} 7d^{-1} with CR. PMN, a measure of the soil capacity to supply mineral N, constitutes an important measure of the soil health due to its strong relationship with the capability of soil to supply N for crop growth.

Krishna *et al.*, (2018) reported that the total organic carbon (TOC) allocated into different pools in order of very labile > less labile > non labile >labile, constituting about 41.4, 20.6, 19.3 and 18.7%, respectively. In comparison with control, system receiving farmyard manure (FYM-10 Mgha^{-1}season^{-1}) alone showed greater C build up (40.5%) followed by 100% NPK+FYM (120:60:40 kg N, P, K ha^{-1}+5 Mg FYM ha^{-1}season^{-1}) (16.2%). In fact, a net depletion of carbon stock was observed with 50% NPK (-1.2 Mg ha^{-1}) and control (-1.8 Mg ha^{-1}) treatments. Only 28.9% of C applied through FYM was stabilized as SOC. A minimal input of 2.34 Mg C ha^{-1} yr^{-1} is needed to maintain SOC level.

In conclusion, conservation Agriculture can play a significant role in SOC sequestration by increasing soil carbon sinks, reducing GHG emissions, and sustaining agricultural productivity at higher level. Conservation agriculture sequesters maximum soil organic carbon near soil surface layer. Adoption of conservation agriculture with use of crop residues mulch, no till farming and efficient use of agricultural inputs help to conserve moisture, reduce soil erosion and enhance SOC sequestration. Conversation tillage with crop straw incorporation provides the best strategy to maintain or improve the long-term quality and productivity of sub-tropical ecosystems temperate arable soils in India. These cultivation methods promote surface accumulation of straw enabling sequestration of C in the surface soil horizons. For weakly structured soils, maintenance of organic matter is vitally important to allow continued use of soil conserving minimum tillage systems. Adoption of no-till and chisel ploughing maintained carbon in the surface soil horizons, but mouldboard ploughing distributed carbon more uniformly throughout the soil profile, particularly when straw was incorporated. Higher SOC stocks or concentrations in the upper soil not only promote a more productive soil with higher biological activity but also provide resilience to extreme weather conditions.

The return of crop residues and the application of manure and fertilizers can all contribute to an increase in soil nutrients and SOC content, but would need to be combined into a management system for more improvement. The practices of crop residue retention and tillage reduction provided an increased supply of C and N which was reflected in terms of increased levels of microbial biomass, N-mineralization rate in soil. Residue retention and tillage reduction both increased the proportion of organic C and total N present in soil organic matter as microbial biomass. The no-tillage system showed a trend to accumulate organic carbon near the soil surface layer. Conventional tillage reduced soil organic C stocks and that of its labile fractions both in top and subsoil (20-100 cm). POC reduction was mainly driven by a decrease in fine POC in topsoil, while DOC was mainly reduced in subsoil. Using a conservative approach, the global technical potential of the life-cycle emission reductions is estimated at 1.8 Pg CO_2-Cequilavent yr^{-1}(1.84 × 10^{9} tn CO_2-Cequilavent yr^{-1}), leading to a total net negative C emission or actual C sequestration of 0.5 to 1.1 Pg C yr^{-1} (0.55 to 1.21 × 10^{9} tn C yr^{-1}), including above- and belowground C accrual. C sequestration can be enhanced by increasing the proportion of C rich macro-aggregates in soils through the utilization of conservation tillage.

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