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Sunil Kumar
ICAR-Indian Institute of Farming System Research, Modipuram, Meerut, Uttar Pradesh, India

RK Naresh
Sardar Vallabhbhai Patel University of Agriculture & Technology, Meerut, Uttar Pradesh, India

AS Panwar
ICAR-Indian Institute of Farming System Research, Modipuram, Meerut, Uttar Pradesh, India

Poonam Kashyap
ICAR-Indian Institute of Farming System Research, Modipuram, Meerut, Uttar Pradesh, India

PC Ghasal
ICAR-Indian Institute of Farming System Research, Modipuram, Meerut, Uttar Pradesh, India

AL Meena
ICAR-Indian Institute of Farming System Research, Modipuram, Meerut, Uttar Pradesh, India

Jairam Chaudhary
ICAR-Indian Institute of Farming System Research, Modipuram, Meerut, Uttar Pradesh, India

LK Meena
ICAR-Indian Institute of Farming System Research, Modipuram, Meerut, Uttar Pradesh, India

Prem Singh
ICAR-Indian Institute of Farming System Research, Modipuram, Meerut, Uttar Pradesh, India

Chethan Kumar G
ICAR-Indian Institute of Farming System Research, Modipuram, Meerut, Uttar Pradesh, India

Correspondence
Sunil Kumar
ICAR-Indian Institute of Farming System Research, Modipuram, Meerut, Uttar Pradesh, India

Prediction of long term conservation tillage effect on soil organic carbon within aggregates and soil microbial community composition under rice-wheat rotation in subtropical India: A review

Sunil Kumar, RK Naresh, AS Panwar, Poonam Kashyap, PC Ghasal, AL Meena, Jairam Chaudhary, LK Meena, Prem Singh and Chethan Kumar G

Abstract
Sustainability is need of the hour. An easiest and fastest way to predict the sustainable yield is modelling or simulating with computer programme. Simulation models can also help in predicting the soil physical and microbial properties of the soil system. Improvising models to forecast regional soil productivity with interaction to various biotic and abiotic factors will be crucial for evaluating the sustainability of any system.

Keywords: Soil carbon fractions, soil carbon dynamics, macro-aggregation, microbial community

Introduction

Atmospheric concentration of CO_2 has increased from ~ 280 ppm in pre-industrial era to ~ 385 ppm in 2008 (+ 37.5%) and is presently increasing at the rate of ~ 2 ppm/yr or 3.5 Pg/yr (1 Pg or pentagram = 1 Gt = 1 gigaton = 1 billion metric ton). The increase in CO_2 emission by human activity is attributed to fossil fuel combustion, deforestation and biomass burning, soil cultivation and drainage of wetlands or peat soils. Increase in fossil fuel combustion is caused by high global energy demand of 475 Quads (1 quad = 1015 BTU) and increasing at the rate of ~ 2.5%yr^{-1}, especially in emerging economies including China, India, Mexico, Brazil, etc. There exists a strong positive correlation between population growths on the one hand and CO_2 emission or the energy demand on the other. The world population of 6.7 billion in 2008 is increasing at the rate of 1.3% yr^{-1} and is projected to be 9.5 billion by 2050 before stabilizing at ~10 billion towards the end of the 21st century. Because of the anthropogenic perturbations of the global C cycle, there are serious concerns about the risks of global warming and the attendant sea level rise. Thus, identifying viable sinks for atmospheric CO_2 is a high priority with the objective of sequestering it into other C pools with long residence time. Several options of CO_2 sequestration being considered are geologic, oceanic, chemical transformations and terrestrial. In contrast to the engineering techniques (e.g., geologic), C sequestration in terrestrial ecosystems is a natural process. It is also cost-effective and has numerous ancillary benefits (Lal, 2008a) [15].

Soil organic carbon (SOC) is important for the long-term sustainability of agro-ecosystems and the environment, because it promotes aggregation, improves soil physical properties and water retention, and increases productivity and the activity of soil organisms (Paradelo *et al*., 2015) [24]. Agricultural SOC accumulation is influenced by numerous factors, such as tillage practices (Zhang *et al*., 2013; Liu *et al*., 2014) [43, 42], soil aggregate size (Zhang *et al*., 2013; Devine *et al*., 2014) [43, 7], and microbial functional diversity (Pritchett *et al*., 2011) [30]. Tillage practices can affect the stability or composition of SOC (Zhang *et al*., 2013; Devine *et al*., 2014) [43, 7], and thus affect SOC concentration and SOC density of the plough layer (Zhang *et al*., 2013) [43]. Conventional intensive tillage (CT) can decrease soil aggregate stability and accelerate soil organic matter oxidation (Gathala *et al*., 2011) [11, 14]. Conservation tillage significantly reduces soil physical disturbance (Uri, 1999) [promotes soil aggregation, and improves soil microorganism dynamics because of more beneficial environmental conditions (Helgason *et al*., 2010; Guo *et al*., 2015) [13, 11].

Soil Aggregates that control the dynamics of soil organic matter and nutrient cycling are structural units within the soil (Six *et al*., 2004; Naresh *et al*., 2017) [36, 22]. The aggregate hierarchy model shows that soil C accumulation in a given system may comprise a hierarchy of biological processes at the spatial dimension of soil physical structure (Wall *et al*., 2012) [38]. The distribution and stability of soil aggregates are important indicators of soil physical quality, highlighting the importance of soil management on particle aggregation and disaggregation (Silva *et al*., 2014) [35]. Aggregate stability is generally strongly correlated with SOC content, because the cohesion of aggregates is promoted mainly by organic polymer binding agents (Majumder *et al*., 2010) [19] and by the physical trapping of particles by fine roots and fungal hyphae (Helfrich *et al*., 2015) [12]. The analysis of soil-particle distribution by laser diffraction is now commonly used (Xiao *et al*., 2014) [42] and allows the categorisation of micro-aggregates into smaller size classes and provides detailed volume information for each size class. The volume fractal dimension (D_v) based on laser diffraction to characterise soil-particle and aggregate distribution model (Chen & Zhou, 2013) [6] and (Xiao *et al*., 2014) [42] reported that D_v well described the changes in the stability of soil aggregates and in soil structure associated with vegetative succession.

Soil microorganisms significantly affect the health of an agro-ecosystem through their functions in residue decomposition and nutrient cycling, as well as their associations with other organisms (Dong *et al*., 2014) [8]. The activities and compositions of soil microbial community and their interactions with environmental factors affect SOC dynamics and crop productivity (Dong *et al*., 2014) [8]. Biolog system, a rapid community-level approach for assessing patterns of sole C source utilization, is used to study microbial community metabolic activities (Qi *et al*., 2010) [31]. However, only a few these studies determined the relationship between soil microbial metabolic activities and SOC, especially within aggregates, in rice–wheat cropping systems. Rice–wheat cropping systems possess important functions in food security in Asia by providing food grains for more than 20% of the population worldwide (Qi *et al*., 2010; Kumari *et al*., 2011) [31, 14]. The effects of conservation tillage on rice–wheat cropping systems are well demonstrated (Guo *et al*., 2015; Naresh *et al*., 2018) [11, 23]. However, limited attention has been given to the relationship between SOC and microbial metabolic characteristics within aggregate fractions under conservation tillage in the rice–wheat system. Thus, we hypothesized that (1) microbial metabolic activity is improved by conservation tillage in the plow layer, and (2) the microbial metabolic activity is correlated to SOC within aggregates under conservation tillage. So, this study aimed to assess the effects of tillage practices on microbial metabolic characteristics and SOC within aggregates and their relationships under a rice–wheat cropping system in subtropical India. We hypothesised that the long-term adoption of conservation tillage (CT) could significantly influence SOC content and the distribution of soil aggregates over time. The specific objectives were thus: (1) to observe the effect of CT on SOC content, aggregate distribution and Dv and illustrate the relationship between them, and (2) to describe the dynamic changes in SOC content and Dv over time and effects on soil microbial community composition.

Zhang *et al*. (2018) observed that the direct path coefficients (P_{ij}) of micro-aggregate fractions are presented by single-headed arrows while simple correlation coefficients (r_{ij}) between variables are represented by double-headed arrows. Subscript designations of 1-9 are <0.002, 0.002-0.005, 0.005-0.01, 0.05-0.1, 0.1-0.2, 0.2-0.25, 0.25- 0.5, 0.5-1 mm micro-aggregates, and fractal dimension (Dv), respectively [Fig.1a]. Parihar *et al*. (2018) [25] also found that ZT and PB increased SOC stock (0–30 cm depth) by 7.22–7.23 Mg C ha^{-1} whereas CT system increased it only by 0.88 Mg C ha^{-1}as compared to initial value. The global warming potential (GWP) under CT system was higher by 18.1 and 17.4%, compared to CA-based ZT and PB, respectively. Among various maize systems, GWP of MMS were higher by 11.2, 6.7 and 6.6%, compared that of MWMb (1212 kg CO_2–eq. ha^{-1}), MCS (1274 kg CO_2–eq. ha^{-1}) and MMuMb (1275 kg CO_2–eq. ha^{-1}), respectively [Fig.1b].

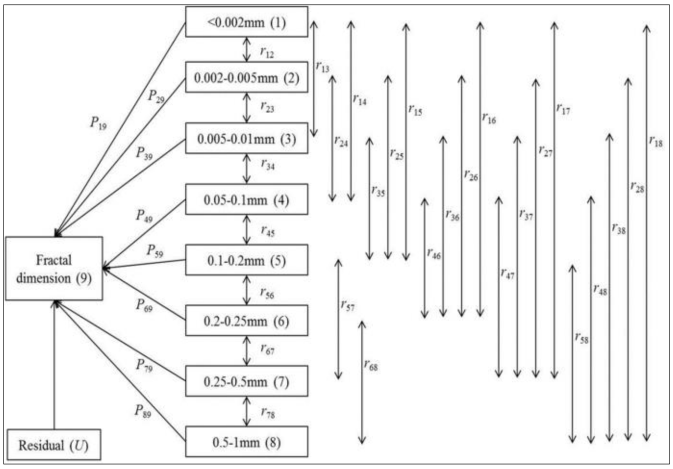


Fig 1(a): Path analysis diagram for the relationships between fractal dimension and micro-aggregate fractions [Source: Zhang *et al*., 2018]

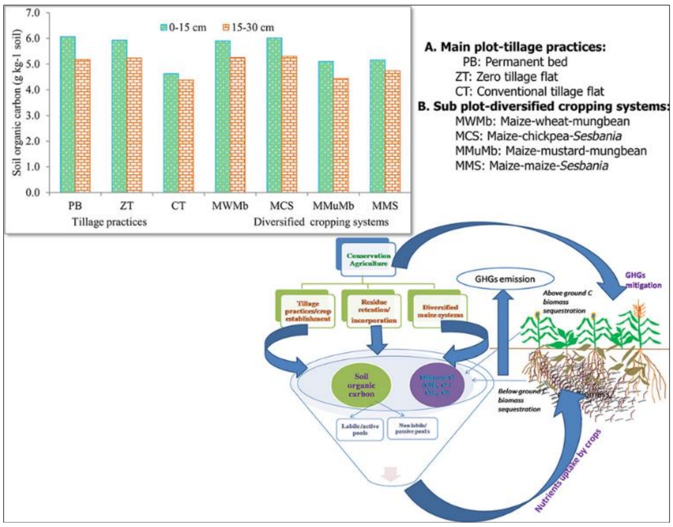
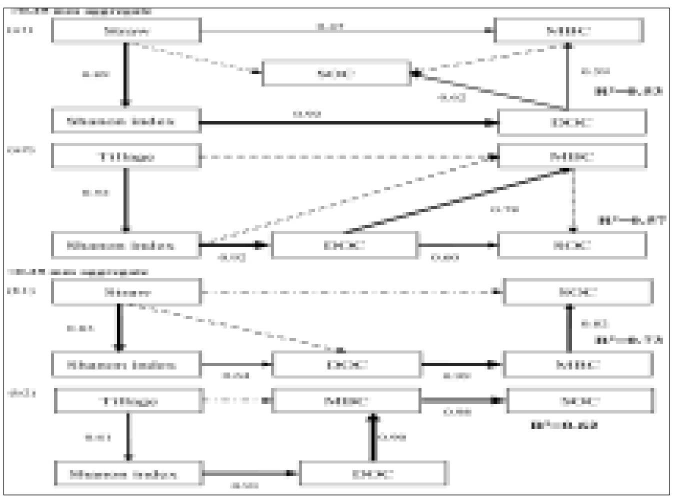


Fig 1(b): Dry-stable and water-stable mean-weight diameter and aggregate-size distribution (0–5 cm) under pasture, conservation tillage (CsT), and conventional tillage (CvT) system [Source: Parihar *et al*., 2018] [25].

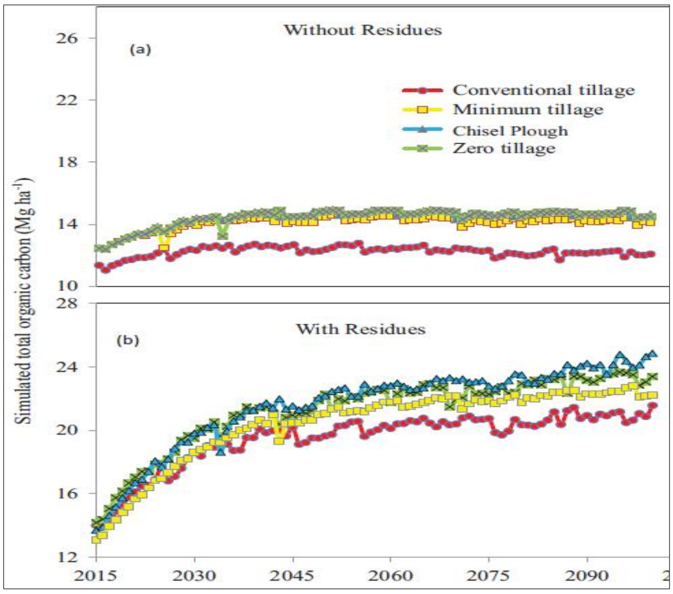
Guo *et al*. (2016) revealed that the relationship between soil microbial metabolic diversity and SOC under tillage and residue systems were analyzed separately using SEM for >0.25 and <0.25 mm aggregates [Fig.2a]. SEM revealed that the predictors explained 53% to 57% of the variation in SOC in >0.25 mm aggregate, and 62% to 73% in <0.25 mm aggregate. In >0.25 and <0.25 mm aggregates, microbial metabolic diversity affected SOC directly and indirectly through DOC and MBC, respectively. Moreover, changes in microbial metabolic diversity induced by tillage or straw systems influenced SOC directly through DOC in >0.25 mm aggregate, and directly and indirectly through DOC and MBC in <0.25 mm aggregate [Fig.2a].

Sharif *et al*. (2016) showed that by the end of this century, TOC will decrease under CT systems, while a minor increase under CP and ZT is expected. Their simulated values were 12 Mg ha^{-1} under CT, 14.65 Mg ha^{-1} under CP and 14.48 Mg ha^{-1} under ZT. When all tillage systems were simulated with retention of crop residue [Fig.2b], future simulations showed that TOC will gradually increase with retention of crop residues in all tillage systems including CT systems, but the increase will be higher under CP and ZT. The expected highest values by the end of this century will be 25 Mg ha^{-1} under CP followed by 23.38 Mg ha^{-1} under ZT. The reason for reducing the trend of TOC under CT systems without retention of crop residues is related to low retention of carbon sources and their rapid decomposition through the intensive mouldboard system in soil (Paustian *et al*. 2000) [26], whereas the CP system slowly mixes and maintains stability of organic material. The crop residue and straw returned back to soil contribute to gathering of SOC (Bierke *et al*. 2008) [2] while reduction in tillage operations keeps it undisturbed. Moreover, the long-term future simulations of different tillage systems without retention of crop residues [Fig.2c] demonstrate that ASC is expected to be 0.26 Mg ha^{-1} under CT, 0.45 Mg ha^{-1} under CP as well as ZT by the end of this century. Thus, the ASC contents will remain low under CT while more increase under alternative tillage systems is expected. The future simulations of different tillage systems with retention of crop residue [Fig.2c] showed that ASC will gradually increase under all tillage systems when residue is retained in order of CP > ZT > MT > CT with predicted values of 1.25, 1.17, 0.98 and 0.90 Mg ha^{-1}, respectively. The reason for low ASC under CT is mainly due to non-retention of crop residues as well as repeated ploughing and intensive tillage that destroys the microbial community while CP provides better environmental conditions for microbial growth. The higher ASC under different tillage systems with retention of crop residues is related to increase TOC in soil. The crop residue is the main source of food for microbial community (Sarathchandra *et al*., 2001) [32]. Soil ASC has been proposed as a sensitive indicator for soil health improvement as affected by different tillage systems and crop residues (Nannipieri *et al*., 2003) [21].



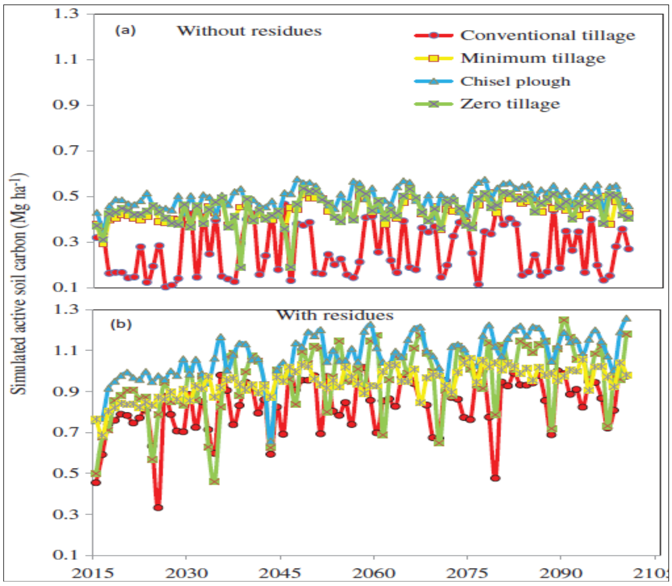
(a)

Fig 2(a): Structural equation modelling relating tillage systems, residue returning and microbial metabolic diversity to SOC in >0.25 mm [Source: Guo *et al*., 2016]



(b)

Fig 2(b): Simulated total organic carbon under the tillage treatments with and without crop residue [*Source*: Sharif *et al*., 2016) [34]



(c)

Fig 2(c): Simulated active soil carbon under the tillage treatments with and without crop residue [*Source*: Sharif *et al*., 2016) [34].

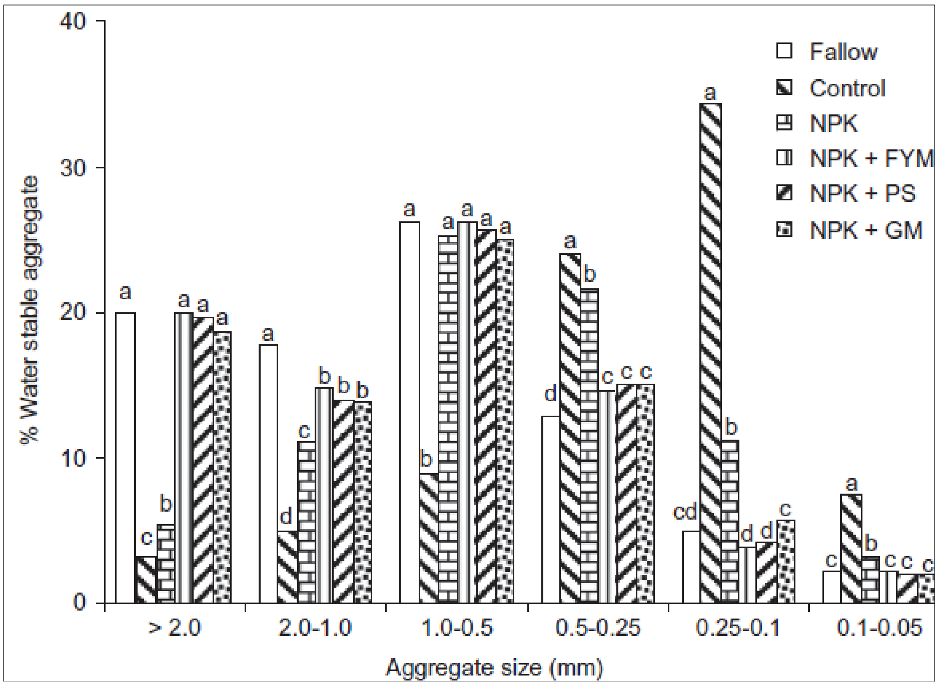
Bandyopadhyay *et al*. (2011) [1] revealed that the native fallow plots and long-term application of organics along with NPK significantly increased the proportion of larger aggregates (>1.0 mm) compared with other treatments. The NPK-treated plots also recorded a significantly greater proportion of aggregates in the ranges of >2, 1–2, and 0.5–1 mm than did the control plots. Water-stable aggregates of >0.5 mm diameter in the control, NPK, FYM, PS, and GM plots were, respectively, 26.6, 65.0, 95.3, 92.5, and 89.7% of fallow, whereas the WSA value in the control was only 40.9% of NPK. Control and NPK treatments were exhibited WSA values of 27.9 and 68.2, 28.7 and 70.3, and 29.6 and 72.5% less than FYM, PS, and GM, respectively. In the 0.5- to 1.0-mm aggregate class fraction, except for the control, the treatment effect was not significant, but in smaller size fractions (0.25–0.5 and 0.1–0.25 mm), the percentage distributions of aggregates in fallow, organically amended, and NPK were significantly lower than control treatment [Fig.3a].

Addition of organic matter might have increased the microbial activity of soil, which helped micro-aggregates to bind together to form water-stable macro-aggregates, as the macro-aggregates are mainly held together by fungal hyphae, fibrous roots, and polysaccharides (Tisdall and Oades 1982) [37]. Aggregation may also be influenced by the quality of organic amendments used, as their biochemical compositions have distinguishing capacity to resist rapid decomposition, which facilitates aggregation.

Bandyopadhyay *et al*. (2011) [1] also found the data revealed that the magnitude of increment was more pronounced at the surface layer than at the other two soil depths and decreased along depth, consisting of 18.3 and 33.1% reduction over surface layer. The MWD values of control and NPK treatments were at par at the 0.15- to 0.45-m depth and decreased by 38.0–61.8 and 36.7–53.0% over the fallow [Fig.3b]. Soil inversion and disruption by tillage with or without C supplementation accelerates decomposition of organic matter present initially, exposes the protected organic matter to soil organisms, and thus affects the MWD (Cambardella and Elliott 1992) [4].

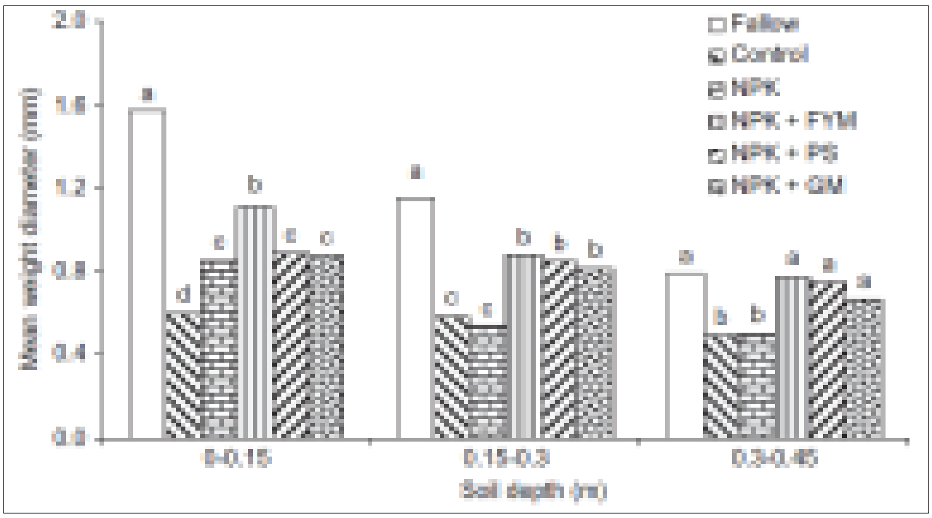
Sharif *et al*. (2016) [34] observed that the slow soil carbon (SSC) is expected to remain low under CT while it will slightly increase under CP and ZT tillage systems if residues are not applied. Their expected values by the end of this century are 3.50 Mg ha^{-1} under CT, 4.56 Mg ha^{-1} under CP and

4.38 Mg ha^{-1} under ZT. The future simulations of tillage systems with residue return [Fig.3c] demonstrate that SSC will gradually increase under all tillage systems with retention of crop residues in order of CP > ZT > MT > CT. Their estimated values at the end of this century are 14.33, 12.46, 11.86 and 10.88 Mg ha^{-1}, respectively, under CP, ZT, MT and CT.



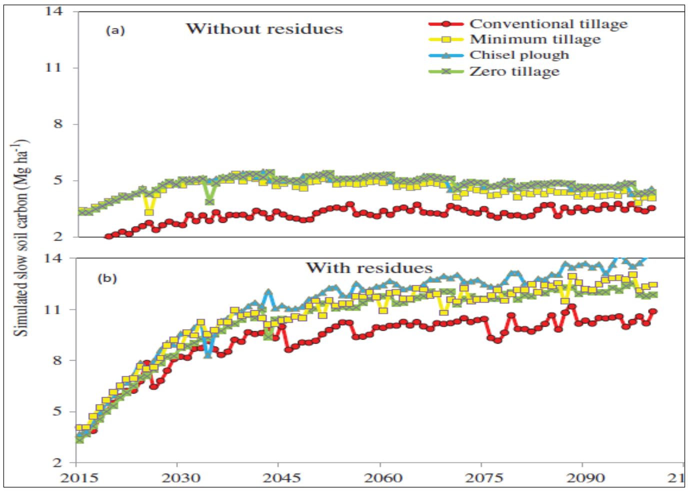
(a)

Fig 3(a): Proportion of different size fractions of water-stable aggregates in the 0- to 0.15-m soil depth as affected by long-term application of different sources of manure along with fertilizer [*Source*: Bandyopadhyay *et al*., 2011] [1].



(b)

Fig 3(b): Distribution of mean weight diameter within water-stable aggregates in the 0- to 0.15-m soil depth as affected by long-term application of different sources of manure along with fertilizer [*Source*: Bandyopadhyay *et al*., 2011] [1].



(c)

Fig 3(c): Simulated slow soil carbon under the tillage treatments with and without crop residue [*Source*: Sharif *et al*., 2016) [34].

Sharif *et al*. (2016) [34] revealed that the long-term future simulations regarding different tillage systems without retention of crop residues [Fig.4a] demonstrate that PSC will drastically decline under CT while will remain stable under alternative tillage systems. Their estimated values by the end of century are 8.27 Mg ha^{-1} under CT and 9.70 Mg ha^{-1} under each of the CP, ZT and MT tillage systems without retention of crop residues. When different tillage systems were simulated with retention of crop residues [Fig.4a], the results show that PSC will slightly improve under CP with value of 9.75 Mg ha^{-1}.The reason for a drastic decline in PSC under CT tillage systems without retention of crop residues is related to the higher decomposition of organic carbon in active and slow pool which ultimately results in reduction of carbon in passive pool. The higher contents of ASC and SSC under

ZT and CP with retention of crop residues will ultimately lead to increased PSC. The passive SOC is more resistant to further decomposition and is important for maintaining the quality of soil.

Poirier *et al*. (2014) [29] revealed that the large macro-aggregates (>1000 mm) in the SOC-poor subsoil were enriched in ^{13}C and ^{15}N in both particulate organic matter (POM, >50 mm) and fine particle size (<50 mm) fractions compared to the SOC-rich topsoil [Fig.4b]. We postulate that the retention of residue-C and -N in both POM and fine fractions within WS macro-aggregates is due to the large-scale occlusion of coarse material and small-scale adsorption of organic substances occurring concomitantly in soil. Although the mass of WS macro-aggregates levelled off at high residue input rate, accumulation of ^{13}C and ^{15}N in both POM and fine fractions continued throughout the incubation, and WS macro-aggregates did not become saturated with C and N in the short-term. Possible mechanisms occurring at increasing input rates include 1) coating of macro-aggregates with residue decomposition products, 2) continual turnover of macro-aggregates and 3) greater stability and formation of larger macro-aggregates. In this heavy clay soil, macro-aggregates represent a dynamic soil fraction that accumulates POM and organic compounds from decomposing plant material Poirier *et al*. (2014) [29] found that POM Cres, POM-Nres, fine-Cres and fine-Nres concentrations were significantly higher in subsoil than topsoil for every residue treatment [Fig.4c]. Within SM, we observed that POM-Cres and fine- Cres concentrations were significantly higher in topsoil than subsoil when 20 and 40 g residue-C kg^{-1} soil were added [Fig.4c]. However, at lower residue addition rates in SM, a tendency towards higher fine-resC concentration was noted in subsoil than topsoil. Within both LM and SM, about 70 and 60% of the residue-C was retained as POM in topsoil and subsoil, respectively. However, within LM and SM, about 66% of the residue-N was retained in the fine fraction in both soils [Fig.4c]. Poirier *et al*. (2013) [28] showed that the adding labelled residues probably provided substrate for the microbial production of organic substances that act as binding agents stabilizing soil aggregates.

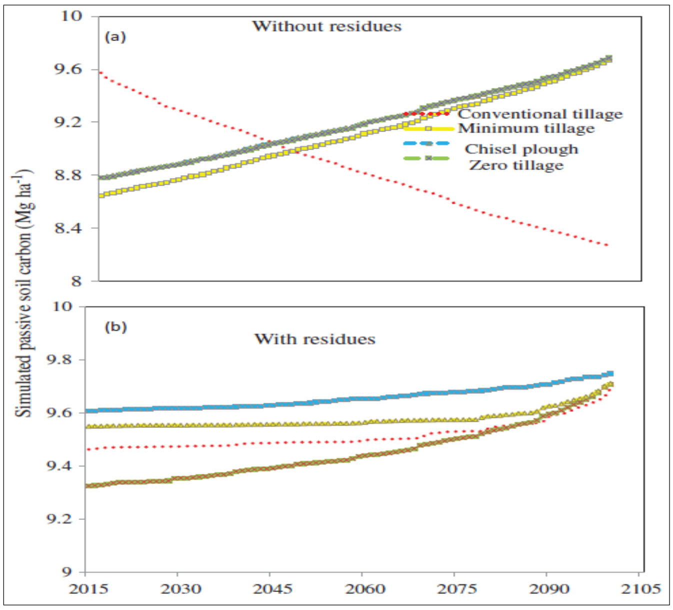


Fig 4(a): Simulated passive soil carbon under the tillage treatments; (a) and (b) with and without crop residue [*Source*: Sharif *et al*., 2016) [34].

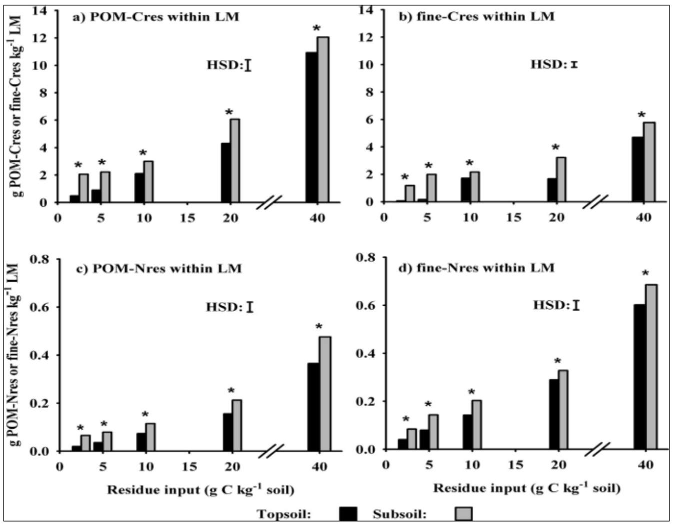


Fig 4(b): Retention of residue-C and -N in particulate organic matter (POM, >50 mm) and in fine particle-size (<50 mm) fractions within large water-stable macro-aggregates (LM, >1000 mm) in topsoil (0-20 cm depth) and subsoil (30-70 cm depth) from a heavy clay soil

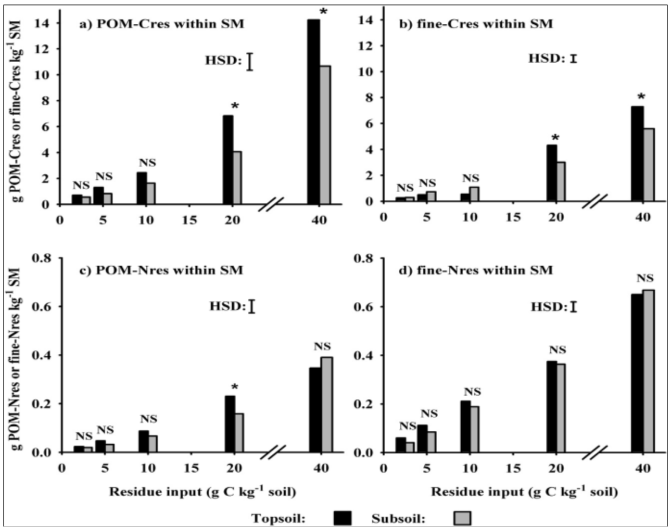


Fig 4(c): Retention of residue-C and -N in particulate organic matter (POM, >50 mm) and in fine particle-size (<50 mm) fractions within small water-stable macro-aggregates (SM, 250-1000 mm) in topsoil (0-20 cm depth) and subsoil (30e70 cm depth) from a heavy clay soil

Sapkota *et al*. (2016]) [33] reported that CA systems (i.e. ZT with residue retention) would sequester more carbon (C) than CT. After seven years, ZTDSRZTW+R and PBDSR-PBW+R increased SOC at 0–0.6 m depth by 4.7 and 3.0 t C/ha, respectively, whereas the CTR-CTW system resulted in a decrease in SOC of 0.9 t C/ha. Over the same soil depth, ZT without residue retention (ZTDSR-ZTW) only increased SOC by 1.1 t C/ha [Fig.5a]. There was no increase in SOC where ZT in either rice or wheat was followed by CT in the next crop (i.e. CTRZTW and ZTDSR-CTW), most likely because the benefit of ZT is lost when followed by tillage. Tillage and crop establishment methods had no significant effect on the SOC stock below the 0.15-m soil layer [Fig.5b]. Over the seven years, the total carbon input from above-ground residues was ca. 14.5 t/ha in ZTDSR-ZTW+R and PBDSR-PBW+R, almost six fold greater than in the other systems. Wang *et al*. (2011) [39] also found that when the N fertilizer application rate was 1.5 times higher or 2/3 lower than the baseline scenarios, the SOC content decreased by 0.14% or increased by 0.60%, respectively [Fig.5c]. This might be due to the parameter setting in the DNDC model. Because 188 $kgNha^{-1}$ N fertilizers is required to have maize reach maximum biomass, if more than 188 $kgNha^{-1}$ N fertilizer is applied, there will not be any further linear increase in yield, and the DNDC-modeled maize yield would no longer be sensitive to N fertilizer. In addition, excessive application of N fertilizer will decrease the ratio of C: N, and higher concentrations of N will increase the activity of soil microbes, which results in a higher decomposition rate, thus causing SOC to have a decreasing trend. Figure 8 also demonstrates that when the rate of crop residue incorporation or manure amendment was increased from 15% to 90% or 2000 kg C ha^{-1} yr^{-1} was added to the soil, the SOC content increased by 42% or 31%, respectively. Long-term simulation results showed that the increase of N fertilization rate alone was not effective in increasing the SOC content. The residue return rate and the manure amendment rate were the key factors governing the SOC content, and there was a positive correlation between them [Fig.5c].

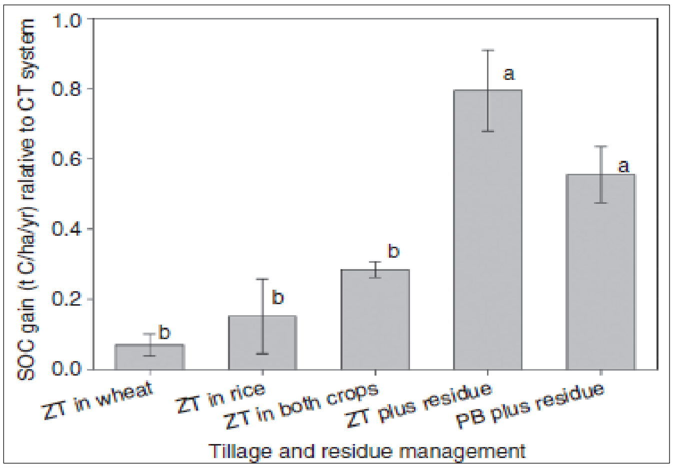


Fig 5(a): Gain in organic carbon stock in 0 to 0.6 m soil layer due to adoption of various components of CA over conventional control in a RW system [*Source*: Sapkota *et al*.,2016] [33].

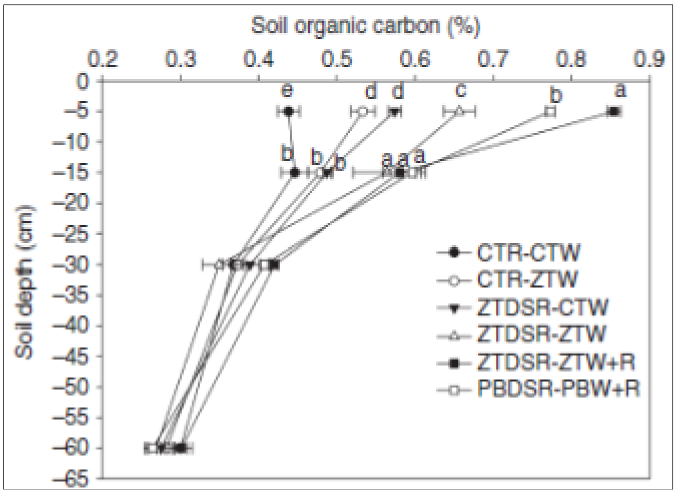


Fig 5(b): Organic carbon content (%) in different soil layers as affected by tillage and crop establishment methods. For each layer, values are presented at the bottom depth (e.g. -5 cm represents 0- to 5-cm soil layer) [*Source*: Sapkota *et al*., 2016] [33].

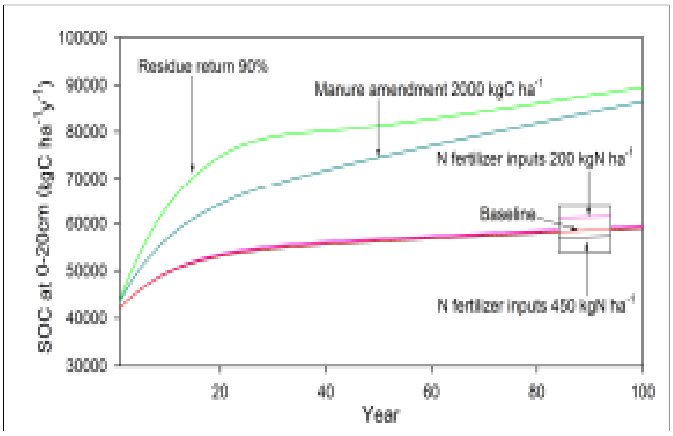


Fig 5(c): Influence of management practices on long-term SOC content [Source: Wang *et al*., 2011] [39].

Guo *et al*. (2016) observed that the compared with CT treatments, NT treatments did not affect SOC concentration of bulk soil in the 5−20 cm soil layer, but significantly increased the SOC concentration of bulk soil in the 0−5 cm soil layer

[Table 1]. In comparison with NS treatments, S treatments had not significant effects on SOC concentration of bulk soil in the 5−20 cm soil layer, but significantly enhanced the SOC concentration of bulk soil in the 0−5 cm soil layer [Table 1]. Therefore, this study only investigated the effects of conservation tillage on microbial metabolic characteristics and the relationships between the metabolic characteristics and SOC within aggregates in the 0−5 cm soil layer.

In the 0−5 cm soil layer, NT treatments significantly increased SOC concentration by 5.8%, 6.8%, and 7.9% of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate, respectively, compared with CT treatments [Table 1]. NT treatments significantly increased MBC of bulk soil, >0.25 mm and <0.25 mm aggregates by 11.2%, 11.5% and 20.0%, respectively, compared with CT treatments. DOC concentrations of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate under NT treatments were 15.5%, 29.5%, and 14.1% higher than those under CT treatments, respectively. In comparison with NS treatments, S treatments significantly increased SOC concentrations of bulk soil by 12.8%, >0.25 mm aggregate by 11.3%, and <0.25 mm aggregate by 14.1%. In addition, MBC of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate under S treatments were 29.8%, 30.2%, and 24.1% higher than those of NS treatments respectively. S treatments exhibited 25.0%, 37.5%, and 23.2% higher DOC concentrations of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate compared with NS treatments, respectively. In the 0−5 cm soil layer, there were significant interactions of tillage and straw returning on SOC concentration of >0.25 mm and <0.25 mm aggregates, MBC of bulk soil and <0.25 mm aggregate, and DOC concentration of >0.25 mm aggregate.

Table 1: Changes in SOC fractions within aggregates under different tillage and residue treatments [Source: Guo *et al*., 2016]

Organic C	Soil fractions	CTNS	CTS	NTNS	NTS	T	S	T×S
SOC (0–5 cm soil layer)	Bulk soil	19.60±0.55 d	21.29±0.12 b	20.33±0.46 c	21.75±0.18 a	*	*	ns
(g kg^{-1})	>0.25 mm	19.70±0.10 c	21.30±0.10 b	20.43±0.06 c	23.37±0.06 a	**	**	**
	<0.25 mm	17.28±0.06 d	19.48±0.12 b	18.41±0.17 c	21.24±0.18 a	**	**	**
SOC (5–10 cm soil layer)	Bulk soil	17.84±0.56 a	18.10±0.20 a	17.87±0.87 a	18.31±0.17 a	ns	ns	ns
(g kg^{-1})	>0.25 mm	/	/	/	/			
	<0.25 mm	/	/	/	/			
SOC (10–20 cm soil layer)	Bulk soil	15.67±0.47 a	15.97±0.41a	15.53±0.41 a	15.50±0.20 a	ns	ns	ns
(g kg^{-1})	>0.25 mm	/	/	/	/			
	<0.25 mm	/	/	/	/			
MBC (0–5 cm soil layer)	Bulk soil	1846±5.84 d	2366±38.58 b	2024±11.40 c	2657±28.71 a	**	**	*
(mg kg^{-1})	>0.25 mm	1962±3.68 d	2538±27.09 b	2173±57.73 c	2844±22.90 a	**	**	ns
	<0.25 mm	1517±10.56 c	1820±14.42 b	1758±11.33 b	2245±33.86 a	*	**	**
DOC (0–5 cm soil layer)	Bulk soil	1.09±0.04 d	1.33±0.03 b	1.22±0.03 c	1.56±0.04 a	**	**	ns
(g kg^{-1})	>0.25 mm	1.05±0.05 d	1.43±0.03 b	1.34±0.01 c	1.86±0.01 a	**	**	*
	<0.25 mm	0.89±0.03 d	1.10±0.02 b	1.01±0.02 c	1.25±0.02 a	**	**	ns

Different letters in a line denote significant differences among treatments.

**, P<0.01

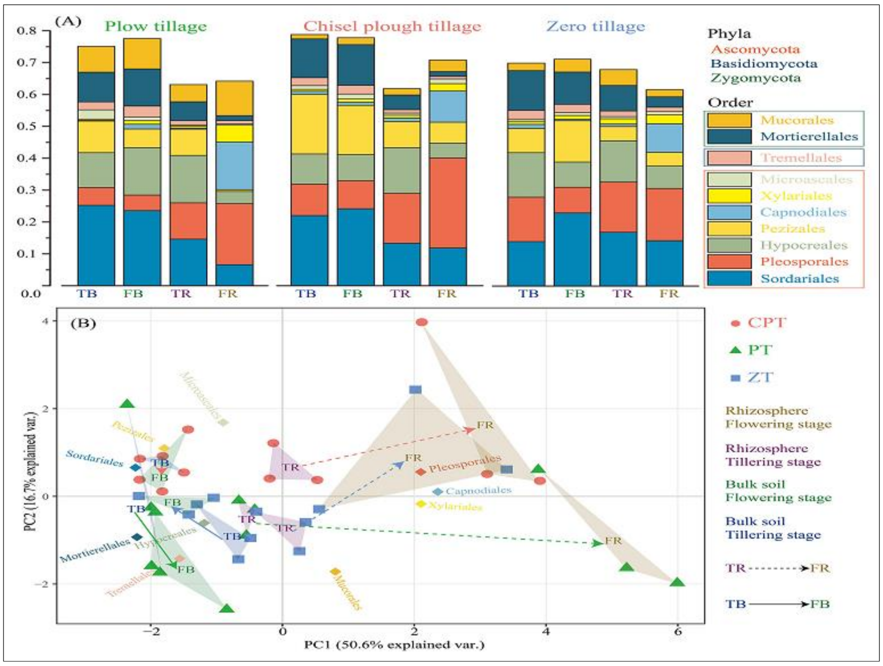
*, P<0.05

ns, not significant. CTNS, conventional intensive tillage with straw removal; CTS, conventional intensive tillage with straw returning; NTNS, no-tillage with straw removal; tillage; NTS, no-tillage with straw returning. T, tillage; S, straw; SOC, soil organic C; MBC, microbial biomass C; DOC, dissolved organic C; values are mean ± standard errors.

Wang *et al*. (2017) [41] observed that among all sequences, 82.2% were classified in bulk soil and 69.8% in rhizosphere soil. The dominant fungal phyla across all soil samples were Ascomycota (average 68.7%), Zygomycota (average 13.3%), and Basidiomycota (average 4.1%); at the order level, the fungal communities of all soil samples were dominated by Sordariales, Pleosporales, Hypocreales, Pezizales, Capnodiales, Xylariales, Microascales, Mortierellales, Mucorales, and Tremellales [Fig.6a]. Zero tillage was considerably closer to each other than chisel plough and plough tillage [Fig.6a]. The relative abundance of fungal orders varied in the rhizome and bulk soil along plant growth, but showed different patterns among the three tillage treatments. Relatively stable SOC and invertase activity indicated that zero tillage was preserving soil nutrient status, promoting fungal diversity (Plaza *et al*., 2013) [27].

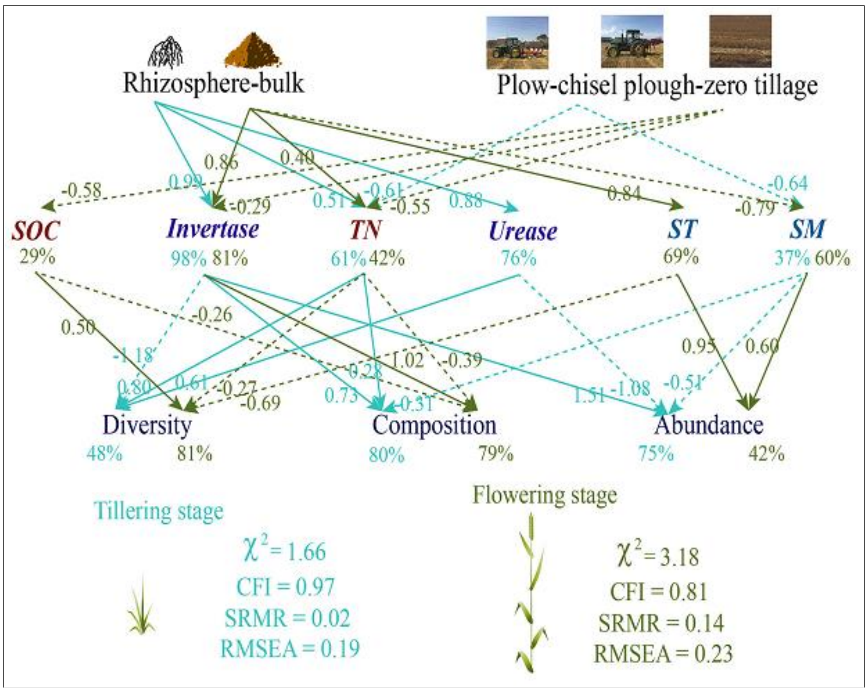
Plant growth stages and indicated that rhizosphere and tillage directly induced more changes in soil properties in the flowering stage (SOC: 29.2%, invertase: 80.5%, soil texture: 69.0%, TN: 42.4%, soil moisture: 60.1%) than in the tillering stage (urease: 76.3%, invertase: 98.4%, TN: 61.3%, soil moisture: 36.9%; [Fig.6b]. Soil invertase activity was the main determinant of the soil fungal community in the tillering stage, whereas soil texture and invertase significantly influenced fungal diversity, composition, and abundance in the flowering stage [Fig.6b]. Zero tillage, plough tillage, which is a conventional management practice that disturbs soil density, results in relatively low nutrient levels (here we observed low SOC and invertase activity), leading to a fungal phylogenetic structure that is more sensitive to plant growth and root activity (Wang *et al*., 2016a) [40]. At the tillering stage, zero tillage resulted in the greatest similarities between rhizosphere and bulk soil had more similar proportions of with respect to dominant fungal orders, which is mostly due to Sordariales preferring fine soils and decomposing residuals in environments with diverse nutrients, such as those associated with decomposing plant residues (Ma *et al*., 2013; Wang *et al*., 2016a) [18, 40]. Moreover, a comparison of the three tillage treatments showed that the soil fungal community was differently influenced by changes in soil properties associated with plant growth [Fig. 6c]. Soil enzyme activities and physical properties lead to changes in fungal communities in chisel plough (invertase: 94.2%, soil moisture: 77.2%) and plough tillage (urease: 68.0%, invertase: 88.2%, soil texture: 79.1%, soil moisture: 45.4%), whereas soil total nutrients (SOC: 29.8%, TN: 61.1%), and physical properties (soil texture: 89.1%, soil moisture: 62.3%) influenced fungal communities in zero tillage soils [Fig.6c]. Compared to plough tillage, fungal diversity (1.2%) and abundance (23.9%) had a lower and non-significant influence on the variation noted in chisel plough and zero tillage, respectively [Fig.6c]. Different patterns of direct and indirect effects on soil fungal community can be considered in relation to the biogeochemical processes occurring under the three tillage treatments, implying that long-term tillage may lead to a unique soil fungal ecology in response to biotic and abiotic factors (Eisenhauer *et al*., 2015) [9].

Causarano *et al*. (2014) [5] revealed that across locations, SOC at a depth of 0 to 20 cm was: pasture (38.9 Mg ha^{-1}) > CsT (27.9 Mg ha^{-1}) > CvT (22.2 Mg ha^{-1}) [Fig.7a]. Variation in SOC was explained by management (41.6%), surface horizon clay content (5.2%), and mean annual temperature (1.0%). Higher clay content and cooler temperature contributed to higher SOC [Fig.7b]. Management affected SOC primarily at the soil surface (0–5 cm). All SOC fractions (i.e., total SOC, particulate organic C, soil microbial biomass C, and potential C mineralization) were strongly correlated across a diversity of soils and management systems. The stratification ratio of SOC fractions differed among management systems and was 4.2 to 6.1 under pastures, 2.6 to 4.7 under CsT, and 1.4 to 2.4 under CvT [Fig.7c].



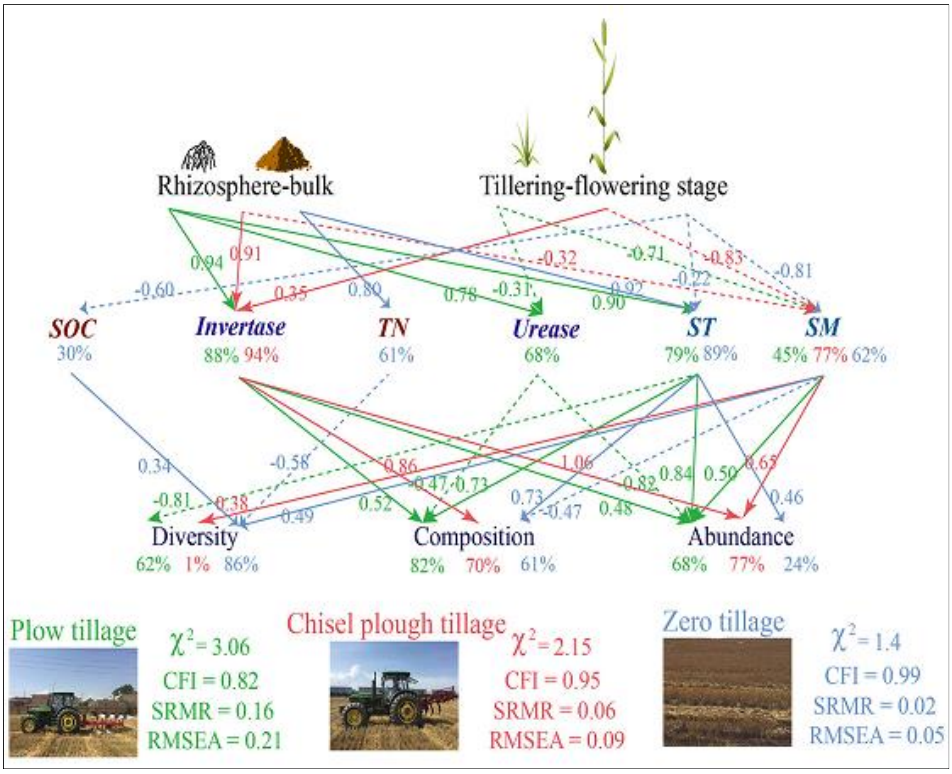
(a)

Fig 6(a): Relative abundance of the dominant fungal orders in all soil samples combined and in each tillage treatment (B) Principal Coordinate Analysis (PCoA) of abundant fungal orders. [*Source:* Wang *et al*., 2017] [41].



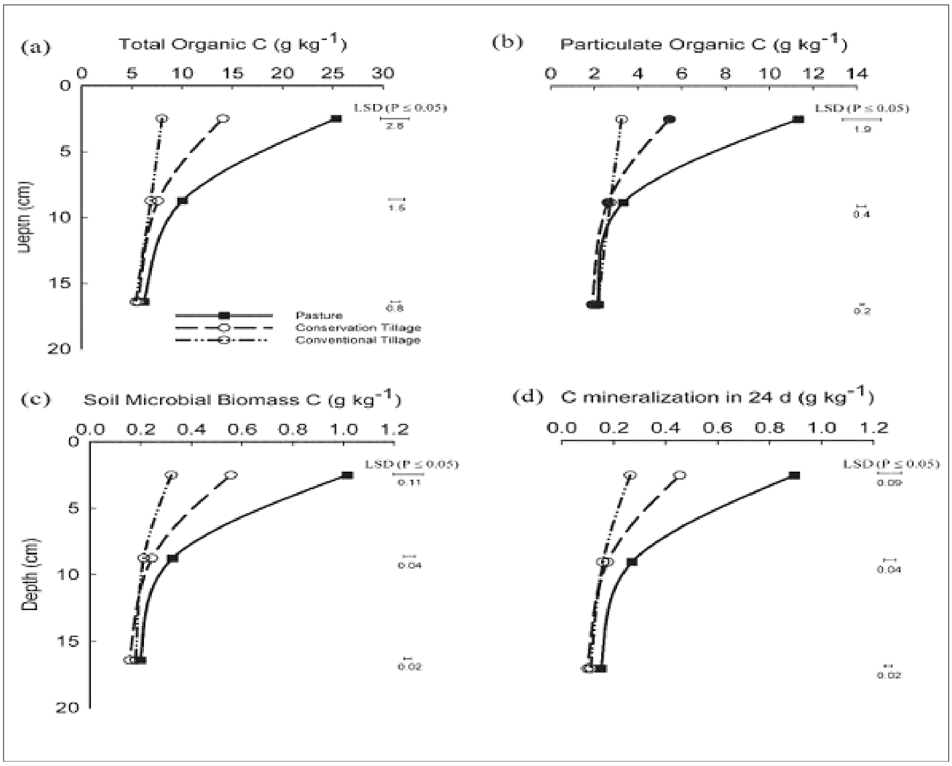
(b)

Fig 6(b): Path diagrams of the structural equation models for the relationship that tillage and plant growth on soil fungal diversity, abundance, and composition [*Source*: Wang *et al*., 2017] [41].



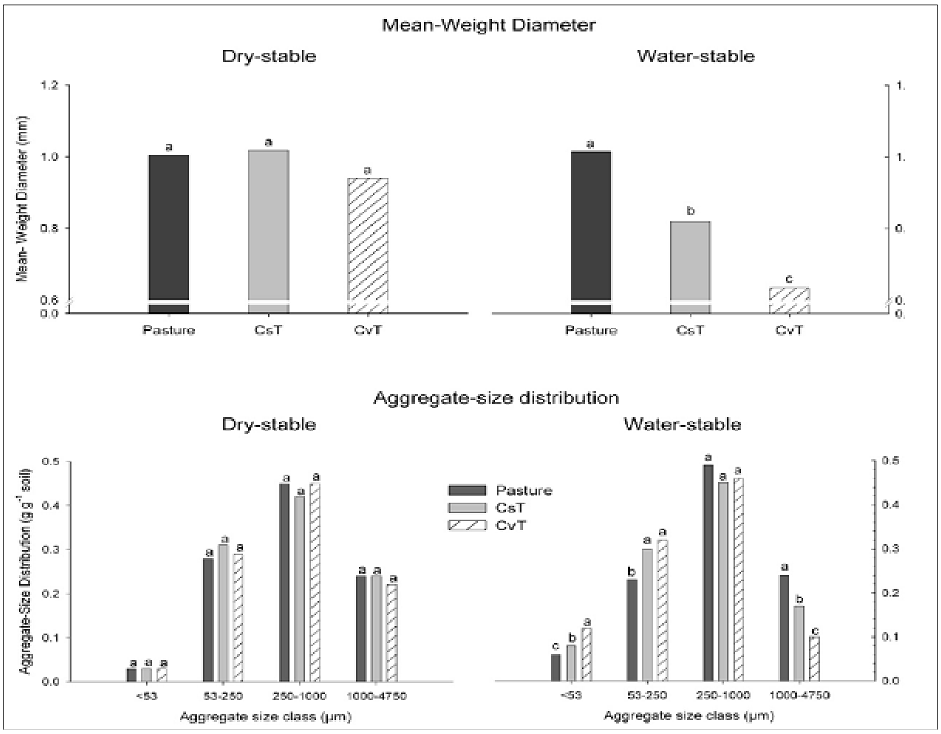
(c)

Fig 6(c): Path diagrams of the structural equation models for soil fungal community influenced by soil properties under the three tillage treatments in response to rhizosphere and plant growth [*Source:* Wang *et al*., 2017] [41].



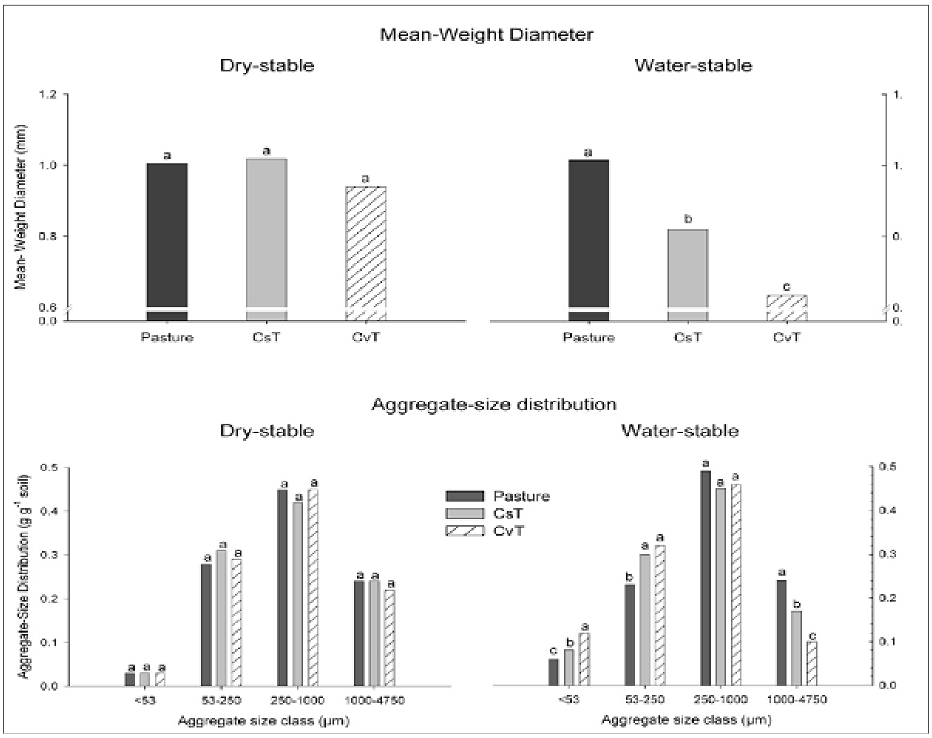
(a)

Fig 7(a): Depth distribution of (a) total soil organic C, (b) particulate organic C, (c) soil microbial biomass C, and (d) C mineralized [***Source:*** Causarano *et al*., 2014] [5].



(b)

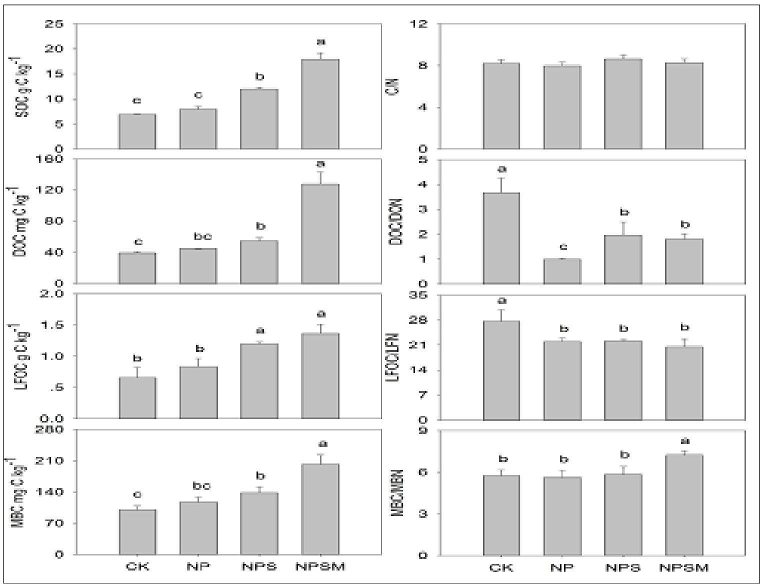
Fig 7(b): Dry-stable and water-stable mean-weight diameter and aggregate-size distribution (0–5 cm) under pasture, conservation tillage (CsT), and conventional tillage (CvT) systems [***Source:*** Causarano *et al*., 2014] [5]



(c)

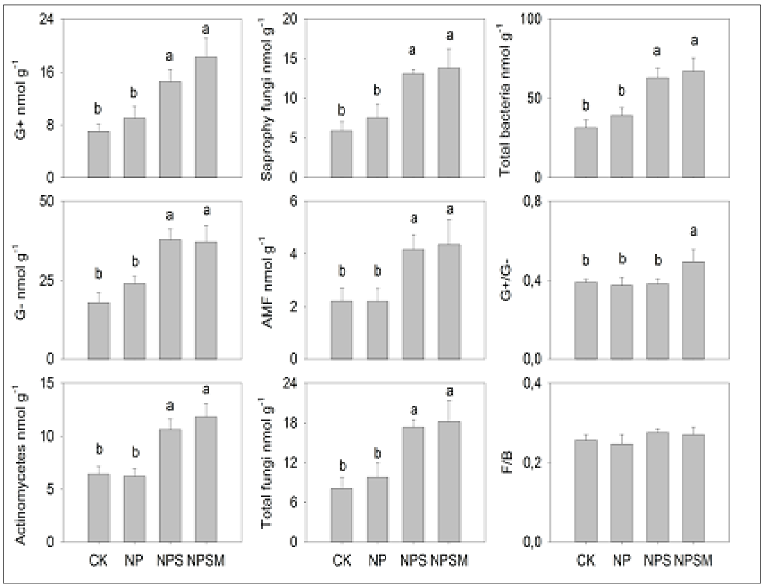
Fig 7(c): Stratification ratio of soil organic C fractions under pasture, conservation tillage, and conventional tillage [***Source:*** Causarano *et al*., 2014] [5]

Li *et al*. (2018) [16] reported that the application of chemical fertilizers (NP) alone did not alter labile C fractions, soil microbial communities and SOC mineralization rate from those observed in the CK treatment [Fig. 8a]. Whereas the use of straw in conjunction with chemical fertilizers (NPS) became an additional labile substrate supply that decreased C limitation, stimulated growth of all PLFA-related microbial communities, and resulted in 53% higher cumulative mineralization of C compared to that of CK [Fig. 8b]. The SOC and its labile fractions explained 78.7% of the variance of microbial community structure. Further addition of manure on the top of straw in the NPSM treatment did not significantly increase microbial community abundances, but it did alter microbial community structure by increasing G+/G- ratio compared to that of NPS [Fig. 8c]. The cumulative mineralization of C was 85% higher under NPSM fertilization compared to that of CK.



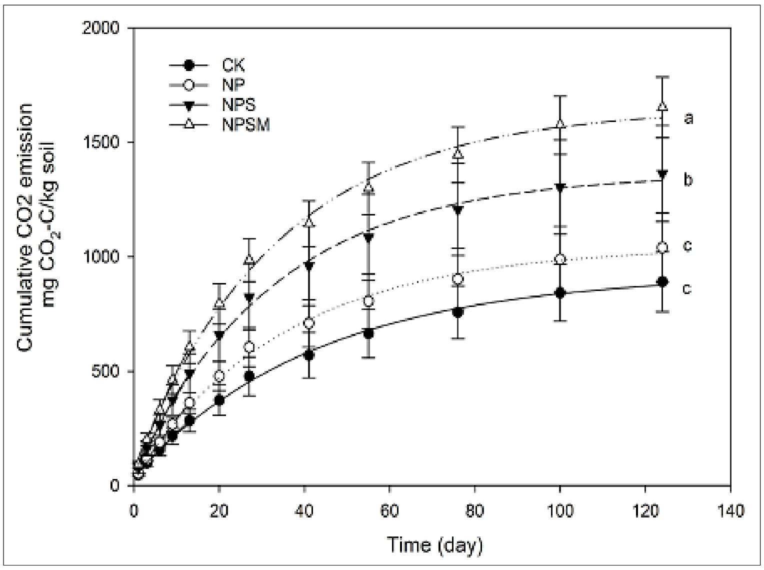
(a)

Fig 8(a): Organic C contents and C/N ratios of bulk soil and labile fractions under different fertilization regimes



(b)

Fig 8(b): Abundance of microbial biomarker groups under different fertilization regimes



(c)

Fig 8(c): Cumulative CO_2 emission over time under different fertilization regimes

Conclusion

This study clearly indicated that conservation agriculture (CA) applied practices significantly increased total SOC contents and labile organic C fractions (DOC, LFOC and MBC) in agricultural soils. Tillage is considered an anthropic agriculture management practice that can alter soil biota causing direct and indirect effects on crop growth and soil nutrient transformation (Brussaard *et al*., 2007) [3]. The results of the present review study revealed that plant growth increased the discrimination of fungal communities between bulk and CA soil, mostly due to increases in relative abundance of Sordariales and Mortierellales in bulk soil, as they decompose crop residues, and increases in Capnodiales and Pleosporales in rhizosphere soil, which can grow quickly by using carbon components from plant roots in rhizosphere soil. This CA study also revealed that the changes were not consistent between tillage; therefore, tillage may contribute to unique soil fungal ecology. However, tillage altered the variability in fungal communities, with zero tillage promoting more stable communities, likely because the practice preserves soil physical structure and nutrient status. Future research should focus on the differences in carbon resources between CA and bulk soils under the tillage practices, quantifying the relationship between organic carbon source utilization and fungal communities. The fungal community responded more strongly than the bacterial community, but in contrast to the bacterial community more taxa of the fungal community were depleted in relative abundance in the presence of straw than enriched. It will be of interest to assess in the future also the longer-term responses of the soil and rhizosphere microbiota to recurring straw applications and microbial carbon cycling in such agricultural systems. Management practices, crop rotation and straw application, affected not only the microbial community in the bulk soil, but to roughly similar extent those in the rhizosphere. This indicates that the rhizosphere microbiota is influenced by crop rotation and may not only profit from root-derived carbon. Actually, this influence may increase with decreasing distance to the root, as the transition from the rhizosphere to bulk soil is continuous. Furthermore, the application of organic fertilizers resulted in 53%-85% greater cumulative mineralization of C. Soil labile C fractions and soil microbial communities predominantly determined the variance in C mineralization, while C/N ratios of labile fractions did not significantly influenced C mineralization in the current agricultural system.

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