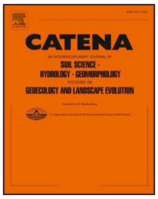
Catena 181 (2019) 104059

Contents lists available at ScienceDirect

Catena

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



Climate Smart Agriculture practices improve soil organic carbon pools, biological properties and crop productivity in cereal-based systems of North-West India

H.S. Jat[a,b], Ashim Datta[b,*], Madhu Choudhary[b,*], P.C. Sharma[b,*], A.K. Yadav[c], Vishu Choudhary[b], M.K. Gathala[d], M.L. Jat[a], A. McDonald[e]

[a] International Maize and Wheat Improvement Center (CIMMYT), New Delhi 110012, India
[b] ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal 132001, Haryana, India
[c] Sri Karan Narendra Agriculture University, Jobner 303329, Rajasthan, India
[d] International Maize and Wheat Improvement Center (CIMMYT), Tehran, Iran
[e] International Maize and Wheat Improvement Center (CIMMYT), Kathmandu, Nepal

ARTICLE INFO

Keywords:
Soil organic carbon (SOC)
Variable pools of SOC
Microbial parameters
Enzyme activities
Stratification ratio
System productivity

ABSTRACT

Intensive tillage coupled with crop residue burning in rice-wheat (RW) system is a serious issue that causes soil degradation and environmental pollution. Soil organic carbon (SOC) is one of the main indicators of soil health and system's sustainability. Zero-tillage has been widely recommended as an alternative for improving carbon sequestration in soil under different ecologies. But the SOC sequestration is very inconsistent and varied as it depends on the crop management practices. This study was performed in the western Indo-Gangetic plains (IGP) of India where RW system contributes 40% to the total country's food grain basket; however there exists issue of its sustainability because of declining SOC coupled with open field crop residue burning. Therefore, we evaluated the effects of different management scenarios (Sc) namely Sc1 (conventional till rice-wheat cropping system; business as usual), Sc2 (partial climate smart agriculture (CSA)-based rice-wheat-mungbean system), Sc3 (CSA-based rice-wheat-mungbean system), and Sc4 (CSA-based maize-wheat-mungbean system) on SOC pools and biological properties after 4 crop cycles (year 2009–2013). Soil samples were collected from surface and sub surface layers (0–15 and 15–30 cm soil depth) after rice harvesting in 2013. Results showed that the SOC stock at surface layer was higher by 70% with Sc4 than Sc1 (16.2 Mg C ha^{-1}) ($P < 0.05$). All the forms of carbon in different pools were higher ($P < 0.05$) with Sc4 and Sc2 over Sc1 at 0–15 and 15–30 cm soil depths, respectively. At surface soil SOC pools were found in order of Sc4 > Sc3 > Sc2 > Sc1 ($P < 0.05$). Higher lability index (LI) (2.1) and stratification ratio (SR) (2.5) of organic carbon were observed in CSA-based systems (Sc2 and Sc4). At surface layer (0–15 cm) the CSA- based scenarios (mean of Sc2, Sc3 and Sc4) showed higher ($P < 0.05$) enzyme activities viz. dehydrogenase (641 μgTPF g^{-1} 24 h^{-1}) and alkaline phosphatase (158 μg p-nitrophenol g^{-1}), and microbial biomass carbon (MBC) (787 μg g^{-1}) and microbial biomass nitrogen (MBN) (98 μg g^{-1}) compared with Sc1. Higher value of the basal soil respiration (34%) was also observed with CSA-based scenarios (Sc2, Sc3, Sc4). Surface soil layer showed maximum counts of fungi, bacteria and actinomycetes in Sc4. MBC, fungal population and SOC were the most sensitive biological soil parameters identified through principal component analysis (PCA) which can be used for soil quality assessment. Therefore, medium term adoption of climate smart agricultural practices involving zero-tillage, crop establishment, residue management and crop diversification in rice-wheat system can significantly improve the systems productivity by improving SOC and soil biological quality.

Abbreviations: Sc1, conventional rice-wheat cropping system; Sc2, partial CSA-based rice-wheat-mungbean system; Sc3, CSA-based rice-wheat-mungbean system; Sc4, CSA-based maize-wheat-mungbean system; CSA, climate smart agriculture; ZT, zero tillage; SOC, soil organic carbon; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; LI, lability index; SR, stratification ratio; PCA, principal component analysis; RW, rice-wheat

[*] Corresponding authors.
E-mail addresses: ashimdatta2007@gmail.com (A. Datta), madhucssri@gmail.com (M. Choudhary), pcsharma.knl@gmail.com (P.C. Sharma).

https://doi.org/10.1016/j.catena.2019.05.005
Received 4 June 2018; Received in revised form 24 April 2019; Accepted 4 May 2019
0341-8162/

1. Introduction

Climate change and food insecurity are the two serious issues to the mankind in 21st century (Datta et al., 2017). In developing countries, 60% more food and feed will have to be produced by 2050 to satisfy the expected demands as per current consumption pattern (http://www.fao.org/3/a-i3325e.pdf) and with expected climate change effects. To feed this burgeoning world population, significant transformation is required in present day agriculture practices. Given the adverse impact of climate change on agriculture, climate smart adaptation mechanisms need to be strengthened in the present day agriculture. In the Indo-Gangetic Plains (IGP) of South Asia, rice-wheat (RW) is a major crop rotation covering ~13.5 million ha in India, Pakistan, Nepal and Bangladesh, providing livelihood to billions of people (Ladha et al., 2000; Timsina and Connor, 2001). Conventional crop management practices coupled with crop residue burning with expected climate change created alarming situations for soil quality, environmental pollution and yield stagnations (Timsina and Connor, 2001). This calls for immediate solution by adopting improved management practices for better soil health, environment quality, enhancing the adaptive capacity and productivity through sustainable intensification in western IGP of India.

Recently climate-smart agriculture (CSA) practices based on conservation agriculture (CA) principles is becoming popular among the farmers and because of that Govt. of India is providing more thrust on CSA adoption to better cope up with extreme weather events. CSA is based on three interlinked pillars of productivity, adaptation, and mitigation (http://www.fao.org/3/a-i3325e.pdf). CSA-based management practices like zero tillage (ZT), residue retention, water and nutrient management, crop diversification, and information and communication tools (ICTs) support to achieve sustainable intensification in RW system compared to conventional (business as usual/ farmer's practice) practices. Rising atmospheric CO_2 concentration (above 400 ppm) (Datta et al., 2015) necessitated considerable interest regarding the sink potential of soil organic carbon (SOC) (Baker et al., 2007). To mitigate the climate change effects on agriculture, soil has the tremendous potential by managing soil organic matter through soil carbon storage (Paustian et al., 2016; Powlson et al., 2016). Minasny et al. (2017) using world data discussed strategies to sequester atmospheric carbon into soils. Paradigm shift in the agricultural practices provides one of the inexpensive solutions proposed to mitigate this increase through carbon sequestration in soil (Smith et al., 2008). Improved site-specific management practices like cover crops, crop residue management, and zero-tillage may be followed in arable soils for carbon sequestration (Smith et al., 2008; Powlson et al., 2012). There is a general consensus that returning of crop residues to soil (Powlson et al., 2011a) and growing catch crops between two main crops regularly (Choudhary et al., 2018b) helped in increasing SOC stocks. For maintaining or increasing SOC (West and Post, 2002) and mitigating CO_2 emissions (Powlson et al., 2011b), zero-tillage is recommended instead of conventional tillage. The widespread adoption of conservation tillage in United States could sequester 24–40 Mt. C year^{-1} (Lal et al., 2003). Zero-till direct seeded rice (DSR) and replacement of rice with maize has proved a suitable alternative to manually transplanted rice as it saves water, energy and labor (Gathala et al., 2013) and improve soil properties (Jat et al., 2018; Choudhary et al., 2018a). Integration of the mungbean in RW system is helpful in increasing the carbon and nitrogen concentration in soil and overall soil quality improvement (Singh et al., 2015).

Hundreds of studies and several meta-analyses were conducted to quantify the benefit of zero-till on SOC stocks, but still there is controversy (Luo et al., 2010; Dimassi et al., 2014). Many studies in 90s and early 2000 reported that C sequestration was observed under ZT, but this conclusion has been challenged later with more rigorous studies and meta-analyses (Dimassi et al., 2014). West and Post (2002) conducted the first meta-analysis by examining 67 long-term experiments and reported that conversion of conventional tillage (CT) to ZT can sequester 0.57 ± 0.14 t C ha^{-1} yr^{-1} with maximum sequestration rates occurring between 5 and 10 years. However, Baker et al. (2007) reported biased results due to sampling protocol, particularly insufficient depth sampling. Another meta-analysis found that the mean C sequestration rate for ZT was 4.9 t C ha^{-1}after 13 years of cultivation (Angers and Eriksen-Hamel, 2008). While a consensus seems to exist on the potential of no tillage for carbon sequestration and climate change mitigation, but recent studies indicate that the abandonment of tillage may yield limited benefits for carbon sequestration (Baker et al., 2007; Geisseler and Horwath, 2009; Luo et al., 2010; Mchunu et al., 2011; Dimassi et al., 2014; Powlson et al., 2014). But Powlson et al. (2014) also argued the beneficial role of ZT in soil quality improvement through SOC sequestration and adaptation of agriculture to climate change, though its role in mitigation is widely overstated.

CA is highly debated, with respect to both its effects on crop yields and its applicability in different farming contexts. In semi-arid Argentina, Diaz-Zorita et al. (2002) showed that about 1.0 Mg ha^{-1} decrease in SOC at surface soil through erosion resulted 40 kg ha^{-1} reduction in wheat yield across 134 farmer's fields, confirming the importance of SOC in maintaining crop productivity. Recently, Pittelkow et al. (2015) conducted a global meta-analysis using 5463 paired yield observations from 610 studies of 63 countries across 48 crops and observed yield reduction under ZT, though in variable extent but under certain situations, it can produce equivalent or greater yields than conventional tillage when combined with residue retention and crop rotation by minimizing its negative impacts.

SOC pools directly influence the soil biological properties (Blanco-Canqui et al., 2013) thereby need thorough investigations. Information on soil properties, especially biological properties, under changing soil and crop management practices is essential for systems sustainability (Franzluebbers, 2002; Singh et al., 2014) as microorganisms play an important role in nutrient availability and improvement in several other soil health parameters (Smith et al., 1993). Lability index and recalcitrance indices can serve as an indicator of stable carbon in the soil (Datta et al., 2017, 2018). Stratification ratio (SR) is a ratio of value of a soil property in the surface soil to its value in the lower depth and it can be used to measure management induced changes such as tillage, residue cover etc. and also normalizes differences generated due to climatic conditions and soil types. Franzluebbers (2002) had shown that the soil quality is directly linked to the degree of stratification.

So many studies have been conducted on conservation tillage, fertilization and crop regimes effect on soil aggregation and carbon pools in soil (Bhattacharyya et al., 2012; Govaerts et al., 2009; Parihar et al., 2018). Indeed very few studies have looked at the dynamics of SOC into different pools as well as their relationships with soil biological properties and system yield under a series of CSA practices involving ZT, crop rotation, residue cover, water management etc. Information on effect of CSA practices on lability index, recalcitrance indices and stratification ratios of SOC are also rare. Studies on the effects of different CSA practices on different indicators of soil biological health is also very limited. We hypothesize that CSA would improve SOC and biological properties than conventional practices and it varies as per the system management practices. Therefore, we evaluated the effect CSA-based sustainable intensification on SOC pools and soil biological properties and their interrelationships with system yield after 4 years of continuous cultivation in cereal-based cropping systems of North-West Indian IGP.

2. Materials and methods

2.1. Study site characteristics

During 2009–2013, a field experiment was conducted at Indian Council of Agricultural Research -Central Soil Salinity Research Institute (29°70′N, 76°95′E), Karnal, Haryana, India with semi-arid and sub-tropical climate with extreme hot and dry (April–June) to wet summers (July–September) and cold dry winters (October–March). The mean maximum temperature was 31.68 °C in the month of June, whereas minimum temperature was 11.62 °C in coldest month of January with an average annual rainfall of 670 mm. The soil was loam in texture, low organic carbon (0.45%) with neutral pH. The soil type was fine-loamy mixed hyperthermic family of *Typic Natrustalf* (Soil Survey Division Staff, 1993).

2.2. Treatments and experimental design

In the study, four cereal-based scenarios varied with different cropping system, tillage, crop establishment methods, and crop residue management practices were imposed. The experiment was laid out in a randomized block design and replicated thrice in production-scale plots (2000 m^2; 20 m × 100 m). The treatments, termed as scenarios were designed keeping in view of present as well as future drivers of agricultural changes in the region and their details can be obtained from earlier publication (Gathala et al., 2013). Briefly, in Scenario 1 (Sc1-conventional till rice-wheat cropping system, residues removed; business-as-usual), both rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) were sown with conventional tillage, manual transplanting of 30-days-old rice seedlings in puddled soil and wheat by manual broadcasting. Scenario 2 (Sc2-partial CSA-based rice-wheat-mungbean system) consisted of transplanting of rice in puddled soil and subsequent wheat and mungbean (*Vigna radiata* L.) both by drill seeding in zero-till conditions, residues were incorporated during rice. Under Scenario 3 (Sc3-full CSA-based rice-wheat-mungbean system), crop residues were retained on soil surface and crops (rice, wheat and mungbean) were sown under ZT condition and Scenario 4 (Sc4-CSA-based maize-wheat-mungbean system), all the three crops (Maize: *Zea mays* L., wheat and mungbean) were drill seeded under ZT with residue retention. In all the scenarios best crop management practices for nutrient, water, weed, pests etc. were followed excepting Sc1 (conventional till rice and wheat), where farmer's practices were followed.

2.3. Recycling of crop residues in soil

The amounts of crop residue recycled varied among the scenarios (Table 1). In Sc1, all the residues were removed from the plots. On the other hand, in Sc2, Sc3, and Sc4, a total of 47.9, 56.15, and 65.8 Mg ha^{-1} of crop residues, respectively, were added in four years of study. Residue load varied from 4.1 to 10.6 Mg ha^{-1} in case of rice, 0.7 to 3.6 Mg ha^{-1} in case of wheat and 9.5 to 13.7 Mg ha^{-1} in case of maize under different scenarios. In Sc2, 2.5 to 4.7 t ha^{-1} of mungbean residue was incorporated into soil during puddling operation of rice. However, in Sc3 and Sc4 all the mungbean residues were retained on the soil surface.

2.4. Soil sampling and processing

Soil samples were collected from 0 to 15 and 15–30 cm soil depths using auger with 5 cm internal diameter both at the initiation of experiment in 2009 and after harvest of rice in October 2013. Each plot was divided into four 50 m × 10 m grids. Within each grid, sub-samples were collected from nine locations and then a composite sample of each depth was prepared. Part of the soil samples were air-dried in shade, ground to pass through a 2-mm sieve, stored in plastic container for analysis of selected soil chemical properties. The remaining portion of the fresh soil samples was kept in refrigerator at 4 °C for analysis of soil biological parameters. Initial soil properties of the experimental field can be obtained from Gathala et al. (2013).

2.5. Measurement of soil parameters

Core method was used for measuring soil bulk density (BD) by collecting triplicate soil cores at 0–15 and 15–30 cm depth (Blake and Hartge, 1986). The data of soil BD was presented by Jat et al. (2018). Wet oxidation method of Walkley and Black (1934) was employed to estimate oxidizable organic carbon content of the soils. Modified Walkley and Black method was used for estimating the SOC fractions using 5, 10 and 20 mL of concentrated H_2SO_4 (which corresponded respectively to 12 *N*, 18 *N* and 24 *N* of H_2SO_4 (Datta et al., 2015). Very labile (C_{VL}), labile (C_L), less labile (C_{LL}) and non-labile (C_{NL}) pools of SOC were the fractions. The above fractions are grouped into active (C_{AP}) [$\Sigma(C_{VL} + C_L)$] and passive (C_{PP}) [$\Sigma(C_{LL} + C_{NL})$] pool (Datta et al., 2015). The total carbon concentration in soil was determined by CHNS analyzer (Elementer vario El III, Germany). As the inorganic carbon concentration was negligible, we assume total carbon as total organic carbon and presented as soil organic carbon (SOC).

SOC stock was calculated by following equation (Datta et al., 2015) Eq. (1).

$$\text{C stock in soil} = \text{C content} \times \text{Bulk density} \times \text{Depth} \tag{1}$$

where, C stock is in Mg ha^{-1}, C content is g C kg^{-1}, bulk density is Mg m^{-3} and depth is in meter.

Lability index (LI) was computed following the Eq. (2) given below (Datta et al., 2015)

$$LI = \frac{C_{VL}}{C_{SOC}} \times \frac{C_L}{C_{SOC}} \times \frac{C_{LL}}{C_{SOC}} \tag{2}$$

where C_{VL}: very labile C; C_L: labile C; C_{LL}: less labile C; C_{soc}: soil organic C.

The recalcitrant index (RI) (Eqs. (3) and (4)) of SOC was derived following two ways for assessing different CSA practices effect on soil C stabilization (Datta et al., 2017):

$$RI_1 = \frac{C_{LL} + C_{NL}}{C_{VL} + C_L} \tag{3}$$

$$RI_2 = \frac{C_{NL}}{C_{SOC}} \tag{4}$$

where RI: recalcitrant index; C_{VL}: very labile C; C_L: labile C; C_{LL}: less labile C; C_{NL}: non labile C; C_{soc}: soil organic C.

Dehydrogenase activity (DHA) was determined from the conversion of 2,3,5-triphenyl tetrazolium chloride (TTC) to triphenyl formazan

Table 1

Amount of residues added (Mg ha^{-1}) to soil from each crop under different scenarios in four years of study.

Scenarios	2009–10			2010–11			2011–12			2012–13			Total
	R/M	W	MB	R/M	W	MB	R/M	W	MB	R/M	W	MB	
Sc1	0	0	F	0	0	F	0	0	F	0	0	F	0
Sc2	4.2	3.5	2.6	4.1	2.6	4.7	7.4	1.6	3.3	10.6	0.7	2.5	47.9
Sc3	9.4	3.6	2.2	10.2	2.8	4.4	7.2	1.6	3.0	5.3	1.8	4.6	56.1
Sc4	10.0	3.5	2.1	13.7	2.6	3.9	9.5	1.6	2.9	10.0	1.4	4.6	65.8

Sc1 - conventional rice-wheat system; Sc2 - partial CSA-based rice-wheat-mungbean system; Sc3 - CSA-based rice-wheat-mungbean system; Sc4 - CSA based maize-wheat-mungbean system.

R = Rice, M = Maize, W = Wheat, MB = Mungbean, F = Fallow.

(TPF) over a 24-h period (Dick et al., 1996). Alkaline phosphatase activity (APA) was determined as described by Dick et al. (1996) and is expressed as µg p-nitrophenol formed per gram of oven dry soil. Soil microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) were determined according to the fumigation-extraction method (Vance et al., 1987; Jenkinson, 1988). The values of K_C and K_N were 0.38 and 0.45, respectively. Stratification ratio (SR) was calculated by dividing the values measured in the 0–15 cm soil depth by the values for the 15–30 cm depth (Franzluebbers, 2002; Geisseler and Horwath, 2009). Mineralizable carbon of 0–15 cm soil depth from different scenarios was estimated by CO_2—C evolution method. The amount of CO_2 evolved during the 23-day incubation period was absorbed in 10 mL of 0.5 *N* NaOH solutions. Evolved CO_2 was calculated by titrating the alkali in the traps with 0.5 *N* HCl using phenolphthalein indicator (Anderson, 1982). Basal soil respiration (BSR), an estimate of potential microbial activity, was calculated as the linear rate of respiration during 10 to 23 days of incubation and expressed as µg CO_2—C per g of oven dry soil per day (Franzluebbers and Arshad, 1996). Respiratory quotient or metabolic quotient (qCO_2) was measured as the ratio of mineralizable carbon (C_{min}) to MBC and expressed as µg CO_2 evolved per day per µg MBC (Vance et al., 1987). The microbial quotient (MQ) was calculated as the MBC as a proportion of SOC.

The total bacterial count was determined on nutrient agar media (NA) after 3 days incubation at 32 °C (Zuberer, 1994). Streptomycin (30 µg/mL) supplemented rose bengal agar (RBA) media was used for fungal count and plates were incubated at 30 °C for 5 days (Martin, 1950). Actinomycetes count was done on nalidixic acid (50 µg mL^{-1}) supplemented actinomycetes isolation agar (AIA) after 7 days incubation at 28 °C (HiMedia Manual, 2009). All the plates were replicated thrice and results were expressed as colony forming units (CFU) g^{-1} dry soil.

2.6. System productivity (rice equivalent yield)

The crops were harvested manually from 4 × 4 m^2 randomly selected 4 quadrates from each plot and the grain yield was recorded. To express the overall impact of scenarios, system productivity was calculated on rice equivalent yield (REY) basis for wheat and mungbean grain yield. Grain yield of crops was recorded at 14% moisture basis. System productivity (Mg ha^{-1}) was computed using below equation.

$$\text{Rice equivalent yield (REY)} = \frac{\{\text{wheat/maize/mungbean yield (Mg/ha)} \times \text{MSP of wheat /maize/mungbean (INR Mg/ha)}\}}{\text{MSP of rice (INR Mg/ha)}}$$

where, MSP is the Minimum Support Price; INR is the Indian Rupee.

2.7. Statistical analysis

The data were subjected to analysis of variance (ANOVA) and using the general linear model (GLM) procedure of the SPSS window version 17.0 (SPSS Inc., Chicago, USA). Principal component analysis (PCA) was performed following the same statistical package mentioned above. Treatment means were separated by Duncan Multiple Range Test at 5% level of significance ($P < 0.05$).

3. Results and discussion

3.1. Soil organic carbon and its pools

The major effect produced by the CSA-based scenarios was higher accumulation of SOC in the surface soil compared to conventional system or business-as-usual (Sc1) (Fig. 1). Results showed that the SOC was increased by 69.7%, 40.7% and 9.0% under CSA-based scenarios; Sc4, Sc3 and Sc2, respectively compared to Sc1 (16.2 Mg C ha^{-1}) at 0–15 cm soil depth (Fig. 1). In surface soil layer, active and passive pool carbon (18.6 and 10.2 Mg C ha^{-1}) was higher by 90% and 59%, with Sc4 compared to Sc1 (9.8 Mg C ha^{-1} and 6.4 Mg C ha^{-1}), respectively after four years of continuous CSA. Sc4 (12.4 Mg C ha^{-1}) and Sc3 (10.6 Mg C ha^{-1}) recorded highest very labile C (C_{VL}) which was about 82% and 56% higher compared with Sc1 (6.8 Mg C ha^{-1}). Sc4 conserved significantly higher C_L (110%), C_{LL} (39%) and C_{NL} (71%) at surface soil layer compared with Sc1 (Fig. 1). Highest active pool (C_{AP}) (72%) and passive pool (C_{PP}) carbon (47%) as per cent of SOC were recorded with Sc3 and Sc2, respectively at 0–15 cm soil depth (Fig. 3a). Sc3 showed higher C_{VL} (45–47%) and C_L (23–25%) carbon content as per cent of SOC compared to other scenarios. Highest C_{LL} (18%) and C_{NL} (29%) carbon were associated with Sc2 at 0–15 cm soil depth (Fig. 3b). At 15–30 cm depth, SOC concentration was about 8% higher in Sc2 (12.5 Mg C ha^{-1}) where crop residues were incorporated into the soil during puddling operation compared with Sc3 and Sc4 where residues were retained on soil surface. Sc2 also showed highest C_{AP} (8.6 Mg C ha^{-1}), C_{PP} (3.9 Mg C ha^{-1}) and C_{VL} (7.6 Mg C ha^{-1}) than the other scenarios at 15–30 cm soil depth (Fig. 2).

The increase in organic carbon content in surface soil under CSA is in accordance with other studies (Murillo et al., 2004; Lopez-Fando and Pardo, 2009; Malecka et al., 2012). In semi-arid Spain, Lopez-Fando and Pardo (2009) observed 2.0 Mg ha^{-1} SOC increase in grey pea-barley cropping system at 0–5 cm soil depth after 5 years of no tillage. The highest SOC concentration (10.2 g kg^{-1}) at 0–5 cm soil depth was reported by Malecka et al. (2012) after 7 years of no tillage in Poland. Luo et al. (2010) reported that conversion from CT to ZT facilitated redistribution of C in the soil profile significantly, but did not increase the total SOC stock (Baker et al., 2007; Luo et al., 2010). After adopting ZT, soil C increased by 3.15 ± 2.42 t ha^{-1} in the surface (10 cm) soil but declined at lower depth (Luo et al., 2010). Luo et al. (2010) also reported the significant increment in soil C by 11% in the 0–60 cm soil with higher crop frequency. In another global meta-analysis, Govaerts et al. (2009) showed the higher SOC stock in > 50% of the cases under CA with ZT and residue retention than in conventional, but not in 40% cases where lower SOC was observed. Another meta-analysis of experiments in Mediterranean climate, small increases in SOC stock of about 0.3–0.4 Mg C ha^{-1} yr^{-1} was reported under zero-till agriculture (Agulilera et al., 2013). Dimassi et al. (2014) found no increase in SOC stock under ZT after 41 years in France. Mchunu et al. (2011) showed for instance that the abandonment of tillage only enhanced soil C stocks in the first 2 cm of the soil while no difference was observed from soil surface to 1.0 m, confirming the theory of Backer (Baker et al., 2007) of carbon redistribution instead of sequestration. But we observed significantly higher SOC stock in CSA-based scenarios such as Sc4 and Sc3 (on average > 55% than conventional) and about 9% in partial CSA (Sc2). In Sc4 and Sc3, total of 66 and 56 tons of residues from maize/rice, wheat and mungbean (Table 1) were recycled during four years which probably helped to increase the SOC as well as other pools in surface soils. Higher quantity of residue additions and their slow decomposition due to less soil disturbance are the main reasons of higher SOC contents in the surface layer under Sc3 and Sc4 (Dikgwatlhe et al., 2014; Saha et al., 2008; Jat et al., 2019). Incorporation of crop residues by tillage in Sc2 may have resulted higher amount of SOC compared with other scenarios at 15–30 cm soil depth. Higher passive pool as well as C_{NL} in Sc4 might be due to the composition of the maize residues resulting in biochemical recalcitrance in soil which is also manifested in longer time required to get decomposed in soil. Higher population of bacteria and fungi in CSA-based systems (Table 6) facilitated the conversion of crop residue carbon to SOC, leading to higher SOC in those systems as evidenced by Choudhary et al. (2018a, 2018b) in CA-based maize-wheat system after 3 years of continuous cultivation in NW India. Maize roots release gel like exudates in soil (Naveed et al., 2017) creating a more stable soil structure around the roots thereby explaining the higher non-labile and passive pool carbon in maize based system (Sc4).

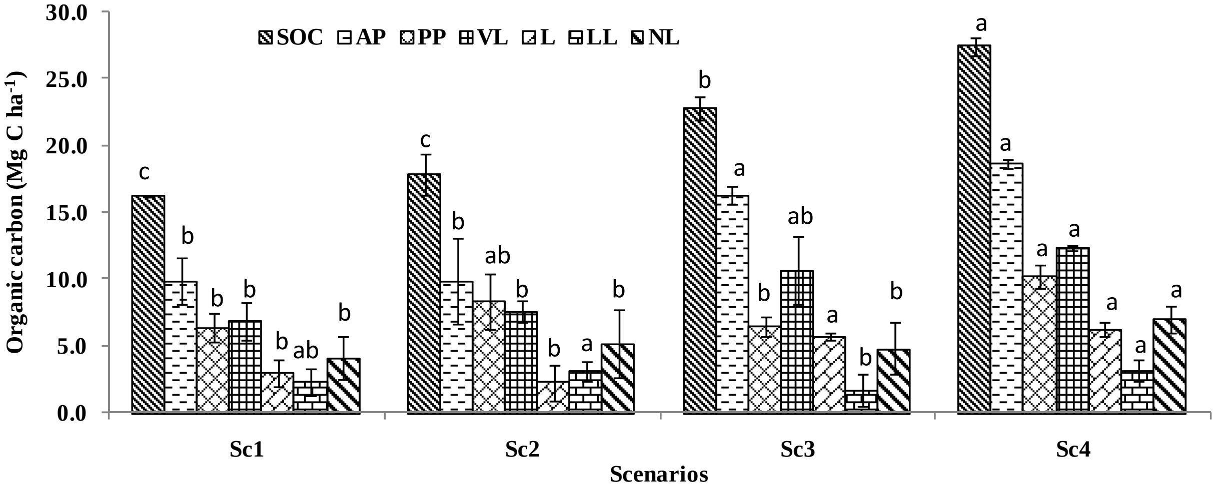


Fig. 1. Influence of scenarios on forms of carbon and distribution of SOC (Mg ha^{-1}) into different pools of oxidizability at 0–15 cm soil depth. Values with different lower case (a–c) letters are significantly different between each scenarios at $P < 0.05$ (Duncan multiple range tests for separation of mean). Vertical bars indicate ± S.E. of mean of the observed values.
(SOC: soil organic carbon; AP: active C pool; PP: passive C pool; VL: very labile C pool; L: labile C pool; LL: less labile C; NL: non labile C)
Sc1 - conventional rice-wheat system; Sc2 - partial CSA-based rice-wheat-mungbean system; Sc3 - CSA-based rice-wheat-mungbean system; Sc4 - CSA based maize-wheat-mungbean system.

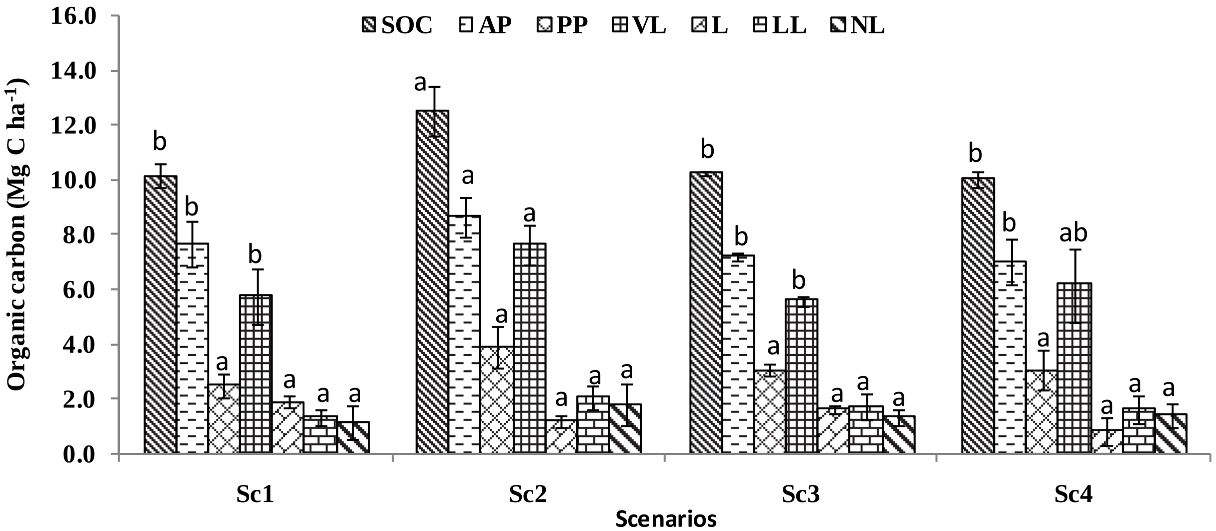


Fig. 2. Influence of scenarios on forms of carbon and distribution of SOC (Mg ha^{-1}) into different pools of oxidizability at 15–30 cm soil depth. Values with different lower case (a–c) letters are significantly different between each scenarios at $P < 0.05$ (Duncan multiple range tests for separation of mean). Vertical bars indicate ± S.E. of mean of the observed values.
(SOC: soil organic carbon; AP: active C pool; PP: passive C pool; VL: very labile C pool; L: labile C pool; LL: less labile C; NL: non labile C)
Sc1 - conventional rice-wheat system; Sc2 - partial CSA-based rice-wheat-mungbean system; Sc3 - CSA-based rice-wheat-mungbean system; Sc4 - CSA based maize-wheat-mungbean system.

3.2. *Lability index, recalcitrance indices (RIs) and stratification ratio (SR)*

The highest lability index (LI) was observed in Sc3 (2.19) followed by Sc4 (2.05) which was significantly higher ($P < 0.05$) than Sc2 and Sc1 at 0–15 cm soil depth (Table 2). At the lower soil depth (15–30 cm), LI was similar in all the scenarios. Higher LI in Sc3 and Sc4 over Sc2 and Sc1 might be due to the presence of easily decomposable crop residues retained on the soil surface (Table 1) which is also manifested in higher AP and C_{VL} in those scenarios. At lower soil depth, decline in LI may be due to the non-availability of easily decomposable C (Datta et al., 2017) and higher BD (Jat et al., 2018). With depth lower LI was also observed by Datta et al. (2017) in rice-wheat cropping systems of North West India. Integrated application of NPK + FYM showed the highest LI (1.64) followed by NPK (1.6) and control (1.5) at 0–15 cm soil depth (Datta et al., 2017). Recently Datta et al. (2018) also reported highest LI (1.22) under NPK + FYM treatment of sorghum-wheat cropping system at surface soil of Vertisols of semi-arid India and significantly decreased at lower depths irrespective of treatments.

The recalcitrance index 1 (RI1) was in the order of Sc3 > Sc4 > Sc1 > Sc2 at 0–15 cm soil depth (Table 2). However, at 15–30 cm soil depth, highest RI1 was associated with Sc1 (3.07) which suggested more stability of SOC than other scenarios. Recalcitrance index 2 (RI2) did not show any significant variation among the scenarios in both the soil depths (Table 2). At lower depth of Sc1, higher RI1 might be due to puddling of soil with stubbles resulting in stable complex formation between silt and clay with organic carbon (Choudhury et al., 2014). Lower system yield and crop residue removal in Sc1 (Table 7) might be the reasons for higher RI1 due to less

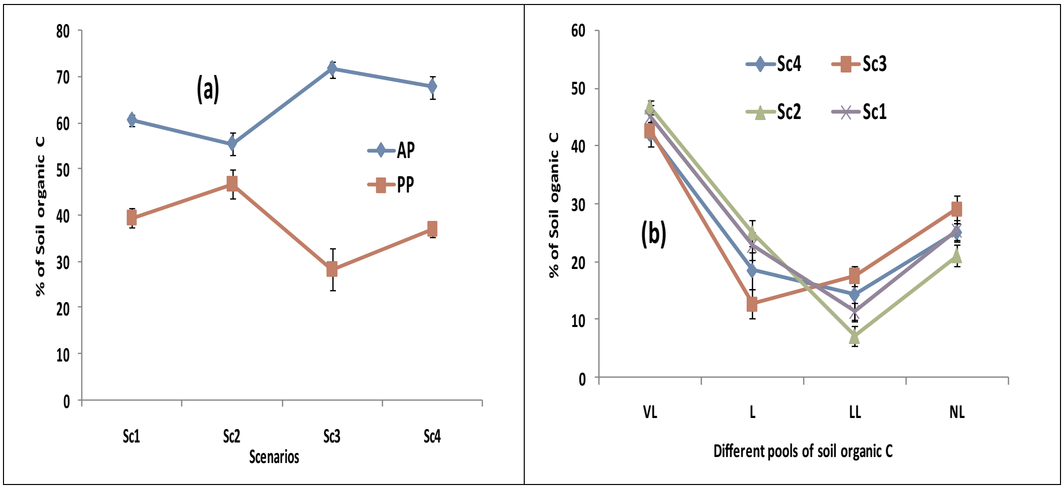


Fig. 3. Influence of treatments on a) AP and PP C; b) different forms of carbon such as VL, L, LL, NL C at 0–15 cm soil depth. Vertical bars indicate ± S.E. of mean of the observed values.

(AP: active C pool; PP: passive C pool; VL: very labile C pool; L: labile C pool; LL: less labile C; NL: non labile C).

Sc1 - conventional rice-wheat system; Sc2 - partial CSA-based rice-wheat-mungbean system; Sc3 - CSA-based rice-wheat-mungbean system; Sc4 - CSA based maize-wheat-mungbean system.

Table 2

Lability index (LI) and recalcitrance indices (RIs) of soil organic carbon under different treatments.

Scenarios/soil depth (cm)	LI		RI1		RI2	
	0–15	15–30	0–15	15–30	0–15	15–30
Sc1	1.79^{b,*}	1.76^{a}	1.54^{c}	3.07^{a}	0.25^{a}	0.11^{a}
Sc2	1.66^{b}	1.76^{a}	1.19^{d}	2.23^{b}	0.29^{a}	0.14^{a}
Sc3	2.19^{a}	1.89^{a}	2.53^{a}	2.36^{b}	0.21^{a}	0.13^{a}
Sc4	2.05^{a}	1.83^{a}	1.83^{b}	2.30^{b}	0.26^{a}	0.14^{a}

Sc1 - conventional rice-wheat system; Sc2 - partial CSA-based rice-wheat-mungbean system; Sc3 - CSA-based rice-wheat-mungbean system; Sc4 - CSA based maize-wheat-mungbean system.

[*] Different lower case letters within the same column show the significant difference at P = 0.05 according to Duncan Multiple Range Test for separation of mean.

availability of soil organic carbon for microbial decomposition (Choudhury et al., 2018). In subsurface soil layer, higher amount of organic C allocated to passive pools than active ones explained the increased values of RI1. Higher C in passive pools at lower layers might be due to the intercalation of organic carbon in clay lattices while moving downward through soil profile (Kennedy et al., 2014; Datta et al., 2017).

The highest SR for SOC was observed in Sc4 (2.7) followed by Sc3 (2.2) thereby indicating improved soil quality with full CSA-based system compared to soils under partial CSA and CT based system (Sc2 and Sc1) (Table 3). Geisseler and Horwath (2009) observed SR for total soil C of 1.49 and 1.31 in the conservation and standard tilled soil, respectively. Significant variation in SR for DHA was not observed among the scenarios but much fluctuations were found for APA, MBC and MBN among the scenarios (Table 4). This might be attributed to variation in SOC content at surface soil layer among the scenarios under different quantities of residue addition (Geisseler and Horwath, 2009). Addition of huge quantities of the crop residues (> 14 Mg ha^{-1} yr^{-1}) in CSA-based systems (Table 1) improved soil physical (Gathala et al., 2011), chemical (Jat et al., 2018) and biological (Choudhary et al., 2018a, 2018b) properties and subsequently overall soil quality under Sc3 and Sc4 which resulted variation in SRs.

Table 3

Stratification ratios for SOC, DHA, APA, MBC and MBN under different scenarios.

Scenarios	SOC	DHA	APA	MBC	MBN
Sc1	1.6^{b,*}	2.31^{b}	1.30^{ab}	1.14^{b}	3.46^{ab}
Sc2	1.4^{b}	2.72^{a}	1.51^{a}	1.91^{a}	3.15^{b}
Sc3	2.2^{ab}	2.53^{ab}	1.01^{b}	1.53^{a}	3.0^{b}
Sc4	2.7^{a}	2.36^{b}	1.08^{b}	1.64^{a}	3.74^{a}

SOC: soil organic carbon; DHA: dehydrogenase activity; APA: alkaline phosphatase activity; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen.

Sc1 - conventional rice-wheat system; Sc2 - partial CSA-based rice-wheat-mungbean system; Sc3 - CSA-based rice-wheat-mungbean system; Sc4 - CSA based maize-wheat-mungbean system.

[*] Different lower case letters within the same column show the significant difference at $P = 0.05$ according to Duncan Multiple Range Test for separation of mean.

3.3. Soil enzymes, microbial biomass C and N

Dehydrogenase activity (DHA) of the soils ranged from 467 to 843 μg TPF g^{-1} soil 24 h^{-1} at 0–15 cm depth (Table 4). The highest value was associated with Sc2, whereas the lowest was with Sc1. A similar trend was observed at 15–30 cm depth. Incorporation of organic residues particularly of rice and mungbean in Sc2 increased DHA activity significantly over the other scenarios. Although SOC concentration in surface soil layer was higher in Sc3 and Sc4 compared with Sc2. The increased DHA in Sc2 might be due to more availability of labile carbon and nitrogen to the microbes compared with other scenarios because of residue incorporation during puddling. Giacomini et al. (2007) observed faster decomposition of crop residues when incorporated into the soil than surface placement leading to greater carbon and nitrogen mineralization. Presence of mungbean residue further facilitated the conversion of crop residue carbon to soil organic carbon (Singh et al., 2015). Saha et al. (2008) and Nannipieri et al. (1990) reported significantly higher DHA with organics than NPK fertilizer. Gracia et al. (1994) showed a strong positive relationship between soil organic matter concentration and enzyme activities. The APA in 0–15 cm soil depth was significantly higher (181 μg p-

Table 4
Effect of different CSA-based scenarios on dehydrogenase activity (DHA), alkaline phosphatase activity (APA), microbial biomass carbon and microbial biomass nitrogen in two soil layers after rice 2013.

Scenarios	Dehydrogenase activity (µg TPF g^{-1} 24 h^{-1})		Alkaline phosphatase activity (µg p-nitrophenol g^{-1} h^{-1})		Microbial biomass carbon (µg g^{-1})		Microbial biomass nitrogen (µg g^{-1})	
	Soil layer (cm)							
	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30
Sc1	$467^{c,*}$	202.0^{c}	127^{c}	98^{c}	441^{c}	387^{c}	45^{c}	13^{c}
Sc2	843^{a}	309.6^{a}	181^{a}	120^{b}	1054^{a}	551^{a}	145^{a}	46^{a}
Sc3	539^{b}	212.8^{bc}	146^{b}	144^{a}	626^{b}	409^{bc}	63^{b}	21^{b}
Sc4	540^{b}	228.4^{b}	148^{b}	137^{a}	681^{b}	416^{b}	86^{b}	23^{b}

Sc1 - conventional rice-wheat system; Sc2 - partial CSA-based rice-wheat-mungbean system; Sc3 - CSA-based rice-wheat-mungbean system; Sc4 - CSA based maize-wheat-mungbean system.

[*] Different lower case letters within the same column show the significant difference at P = 0.05 according to Duncan Multiple Range Test for separation of mean.

nitrophenol g^{-1}soil h^{-1}) in Sc2 compared with all the others (Table 3). It was significantly lower in Sc1 compared with Sc3 and Sc4 which had similar APA. At 15–30 cm depth, values of APA were significantly higher in Sc3, Sc4 and Sc2 compared with Sc1. Overall 37% and 25% increase in DHA and APA, respectively was observed in CSA based scenarios (Sc2, Sc3 and Sc4) at surface soil depth than Sc1. Choudhary et al. (2018b) also found 140% and 42% increase in DHA and APA, respectively in CA-based rice-wheat system compared to conventional rice-wheat system.

Like enzyme activities, soil MBC (1054 µg g^{-1} and 551 µg g^{-1}) and MBN (145 µg $g^{-1}$and 46 µg g^{-1}) were significantly ($P < 0.05$) higher in Sc2 compared with others (Table 3) at both the soil depths, respectively. The MBC and MBN were also significantly higher in CSA-based Sc3 and Sc4 compared with Sc1 at both the soil depths. Results from our study showed that the scenarios with crop residues retention and ZT enhanced the MBN and MBC in soil. Consistent with our study, Choudhary et al. (2018b) reported increase in MBC by 29% and 56%, whereas, in MBN by 27% and 84%, respectively in ZT and residue recycling compared to conventional and residue removal scenarios. The residues in ZT scenario decompose slowly and thus, organic matter gradually accumulates on soil surface. The microbial biomass depends on soil organic matter as it serves as a good source of energy. Higher levels of SOC, MBC and MBN were directly related to surface accumulation of crop residues promoted by conservation tillage (Dolan et al., 2006), residue quality (Hema et al., 1999), continuous cropping (Sainju et al., 2008) and greater C input via crop roots (Franzluebbers et al., 1995).

3.4. Mineralizable carbon

The cumulative C mineralization in soil (0–15 cm depth) over 23 days under different scenarios varied from 61.4 to 91.5 µg C g^{-1} soil (Table 5). The amount of mineralizable C was highest in Sc2 (91.5 µg C g^{-1}) followed by Sc4, Sc3, and minimum under Sc1 (61.4 µg C g^{-1}) at 0–15 cm soil depth. As expected, mineralization rate was highest during initial 3 days of incubation and decreased gradually with the progress of incubation time (Fig. 4). The higher rate of CO_2 production in the first few days after incubation was due to the faster rate of decomposition of labile carbon and increased agitation of microbes at the time of sampling, which resulted in greater availability of metabolically accessible compounds initially (Saggar et al., 2001). Datta et al. (2019) also observed the faster rate of C mineralization upon addition of crop residues irrespective of their placements during initial days of the experiment. The differences in basal soil respiration (BSR) among the scenarios were relatively lower however, it was significantly higher under Sc2 and Sc4 due to higher organic C and favorable soil conditions for microbial activities compared with Sc1 and Sc3 (Table 5). Variation in the respiration rate under different scenarios was possibly associated with amount and quality (lignin, cellulose and polyphenol content) of crop residues retained in the field (Majumder et al., 2008). The microbial quotient (MQ) ranged from 0.06 to 0.13 among the scenarios with significantly higher values for Sc2 compared with the other scenarios (Table 5). The higher value of MQ indicates a greater stability of organic C in soils. The highest value of MQ with Sc2 suggests that a higher amount of C was stabilized in this scenario (Sparling, 1992). The respiratory quotient (qCO_2), ratio of microbial respiration to MBC, followed the opposite trend as for BSR (Table 5). Higher qCO_2 suggests a stress response with loss of more carbon (Anderson and Domsch, 1990). The lower values of qCO_2 in Sc2 and Sc3 suggest efficient use of available C by the microbes in soils (Majumder et al., 2008).

Table 5
Mineralizable C, microbial quotient (MQ), basal soil respiration (BSR) and respiratory quotient (qCO_2) in surface layer (0–15 cm) under different scenarios after rice 2013.

Scenarios	Mineralizable C (µg C g^{-1})				MQ × 100	BSR	qCO_2
	0–3d	0–6d	0–13d	0–23d	(µg C_{mic} µg^{-1} TOC × 100)	µg CO_2 d^{-1}	(µg CO_2-C µg^{-1} C_{mic} d^{-1})
Sc1	42.6b*	50.7c	54.1d	61.4d	0.07b	0.73b	0.0061a
Sc2	55.5a	71.8a	81.4a	91.5a	0.13a	1.01a	0.0038c
Sc3	39.9b	58.7b	62.5c	70.7c	0.06b	0.83b	0.0049a
Sc4	57.7a	69.8a	72.7b	83.6b	0.06b	1.10a	0.0053a

Sc1 - conventional rice-wheat system; Sc2 - partial CSA-based rice-wheat-mungbean system; Sc3 - CSA-based rice-wheat-mungbean system; Sc4 - CSA based maize-wheat-mungbean system.

[*] Different lower case letters within the same column show the significant difference at P = 0.05 according to Duncan Multiple Range Test for separation of mean.

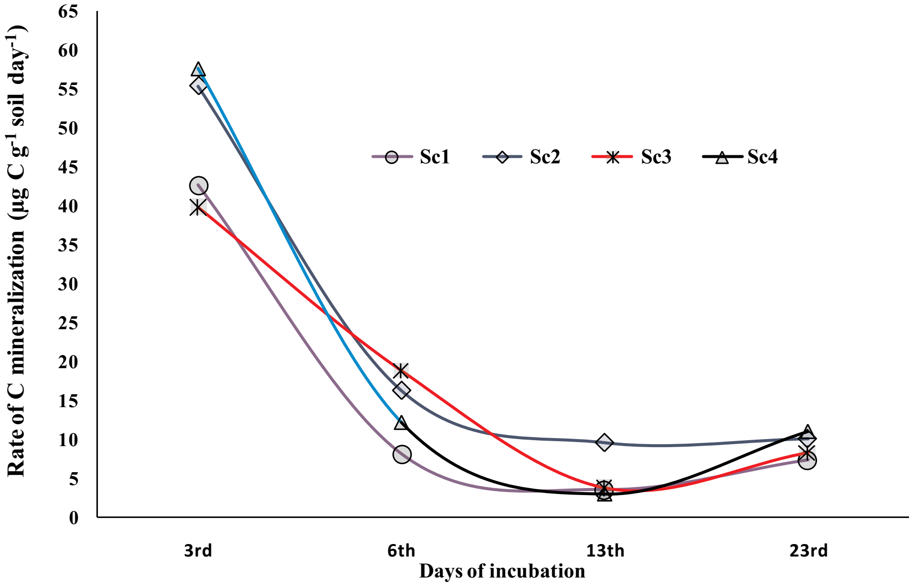


Fig. 4. Rate of C mineralization (µg C g^{-1}d^{-1}) of surface soil (0–15 cm) under different scenarios at different days after incubation
Sc1 - conventional rice-wheat system; Sc2 - partial CSA-based rice-wheat-mungbean system; Sc3 - CSA-based rice-wheat-mungbean system; Sc4 - CSA based maize-wheat-mungbean system.

3.5. *Microbial population*

Microbial population was significantly affected by different soil and crop management scenarios (Table 6). The microbial population at 0–15 cm soil depth was highest in Sc4 followed by Sc2. The population of fungal, bacterial and actinomycetes was 58–92%, 13–48% and 15–91% higher under Sc4 than others, respectively. Microbial counts were higher at the surface (0–15 cm) and decreased markedly at the lower depth (15–30 cm) in all the scenarios (Table 6). Bacterial counts were however, not affected by different scenarios at the lower depth, however higher actinomycetes counts were recorded with Sc3 and Sc4 (Table 6). CA-based management influenced the microbial counts at the upper soil depth possibly through influencing organic C, water and nutrient supply, and aeration (Alam et al., 2014; Munoz et al., 2007). The lowest microbial count in Sc1was in accordance with Choudhary et al. (2018a) who reported an increase of 29%, 71% and 100%, respectively of bacteria, fungi and actinomycetes under CA-based maize-wheat system compared to conventional rice-wheat system.

3.6. *Systems productivity and relationship with the soil biological properties*

The highest systems productivity (rice equivalent yield basis) was recorded with Sc2 and Sc4 (Table 7). On average (4 yrs' mean), 20% and 16% higher system productivity was recorded with Sc2 and Sc4, respectively compared with Sc1 (12.39 Mg ha^{-1}). Sc3 registered 11% yield improvement over Sc1. The results of this 4 year study clearly showed differential benefits of CSA-based management practices in both rice and maize based systems. Tillage and cropping systems, crop residue management, soil type and climate, control the magnitude at which SOC affects crop yields (Blanco-Canqui et al., 2013). Blanco-Canqui et al. (2012) found that about 0.1% increase in SOC concentration enhanced sorghum yield by 0.36 Mg ha^{-1} and wheat yield by 0.04 Mg ha^{-1} at 0 kg N ha^{-1}. Direct relation between SOM stocks and crop productivity was observed by Oldfield et al. (2018) though variable for soils and amendments. In a global meta-analysis, Pittelkow et al. (2015) compared ZT with CT practices and found yield reduction in ZT, though it was in variable extent. But ZT when combined with the residue retention and crop rotation can produce equivalent or greater

Table 6
Effect of different CSA-based scenarios on total population of fungi, bacteria and actinomycetes in soil after rice 2013.

Scenarios	Fungi (c.f.u × 10^3 g^{-1} soil)		Bacteria (c.f.u × 10^5 g^{-1} soil)		Actinomycetes (c.f.u × 10^5 g^{-1} soil)	
	0–15	15–30	0–15	15–30	0–15	15–30
Sc1	$6.1^{c,*}$	4.3^{ab}	11.4^{c}	5.5^{a}	4.4^{b}	2.1^{b}
Sc2	7.4^{b}	7.0^{a}	14.9^{b}	6.3^{a}	7.3^{a}	1.7^{b}
Sc3	6.2^{c}	2.6^{b}	12.3^{c}	5.8^{a}	7.2^{a}	2.9^{a}
Sc4	11.7^{a}	5.5^{a}	16.9^{a}	6.9^{a}	8.4^{a}	2.6^{a}

Sc1 - conventional rice-wheat system; Sc2 - partial CSA-based rice-wheat-mungbean system; Sc3 - CSA-based rice-wheat-mungbean system; Sc4 - CSA based maize-wheat-mungbean system.

[*] Different lower case letters within the same column show the significant difference at P = 0.05 according to Duncan Multiple Range Test for separation of mean.

yields than conventional tillage, by minimizing its negative impacts. Moreover, ZT in combination with crop rotation and residue retention significantly increased rainfed crop productivity in dry semiarid/arid climates. Higher system productivity in CSA-based scenarios might be due to integration of mungbean (Gathala et al., 2013), less terminal heat effects on wheat crop (Gathala et al., 2013; Sharma et al., 2015), higher carbon mineralization (Datta et al., 2019) with better nutrient availability (Jat et al., 2018) and improved soil biological properties (Choudhary et al., 2018a, 2018b).

Pearson's correlation coefficient values among different soil biological properties are presented in Table 8. SOC was weakly correlated with other soil biological properties. C_{VL} ($r = 0.99$, $P < 0.01$) and C_L ($r = 0.98$, $P < 0.05$) were positively correlated with C_{AP}. The C_{NL} and C_{PP} were also positively correlated ($r = 0.95$, $P < 0.05$) with each other. Datta et al. (2015) also observed similar correlations among the carbon pools under different land uses in semiarid NW India. MBC (r = 0.98, $P < 0.05$ and 0.99, $P < 0.01$) and MBN ($r = 0.87$ and 0.96, $P < 0.01$) were positively correlated with DHA and APA, respectively. Mineralizable carbon was positively correlated with DHA ($r = 0.83$, $P < 0.05$), APA ($r = 0.91$, $P < 0.05$), MBC ($r = 0.92$, $P < 0.05$), MBN ($r = 0.96$, $P < 0.05$), bacteria (r = 0.83, $P < 0.05$) and actinomycetes ($r = 0.77$, $P < 0.05$) population. MQ also followed similar trend as MinC except with the microbial population which did not show any relation with MQ. Significant positive correlation ($r = 0.64$, $P < 0.05$) was observed between MQ and mineralizable carbon. The basal soil respiration was positively correlated with almost all the biological soil properties except soil enzymes and organic carbon. Significant negative correlation was observed between respiratory quotient and biological soil properties except microbial population. MBC ($r = 89$, $P < 0.05$), MBN ($r = 98$, $P < 0.05$), mineralizable C ($r = 97$, $P < 0.05$) and microbial population particularly bacteria ($r = 0.80$, $P < 0.05$) and actinomycetes ($r = 0.88$, $P < 0.05$) population and basal soil respiration (r = 0.88, $P < 0.05$) were positively correlated with system yield (Table 8). Increase in microbial population might have facilitated the decomposition of the crop residues and subsequent mineralization of nutrients which become available to plants (Jat et al., 2018) and manifested in higher crop yields. Higher microbial decomposition led to the conversion of crop residue C to SOC thereby enhancing the MBC, MBN and mineralizable C which supplies nutrients to plants resulting in higher system yield. Oldfield et al. (2018) also observed the direct role of SOM in increased crop productivity. Crop rotation has positive effect on microorganism's population (Zhou et al., 2014). Cropping systems significantly affect abundance, diversity and activity of soil bacterial communities. Colonization of *Bradyrhizobium* sp. and *Herbaspirillum* sp. inside the rice roots was observed when rice was grown in rotation with legume crop thereby promoting rice growth and productivity (Yanni et al., 1997). The availability of nutrients to plants increases with the abundance of soil microorganisms particularly N and P (Turmuktini et al., 2012; Jat et al., 2018).

3.7. *Principal component analysis (PCA)*

In the PCA of 14 variables, three principal components (PCs) were extracted with eigen value of > 0.9 and explained 100% of the variance in the data (Fig. 5). DHA, APA, MBC, MBN, MQ, qCO_2 and BD were the highly weighted variables under PC1. In PC2, fungi and bacteria population were the highly weighted variables. The SOC was highly weighted variable in PC3 (Fig. 5). Based on PCA, about 66.4% loadings were provided by the parameters in PC1that can be used as key indicators for assessing soil quality. Correlation matrix was made (data not shown) and MBC was found to have the highest correlation sum and best represent the PC. Andrews and Carroll (2001) also followed correlation sum among the variables as the basis for selection as minimum data set (MDS) in PCA. Moreover, MBC represents most of the other variables in PC1 and therefore qualified as MDS. Choudhary et al. (2018a, 2018b) also observed MBC as the key soil quality indicator in CA based maize/rice-wheat system in North-West India. From 2nd PC, fungal population was selected as MDS. Therefore, MBC, fungal population and SOC were the key indicators identified and can be used for soil quality indexing under conservation agriculture practices.

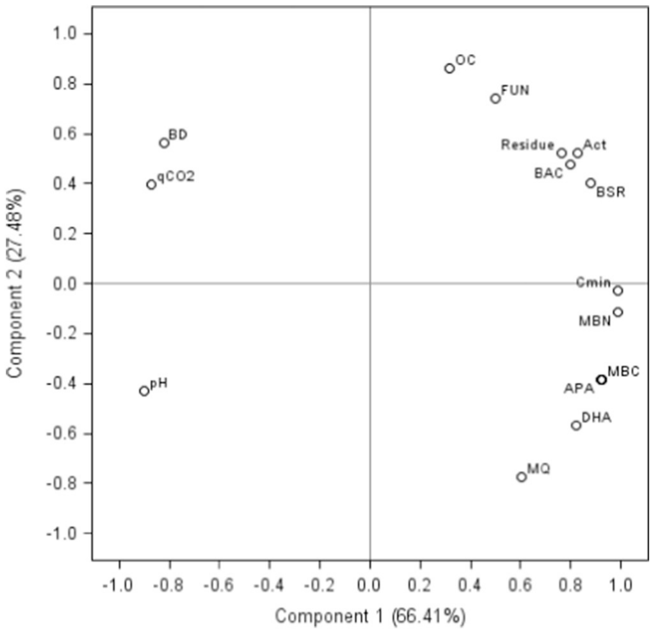


Fig. 5. Principal component plot of soil physicochemical properties, enzyme activities and microbial parameters under different scenarios.
OC: Soil organic carbon; BD: Bulk density; DHA: Dehydrogenase activity; APA: Alkaline Phosphatase activity; MBC: Microbial biomass carbon; MBN: Microbial biomass N; Fun: Fungal population; Actino: Actinomycetes population; Bac: Bacteria population; BSR: basal soil respiration; Cmin: mineralizable C; MQ: microbial quotient; qCO_2: respiratory quotient.

Table 7
Grain yield of rice/maize under different scenarios after 4 years of continuous CSA (mean of 4 years).

Scenarios	Rice equivalent yield (Mg ha^{-1})
Sc1	12.39c*
Sc2	14.87a
Sc3	13.73b
Sc4	14.38a

Sc1 - conventional rice-wheat system; Sc2 - partial CSA-based rice-wheat-mungbean system; Sc3 - CSA-based rice-wheat-mungbean system; Sc4 - CSA based maize-wheat-mungbean system.

[*] Means within a column followed by the same lower case letter are not different at 0.05% level using Fischer protected LSD test.

Table 8

Pearson's correlations among the biological soil properties with system yield irrespective of scenarios.

	VL	L	LL	NL	AP	PP	SOC	LI	RI1	RI2	DHA	APA	MBC	MBN	Fun	Bac	Acti	MinC	MQ	BSR	qCO2	Yield
VL	1																					
L	**0.95**[*]																					
LL	0.08	−0.18																				
NL	0.81	0.61	0.65																			
AP	**0.99**[**]	**0.98**[*]	−0.04	0.72																		
PP	0.58	0.34	0.85	**0.95**[*]	0.47																	
SOC	**0.99**[**]	0.93	0.16	0.85	**0.98**[*]	0.65																
LI	0.79	0.94	−0.46	0.32	0.87	0.03	0.75															
RI1	0.61	0.78	−0.74	0.03	0.70	−0.28	0.54	0.90														
RI2	−0.34	−0.59	0.89	0.27	−0.46	0.55	−0.26	−0.81	−0.94													
DHA	−0.26	−0.52	0.49	0.10	−0.38	0.27	−0.24	−0.73	−0.56	0.67												
APA	−0.04	−0.31	0.50	0.28	−0.16	0.39	−0.02	−0.56	−0.41	0.61	**0.97**[*]											
MBC	−0.05	−0.34	0.55	0.29	−0.18	0.42	−0.03	−0.59	−0.46	0.66	**0.98**[*]	**0.99**[**]										
MBN	0.24	−0.04	0.53	0.51	0.12	0.56	0.25	−0.33	−0.25	0.52	**0.87**[*]	**0.96**[*]	**0.95**[*]									
Fun	0.72	0.55	0.72	0.97[*]	0.65	**0.96**[*]	0.79	0.28	−0.08	0.33	−0.05	0.14	0.16	0.36								
Bac	0.60	0.34	0.82	0.94	0.49	**0.98**[*]	0.66	0.01	−0.24	0.54	0.39	0.52	0.55	0.69	0.91							
Acti	0.79	0.58	0.4	0.85	0.712	0.74	0.80	0.29	0.22	0.11	0.37	0.57	0.56	0.78	0.70	0.83						
MinC	0.25	−0.05	0.73	0.64	0.12	0.74	0.29	−0.37	−0.40	0.68	**0.83**[*]	**0.91**[*]	**0.92**[*]	**0.96**[*]	**0.53**	**0.83**[*]	**0.77**[*]					
MQ	−0.56	−0.78	0.47	−0.13	−0.664	0.10	−0.54	−0.91	−0.75	0.78	**0.94**[*]	**0.84**[*]	**0.85**[*]	**0.66**[*]	−0.18	0.18	0.05	**0.64**[*]				
BSR	0.58	0.30	0.79	0.91	0.463	0.95	0.63	−0.03	−0.23	0.54	0.49	0.63	0.65[*]	0.79[*]	0.85[*]	**0.99**[*]	0.87[*]	0.89[*]	0.27			
qCO2	0.01	0.25	−0.29	−0.18	0.115	−0.24	0.02	0.46	0.23	−0.43	−0.93[*]	−**0.97**[*]	−**0.96**[*]	−0.93[*]	−0.09	−0.40	−0.57	−0.83	−0.77	−0.52		
Yield	0.41	0.12	0.57	0.66	0.28	0.68	0.42	−0.19	−0.17	0.48	0.77	0.89	0.89[*]	0.98[*]	0.51	**0.80**[*]	0.88[*]	**0.97**[*]	0.53	**0.88**[*]	−0.86	1

VL: very labile C pool; L: labile C pool; LL: less labile C; NL: non labile C; AP: active C pool; PP: passive C pool; SOC: soil organic carbon; LI: lability index; RI1: recalcitrance index 1; RI2: recalcitrance index 2; DHA: Dehydrogenase activity; APA: alkaline phosphatase activity; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen; Bacteri: total bacterial population; Acti: total actinomycetes population; MinC: mineralizable carbon; MQ: microbial quotient; BSR: Basal soil respiration; qCO_2: Respiratory quotient.

[*] Correlation is significant at the 0.05 level (2-tailed).

[**] Correlation is significant at the 0.01 level (2-tailed).

4. Conclusions

CSA-based management systems improved soil organic carbon pools, soil biological properties (DHA, APA, MBC, MBN) and microbial population. Microbial biomass carbon, fungal population and SOC were identified as the most sensitive biological indicators for studying the effect of CSA-based management on soil biological quality. Our study showed that CSA-based sustainable intensification of cereal-based systems was found effective in building SOC with subsequent improvement in soil biological properties after 4 years of its adoption, which helped in improving the systems (rice-wheat system) productivity in North-West India. Therefore, CSA-based practices can be recommended to the farmers for sustainability of the cereal based system. Further combined effect of CSA practices on SOC pools and biological soil properties at lower soil depths (up to 1.0 m) should be studied for confirming the redistribution of organic carbon.

Acknowledgments

We are thankful to the Director, ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, and the U.S. Agency for International Development (USAID) and the Bill & Melinda Gates Foundation (BMGF) for funding through Cereal System Initiatives for South Asia (CSISA) project, CIMMYT (International Maize and Wheat Improvement Centre). We thank Dr. Yadvinder Singh, Fellow, Indian National Science Academy for his constructive comments. We are also thankful to the chief editor, associate editor and two anonymous reviewers for their constructive comments which tremendously helped to improve the quality of the manuscript.

References

Agulilera, E., Lassaletta, L., Gattinger, A., Gimeno, B., 2013. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a meta-analysis. Agric. Ecosyst. Environ. 168, 25–36. https://doi.org/10.1016/j.agee.2013.02.003.

Alam, K., Islam, M., Salahin, M.M., Hasanuzzaman, N.M., 2014. Effect of tillage practices on soil properties and crop productivity in wheat-mungbean-rice cropping system under subtropical climatic conditions. The Scientific World J. Article ID 437283https://doi.org/10.1155/2014/437283. 15 pages.

Anderson, J.E.E., 1982. Soil Respiration. In: Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties. American Society of Agronomy, Madison, Wisconsin, pp. 831–871.

Anderson, T.H., Domsch, K.H., 1990. Application of eco-physiological quotients (qCO_2 and qD) on microbial biomasses from soils of different cropping histories. Soil Biol. Biochem. 22, 251–255. https://doi.org/10.1016/0038-0717(90)90094-G.

Andrews, S.S., Carroll, C.R., 2001. Designing a soil quality assessment tool for sustainable agroecosystem management. Ecol. Appl. 11, 1573–1585. https://doi.org/10.1890/1051-0761(2001)011[1573:DASQAT]2.0.CO;2.

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

Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration-what do we really know? Agric. Ecosyst. Environ. 118, 1–5. https://doi.org/10.1016/j.agee.2006.05.014.

Bhattacharyya, R., Tuti, M.D., Kundu, S., Bisht, J.K., Bhatt, J.C., 2012. Conservation tillage impacts on soil aggregation and carbon pools in a sandy clay loam soil of the Indian Himalayas. Soil Sci. Soci. Am. J. 76, 617–627. https://doi.org/10.2136/sssaj2011.0320.

Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A. (Ed.), Methods of Soil Analysis. ASA and SSSA, Madison, Wisconsin, USA, pp. 363–375.

Blanco-Canqui, H., Claassen, M.M., Presley, D.R., 2012. Summer cover crops fix nitrogen, increase crop yield and improve soil-crop relationships. Agron. J. 104 (1), 137–147. https://doi.org/10.2134/agronj2011.0240.

Blanco-Canqui, H., Shapiro, C.A., Wortmann, C.S., Drijber, R.A., Mamo, M., Shaver, T.M., Ferguson, R.B., 2013. Soil organic carbon: the value to soil properties. J. Soil Water Conserv. 68 (5), 129A–134A. https://doi.org/10.2489/jswc.68.5.129A.

Choudhary, M., Datta, A., Jat, H.S., Yadav, A.K., Gathala, M.K., Sapkota, T.B., Das, A.K., Sharma, P.C., Jat, M.L., Singh, R., Ladha, J.K., 2018a. Changes in soil biology under conservation agriculture based sustainable intensification of cereal systems in indo-Gangetic Plains. Geoderma 313, 193–204. https://doi.org/10.1016/j.geoderma.2017.10.041.

Choudhary, M., Jat, H.S., Datta, A., Yadav, A.K., Sapkota, T.B., Mondal, S., Meena, R.P., Sharma, P.C., Jat, M.L., 2018b. Sustainable intensification influences soil quality, biota, and productivity in cereal-based agroecosystems. Appl. Soil Ecol. 126, 189–198. https://doi.org/10.1016/j.apsoil.2018.02.027.

Choudhury, S.G., Srivastava, S., Singh, R., Chaudhari, S.K., Sharma, D.K., Singh, S.K., Sarkar, D., 2014. Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice-wheat cropping system under reclaimed sodic soil. Soil Till. Res. 136, 76–83. https://doi.org/10.1016/j.still.2013.10.001.

Choudhury, S.G., Yaduvanshi, N.P.S., Chaudhari, S.K., Sharma, D.R., Sharma, D.K., Nayak, D.C., Singh, S.K., 2018. Effect of nutrient management on soil organic carbon sequestration, fertility, and productivity under rice-wheat cropping system in semi-reclaimed sodic soils of North India. Environ. Monit. Assess. 190, 117. https://doi.org/10.1007/s10661-018-6486-9.

Datta, A., Basak, N., Chaudhari, S.K., Sharma, D.K., 2015. Soil properties and organic carbon distribution under different land uses in reclaimed sodic soils of north-West India. Geoderma Reg 4, 134–146. https://doi.org/10.1016/j.geodrs.2015.01.006.

Datta, A., Mandal, B., Basak, N., Badole, S., Krishna Chaitanya, A., Majumder, S.P., Thakur, N.P., Kumar, P., Kachroo, D., 2017. Soil carbon pools under long-term rice-wheat cropping system in Inceptisols of Indian Himalayas. Arch. Agron. Soil Sci. https://doi.org/10.1080/03650340.2017.1419196.

Datta, A., Mandal, B., Badole, S., Chaitanya, A.K., Majumder, S.P., Padhan, D., Basak, N., Barman, A., Kundu, R., Narkhede, W., 2018. Interrelationship of biomass yield, carbon input, aggregation, carbon pools and its sequestration in Vertisols under long-term sorghum-wheat cropping system in semi-arid tropics. Soil Tillage Res. 184, 164–175. https://doi.org/10.1016/j.still.2018.07.004.

Datta, A., Jat, H.S., Yadav, A.K., Choudhary, M., Sharma, P.C., Rai, M., Singh, L.K., Majumder, S.P., Choudhary, V., Jat, M.L., 2019. Carbon mineralization in soil as influenced by crop residue type and placement in an *Alfisols* of Northwest India. Carbon Management 10, 37–50. https://doi.org/10.1080/17583004.2018.1544830.

Diaz-Zorita, M., Duarte, G.A., Grove, J.H., 2002. A review of no-till systems and soil management for sustainable crop production in the sub-humid and semi-arid pampas of Argentina. Soil and Till. Res. 65 (1), 1–18. https://doi.org/10.1016/S0167-1987(01)00274-4.

Dick, R.P., Breakwell, D.P., Turco, R.E., 1996. Soil enzyme activities and biodiversity measurements and integrative microbiological indicators. In: Soil Sci. Society America. Methods for Assess, 49 Special Publication.

Dikgwatlhe, S.B., Chen, Z., Lal, R., Zhang, H., Chen, F., 2014. Changes in soil organic carbon and nitrogen as affected by tillage and residue management under wheat–maize cropping system in the North China plain. Soil Tillage Res. 144, 110–118. https://doi.org/10.1016/j.still.2014.07.014.

Dimassi, B., Mary, B., Wylleman, R., Labreuche, J., Couture, D., Piraux, F., Cohan, J.P., 2014. Long-term effect of contrasted tillage and crop management on soilcarbon dynamics during 41 years. Agric. Ecosyst. Environ. 188, 134–146. https://doi.org/10.1016/j.agee.2014.02.014.

Dolan, M.S., Clapp, C.E., Allmarasd, R.R., Baker, J.M., Molina, J.A.E., 2006. Soil organic carbon and nitrogen in a Minnesota soil as related to tillage, residue and nitrogen management. Soil Tillage Res. 89, 221–231. https://doi.org/10.1016/j.still.2005.07.015.

Franzluebbers, A.J., 2002. Soil organic matter stratification ratio as an indicator of soil quality. Soil Tillage Res. 66, 95–106.

Franzluebbers, A.J., Arshad, M.A., 1996. Soil organic matter pools during early adoption of conservation tillage in north western Canada. Soil Sci. Soc. Am. J. 60, 1422–1427. https://doi.org/10.2136/sssaj1996.03615995006000050019x.

Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1995. Soil Organic Carbon, Microbial Biomass, and Mineralizable Carbon and Nitrogen in Sorghum. Soil Sci. Soc. Am. J. 59, 460–466. https://doi.org/10.1016/S0167-1987(02)00018-1.

Gathala, M.K., Ladha, J.K., Saharawat, Y.S., Kumar, V., Kumar, V., Sharma, P.K., 2011. Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice–wheat rotation. Soil Sci. Soc. Am. J. 75, 1851–1862. https://doi.org/10.2136/sssaj2010.0362.

Gathala, M.K., Kumar, V., Sharma, P.C., Saharawat, Y.S., Jat, H.S., Singh, M., Kumar, A., Jat, M.L., Humphreys, E., Sharma, D.K., Sharma, S., Ladha, J.K., 2013. Optimizing intensive cereal-based cropping systems addressing current and future drivers of agricultural change in the north western indo-Gangetic Plains of India. Agri. Ecosyst. Environ. 177, 85–97. https://doi.org/10.1016/j.agee.2013.06.002.

Geisseler, D., Horwath, W.R., 2009. Short-term dynamics of soil carbon, microbial biomass, and soil enzyme activities as compared to longer-term effects of tillage in irrigated row crops. Biol. Fertil. Soils 46, 65–72. https://doi.org/10.1007/s00374-009-0400-0.

Giacomini, S.J., Recous, S., Mary, B., Aita, C., 2007. Simulating the effects of N availability, straw particle size and location in soil on C and N mineralization. Plant Soil 301, 289–301. https://doi.org/10.1007/s11104-007-9448-5.

Govaerts, B., Verhulst, N., Castellanos-Navarrete, A., Sayre, K.D., Dixon, J., Dendooven, L., 2009. Conservation agriculture and soil carbon sequestration: between myth and farmer reality. Crit. Rev. Plant Sci. 28 (3), 97–122. https://doi.org/10.1080/07352680902776358.

Gracia, C., Hernandez, T., Costa, F., 1994. Microbial activity in soils under Mediterranean environmental conditions. Soil Biol. Biochem. 26, 1185–1191. https://doi.org/10.1016/0038-0717(94)90142-2.

Hema, S., Singh, S.K., Singh, A.N., Raghubanshi, A.S., Singh, H., 1999. Impact of plant residue quality on the size of the microbial biomass pool and net N- mineralization. Trop. Ecol. 40, 313–318.

Jat, H.S., Datta, A., Sharma, P.C., Kumar, V., Yadav, A.K., Choudhary, M., Choudhary, V., Gathala, M.K., Sharma, D.K., Jat, M.L., Yaduvanshi, N.P.S., Singh, G., McDonald, A., 2018. Assessing soil properties and nutrient availability under conservation agriculturepractices in a reclaimed sodic soil in cereal-based systems of north-West India. Arch. Agron. Soil Sci. 64, 531–545. https://doi.org/10.1080/03650340.2017.1359415.

Jat, H.S., Datta, A., Choudhary, M., Yadav, A.K., Choudhary, V., Sharma, P.C., Gathala, M.K., Jat, M.L., McDonald, A., 2019. Effects of tillage, crop establishment and diversification on soil organic carbon, aggregation, aggregate associated carbon and productivity in cereal systems of semi-arid Northwest India. Soil Tillage Res. 190, 128–138. https://doi.org/10.1016/j.still.2019.03.005.

Jenkinson, D.S., 1988. Determination of microbial biomass carbon and nitrogen in soils. In: Wilson, R.J. (Ed.), Advances in Nitrogen Cycling in Agricultural Ecosystems. CAB International, Wallingford (378-386p).

Kennedy, M.J., Lohr, S.C., Fraser, S.A., Baruch, E.T., 2014. Direct evidence for organic carbon preservation as clay-organic nanocomposites in a Devonian black shale; from deposition to diagenesis. Earth Planet. Sci. Lett. 388, 59–70. https://doi.org/10.1016/j.epsl.2013.11.044.

Ladha, J.K., Fischer, K.S., Hossain, M., Hobbs, P.R., Hardy, B., 2000. Improving the productivity and sustainability of rice-wheat of the indo-Gangetic Plains: A synthesis of NARS IRRI partnership research. In: IRRI Discussion Paper Sereminer 40. IRRI, Manila, Philippines, pp. 1–31.

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

Lopez-Fando, C., Pardo, M.T., 2009. Changes in soil chemical characteristics with different tillage practices in a semi-arid environment. Soil Till. Res. 104, 278–284. https://doi.org/10.1016/j.still.2009.03.005.

Luo, Z., Wang, E., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in-agricultural soils? A meta-analysis of paired experiments. Agric. Ecosyst. Environ. 139, 224–231. https://doi.org/10.1016/j.agee.2010.08.006.

Majumder, B., Mandal, B., Bandyopadhyay, P.K., Gangopadhyay, A., Mani, P.K., Kundu, A.L., Mazumder, D., 2008. Organic amendments influence soil organic carbon pools and crop productivity in a nineteen-year-old rice-wheat agroecosystem. Soil Sci. Soc. Am. J. 72, 1–11. https://doi.org/10.2136/sssaj2006.0378.

Malecka, I., Blecharczyk, A., Sawinska, Z., Dobrzeniecki, T., 2012. The effect of various long-term tillage systems on soil properties and spring barley yield. Turk. J. Agric. For. 36, 217–226. https://doi.org/10.3906/tar-1104-20.

HiMedia Manual, 2009. HiMedia Manual for microbiology laboratory practice. In: HiMedia Laboratories Pvt. Ltd, India. http://www.fao.org/3/a-i3325e.pdf.

Martin, J.P., 1950. Use of acid, rosebengal and streptomycin in the plate method for estimating soil fungi. Soil Sci. 69, 215–232. https://doi.org/10.1097/00010694-195003000-00006.

Mchunu, C.N., Lorentz, S., Jewitt, G., Manson, A., Chaplot, V., 2011. No-till impact on soil and soil organic carbon Erosion under crop residue scarcity in Africa. Soil Sci. Soc. Am. J. 75, 1503–1512. https://doi.org/10.2136/sssaj2010.0359.

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., et al., 2017. Soil carbon 4 per mille. Geoderma 292, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002.

Munoz, A., Lopez, P., Ramirez, M., 2007. Soil quality attributes of conservation management regimes in a semi-arid region of south western Spain. Soil Tillage Res. 95 (1–2), 255–265. https://doi.org/10.1016/j.still.2007.01.009.

Murillo, J.M., Moreno, F., Girón, I.F., Oblitas, M.I., 2004. Conservation tillage: long term effect on soil and crops under rainfed conditions in south-west Spain (Western Andalusia). Span. J. Agric. Res. 2, 35–43.

Nannipieri, P., Grego, S., Ceccanti, B., 1990. Ecological significance of the biological activity in soils. In: Bollag, J.M., Stotzky, G. (Eds.), Soil Biochemistry. Marcel Dekker, New York, pp. 293–355.

Naveed, M., Brown, L.K., Raffan, A.C., George, T.S., Bengough, A.G., Roose, T., Sinclair, I., Koebernick, N., Cooper, L., Hackett, C.A., Hallett, P.D., 2017. Plant exudates may stabilize or weaken soil depending on species, origin and time. European J. Soil Sci. 68, 806–816. https://doi.org/10.1111/ejss.12487.

Oldfield, E.E., Wood, S.A., Bradford, M.A., 2018. Direct effects of soil organic matter on productivity mirror those observed with organic amendments. Plant Soil. https://doi.org/10.1007/s11104-017-3513-5.

Parihar, C.M., Jat, S.L., Singh, A.K., Datta, A., Parihar, M.D., Varghese, E., Bandyopadhyay, K.K., Nayak, H.S., Kuri, B.R., Jat, M.L., 2018. Changes in carbon pools and biological activities of a sandy loam soil under medium-term conservation agriculture and diversified cropping systems. European J. of Soil Sci. 69 (5), 902–912. https://doi.org/10.1111/ejss.12680.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532 (7597), 49–57. https://doi.org/10.1038/nature17174.

Pittelkow, C.M., Liang, X., Linquist, B.A., Groenigen, K.J.V., Lee, J., Lundy, M.E., Gestel, N.V., Six, J., Venterea, R.T., Chris, C.V., 2015. Productivity limits and potentials of the principles of conservation agriculture. Nature 517, 365–370. https://doi.org/10.1038/nature13809.

Powlson, D.S., Glendining, M.J., Coleman, K., Whitmore, A.P., 2011a. Implications for soil properties of removing cereal straw: results from long-term studies. Agron. J. 103, 279–287. https://doi.org/10.2134/agronj2010.0146s.

Powlson, D.S., Whitmore, A.P., Goulding, K.W.T., 2011b. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. Eur. J. Soil Sci. 62, 42–55. https://doi.org/10.1111/j.1365-2389.2010.01342.x.

Powlson, D.S., Bhogal, A., Chambers, B.J., Coleman, K., Macdonald, A.J., Goulding, K.W.T., Whitmore, A.P., 2012. The potential to increase soil carbon stocksthrough reduced tillage or organic material additions in England and Wales: a case study. Agric. Ecosyst. Environ. 146, 23–33. https://doi.org/10.1016/j.agee.2011.10.004.

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Chang. 4, 678–683. https://doi.org/10.1038/nclimate2292.

Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jat, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agric. Ecosyst. Environ. 220, 164–174. https://doi.org/10.1016/j.agee.2016.01.005.

Saggar, S., Headley, C.B., Salt, G.J., 2001. Soil microbial biomass, metabolic quotient and carbon and nitrogen mineralization in 25-years-old *Pinus radiata* agroforestry regimes. Aus. J. Agril. Res. 39, 491–504. https://doi.org/10.1071/SR00012.

Saha, S., Prakash, V., Kundu, S., Kumer, N., Mina, B.L., 2008. Soil enzymatic activity as affected by long term application of farm yard manure and mineral fertilizer under a rainfed soybean–wheat system in N-W Himalaya. Euro. J. Soil Biol. 44, 147–157. https://doi.org/10.1016/j.ejsobi.2008.02.004.

Sainju, U.M., Senwo, Z.N., Nyakatawa, E.Z., Tazisong, I.A., Reddy, K.C., 2008. Tillage, cropping systems, and nitrogen fertilizer source effects on soil carbon sequestration and fractions. J. Environ. Qual. 37, 880–888. https://doi.org/10.2134/jeq2007.0241.

Sharma, P.C., Jat, H.S., Kumar, V., Gathala, M.K., Datta, A., Yaduvanshi, N.P.S., Choudhary, M., Sharma, S., Singh, L.K., Saharawat, Y., Yadav, A.K., Parwal, A., Sharma, D.K., Singh, G., Jat, M.L., Ladha, J.K., McDonald, A., 2015. Sustainable intensification opportunities under current and future cereal systems of north-West India. In: Technical Bulletin: CSSRI/Karnal/2015/4. Central Soil Salinity Research Institute, Karnal India, pp. 46. https://doi.org/10.13140/RG.2.2.16550.83521.

Singh, A., Phogat, V.K., Dahiya, R., Batra, S.D., 2014. Impact of long-term zero till wheat on soil physical properties and wheat productivity under rice–wheat cropping system. Soil Tillage Res. 140, 98–105. https://doi.org/10.1016/j.still.2014.03.002.

Singh, G., Kumar, D., Sharma, P., 2015. Effect of organics, biofertilizers and crop residue application on soil microbial activity in rice-wheat and rice-wheat mungbean cropping systems in the Indo-Gangetic plains. Cogent Geosci. 1, 1085296. https://doi.org/10.1080/23312041.2015.1085296.

Smith, J.L., Papendick, R.I., Bezdicek, D.F., Lynch, J.M., 1993. Soil organic matter dynamics and crop residue management. In: Blaine Metting Jr. F. (Ed.), Soil Microbial Ecology – Applications in Agricultural and Environmental Management. Environmental Sciences Department, Washington, pp. 65–94.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, K., et al., 2008. Greenhouse gas mitigation in agriculture. Philos. Trans. R. Soc. Lond. B 363, 789–813. https://doi.org/10.1098/rstb.2007.2184.

Soil Survey Division Staff, 1993. Soil Survey Manual. United States Department of Agriculture, pp. 63–65.

Sparling, G.P., 1992. Ratio of microbial biomass carbon to soil organic carbon as a sensitive indicator of changes in soil organic matter. Aus. J. Soil Res. 30, 195–207. https://doi.org/10.1071/SR9920195.

Timsina, J., Connor, D.J., 2001. Productivity and management of rice–wheat cropping systems: issues and challenges. Field Crops Res 69, 93–132. https://doi.org/10.1016/S0378-4290(00)00143-X.

Turmuktini, T., Kantikowati, E., Natalie, B., Setiawati, M., Yuwariah, Y., Joy, B., Simarmata, T., 2012. Restoring the health of paddy soil by using straw compost and biofertilizers to increase fertilizer efficiency and rice production with Sobari (system of organic based aerobic rice intensification) technology. Asian J. Agri. Rural Deve. 2, 519–526 (ISSN (P): 2304-1455, ISSN (E): 2224-4433).

Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass carbon. Soil Biol. Biochem. 19, 703–707. https://doi.org/10.1016/0038-0717(87)90052-6.

Walkley, A., Black, I.A., 1934. An experiment of the Degtareff method for determination of soil organic matter and a proposed modification of the chronic acid titration method. Soil Sci. 37, 29–38. https://doi.org/10.1097/00010694-193401000-00003.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci. Soc. Am. J. 66, 1930–1946. https://doi.org/10.2136/sssaj2002.1930.

Yanni, Y.G., Rizk, R.Y., Corich, V., Squartini, A., Ninke, K., Philip-Hollingsworth, S., Orgambide, G., de Bruijn, F., Stoltzfus, J., Buckley, D., Schmidt, T.M., Mateos, P.F., Ladha, J.K., Dazzo, F.B., 1997. Natural endophytic association between *Rhizobium leguminosarum* bv. Trifolii and rice roots and assessment of its potential to promote rice growth. Plant Soil 194, 99–114. https://doi.org/10.1023/A:1004269902246.

Zhou, W., Lv, T.F., Chen, Y., Westby, A.P., Ren, W.J., 2014. Soil physicochemical and biological properties of paddy-upland rotation: a review. Sci. World J. https://doi.org/10.1155/2014/856352).17.

Zuberer, D.A., 1994. Recovery and enumeration of viable bacteria. In: Weaver, R.W., Angle, S., Bottomley, P., Bezdicek, D., Smith, S., Tabatabai, A., Wollum, A., Mickelson, S.H. (Eds.), Methods of Soil Analysis: Part 2- Microbiological and Biochemical Properties. SSSA, Madison, Wis., pp. 119–144.