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Soil carbon pools, carbon and nitrogen storage pattern in a soybean-wheat cropping system based on 21-year field experiment of Indian mid-Himalayas

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Abstract: Long-term organic and mineral fertilization can bring in changes in the different pools of soil carbon (C) and nitrogen (N), and sequestration under irrigated soybean-wheat cropping system (SW). Results showed that long-term mineral and organic fertilization (NPK + FYM) significantly ($P < 0.05$) increased soil reaction (5.96, 6.41 and 6.56) as compared to unfertilized control (CK), however, it was 0.24, 0.11 and 0.12 units lower than FYM in all three soil depths. NPK + FYM fertilization clearly indicated that ~54, 51 and 52% higher total organic carbon (TOC) and ~46, 56 and 55% higher total nitrogen (TN) as compared to CK in 0–15 cm, 15–30 cm and 30–45 cm soil depths, respectively. Average values for TOC and TN with different treated plots were 9.89, 9.23 and 8.57 g kg^{-1} and 0.80, 0.74 and 0.68 g kg^{-1} under all three soil depths. We conclude that, significantly higher C (~22, 20 and 19 Mg C ha^{-1}) and N (1.79, 1.67 and 1.53 Mg N ha^{-1}) storage was recorded with NPK + FYM as compared to CK in 0–15 cm, 15–30 cm and 30–45 cm soil depths, respectively. Nevertheless, higher total C and N sequestration rate in 0-45 cm soil depth was noted under NPK + FYM (~1153 and 91 kg ha^{-1} $year^{-1}$) treated plot, followed by N + FYM (~981 and 78 kg ha^{-1} $year^{-1}$) and FYM alone (~873 and 63 kg C ha^{-1} $year^{-1}$). These results clearly indicated that combined organic and mineral fertilization have its positive effect on soil C and N pools, and sequestration in the long-run, and thus, help in maintaining long-term soil sustainability.

Key words: Farm-yard manure (FYM), sequestration, SOC, soil sustainability, storage.

Introduction

Soil carbon (C) and nitrogen (N) dynamics are central to soil sustainability and crop productivity (Wang *et al*. 2015) because these soil C and N pools storage enhance the C and N trading and decrease CO_2 and N_2O emissions and also improves soil quality (Qiu *et al*. 2016). Augmentation of soil C and N through sequestration in soil system develops soil sustainability (Manna *et al*. 2017). Long-term organic fertilization significantly reduces soil bulk density and increased total porosity by altering soil structure and aggregation (Ghosh *et al*. 2016; Shi *et al*. 2016). The long-term field experiments (LTFE) with organic and mineral fertilization have been widely used to augment or preserve soil C and N content and nutrient cycling (He *et al*. 2015).

Long-term NPK + FYM fertilization significantly enhance C and N concentration in stable pool (Jha *et al*. 2014). Soil C and N pools are the fine indicators of soil quality which are significantly influenced by mineral and organic ferti-

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lization (Das *et al*. 2016). The balanced nutrients fertilization can effectively restrain decreases in soil C and N, and significantly enhance sequestration in agricultural soils (Qiu *et al*. 2016). Carbon management provide a pragmatic and effective means for obtaining precious information for maintaining the soil quality (Manna *et al*. 2017).

In Indian Himalayan region soils are high in organic matter, fertile and productive, but due to imbalanced uses of mineral fertilization (Sharma *et al*. 2017) with a concomitant decrease in the use of organic manure. This could result in a decline of soil organic carbon (SOC) content, a depletion of C stocks, deterioration of soil structure, and soil fertility due to heavy loss of nutrient by severe soil erosion (Ling *et al*. 2014). Therefore, our research focused on finding out fertilization sheds that can help in restoration or preservation of SOC in the soybean-whea cropping system (SW), enhances crop productivity by stabilization of soil structure; improves permeability; mineralize plant nutrient and ultimately mitigate climate change by sequestering C and N in agricultural soil. In present investigation, we conjectured that impact from over the periods on irrigated SW would significantly increase soil C and N content, its pools, and sequestration. Objective of the investigation were: (i) how long-term chemical and organic fertilization has potentially influenced the soil pH, bulk density and total porosity of soil, (ii) how long-term chemical and organic fertilization affects C and N content and their pools, and (iii) the long-term fertilization effects on soil C and N storage and sequestration under SW under Indian mid-Himalayas conditions.

Materials and methods

Site description

The research site is located at the Research Station of the institute (29°36´N and 79°40´E), in the State of Uttarakhand, India. A LTFE was commenced in 1995–1996 in a silty clay loam soil with sowing under SW. The climate of this mid-hill region is sub-temperate which have lot of variations in rainfall and temperature throughout the year. The mean annual rainfall of last 21-years crop growth period was ~1005 mm with ~722 mm in kharif season (June-September) and ~225 mm in rabi season (October-May). Climatic data during the experimentation period is presented in figure 1.

Experimental design and treatments

This experiment involved SW with six treatments. The treatments included mineral fertilizer application in combination with organic manure *viz*. Control (CK), N-120, NPK, FYM, N + FYM, NPK + FYM experiment was performed in random block design (RBD) with four replications. The details of treatments, soil and crop management practices are presented in Choudhary *et al*. (2018).

Soil sampling and analysis

Soil sampling was done in October, 2016 after soybean harvesting. Soil samples were collected from each plot using a core soil sampler from three soil depths (0–15, 15–30 and 20–45 cm). Soil analysis has been done by following standards procedure *i.e.* for pH and EC (Jackson 1973), Walkley and Black C (WBC, Walkley & Black 1934), total organic C (TOC, Nelson & Sommers 1996), $KMnO_4$-oxidizable C (Blair *et al*. 1995) and carbon storage was calculated as follows (Lal *et al*. 1998). Initial physico-chemical properties and fertility status of the experimental soil are presented in Choudhary *et al*. (2018).

Statistical Analyses

ANOVA was performed to observe the effect of different treatments combination on different soil properties. Duncan's Multiple Range test was performed to observe the significant differences for the studied parameters between the treatment combinations using the SAS package (ver. 9.3, SAS Institute, Cary, North Carolina, USA).

Results

Soil physical properties (pH, bulk density and total porosity)

The data showed that LTFE (21-years) significantly influenced soil reaction, bulk density and porosity of different treatments (Table 1). Significantly an average of all treatments lowest (5.87) pH was observed with 0–15 cm depth, followed by (6.26) 15–30 cm and (6.36) 30–45 cm soil depth (P < 0.05) (Fig. 2a). The significantly highest pH was recorded with FYM applied plots (6.20 and 6.67), and it was statistically at par with N + FYM (5.93 and 6.37), NPK + FYM (5.96 and 6.56) and lowest (5.62 and 6.16) in N plots in 0-15 and 30–45 cm soil depth, respectively.

Plot with NPK + FYM application resulted into

Table 1. Soil total porosity under different soil depths as affected long-term organic and inorganic fertilization.

Treatments	Total porosity (%)		
	0–15 cm	15–30 cm	30–45 cm
CK	49.90^{d}	49.76^{d}	49.33^{c}
N	50.51^{d}	50.18^{d}	50.18^{c}
NPK	51.03^{cd}	50.75^{cd}	50.56^{bc}
FYM	52.06^{bc}	51.69^{bc}	51.60^{ab}
N + FYM	52.83^{ab}	52.35^{ab}	51.92^{a}
NPK + FYM	53.49^{a}	53.01^{a}	52.35^{a}
Mean	51.64^{a}	51.29^{a}	50.99^{a}

Different superscript indicates significant differences at $P < 0.05$ between different treatment combinations.

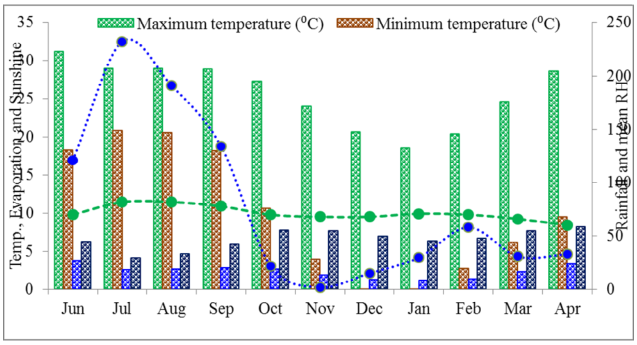

Fig. 1. Mean climatic parameters, (a) maximum and minimum temperature, (b) rainfall pattern, (c) evaporation, (d) sunshine hours (e) relative humidity during crop growth period of 1995–2016 (Source: ICAR-VPKAS, Almora meteorological observatory).

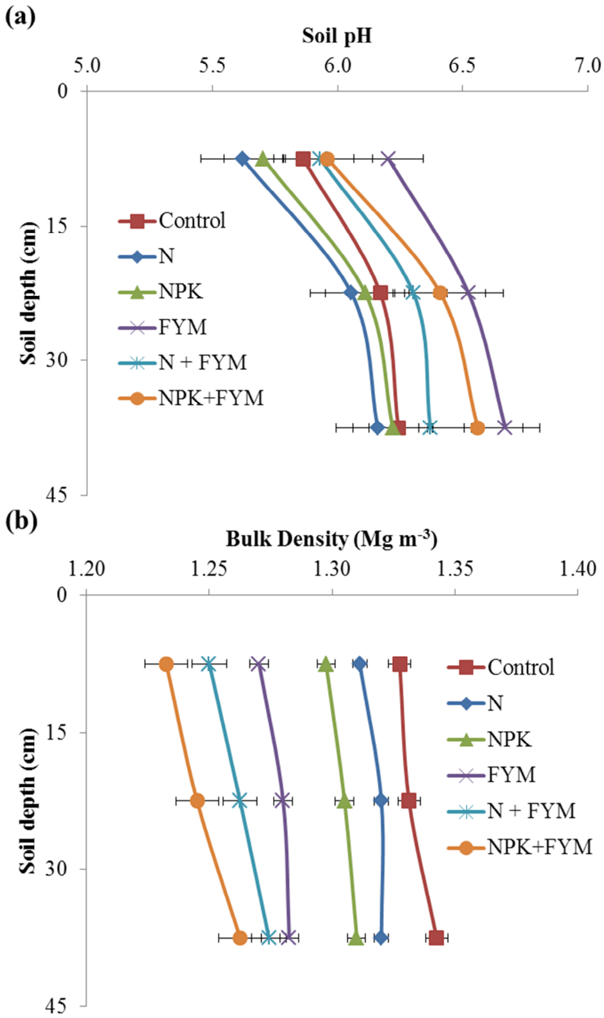

Fig. 2. Depth distribution of soil pH (a), and bulk density (b) as affected by 21-years long-term organic and inorganic fertilization.

significantly lowest bulk density (1.23, 1.24 and 1.26 Mg m^{-3}) followed by N + FYM, FYM, NPK, N and CK. Nevertheless, bulk density with the application of NPK + FYM and N + FYM was non-significantly influenced at various soil depths (Fig. 2b and Table 1).

Carbon Pools

Soil organic C

Results showed that the total SOC concentration increased significantly by ~8, 20 and 32% as compared to initial under 0–15, 15–30 and 30–45 cm soil depth, respectively (Table 2). Significantly higher total SOC concentration was observed for NPK + FYM followed by N + FYM, FYM, NPK, N and CK. The plot with NPK + FYM have ~54, 51 and 52% higher total SOC concentration than CK in 0–15, 15–30 and 30–45 cm soil depths, respectively. However, plot with application of FYM increased the SOC by ~33 (0–15 cm), 36 (15–30 cm) and 35% (30–45 cm soil depth) as compared to CK plot. Total SOC concentrations in NPK + FYM and N + FYM were not significantly different in 0–15 cm depth but below 15 cm they differed significantly. Plots with N + FYM and FYM were not significantly different for total SOC concentration under 0–15 and 15–30 cm soil depths but they differed statically at 30–45 cm depth (Table 2).

Water soluble C

Data pertaining to WSC are presented in Table 2. Results showed that significant differences in WSC between mineral fertilizer treatment (N,

Table 2. Carbon pools under different soil depths as affected long-term organic and inorganic fertilization. WSC = Water soluble C, WBC = Walkley & Black C, $KMnO_4$-C = available C, and SOC = soil organic C.

Treat-ments	WSC			WBC			$KMnO_4$-C			SOC		
	g kg^{-1} soil layers (cm)											
	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45
CK	0.03^{c}	0.03^{c}	0.03^{d}	4.97^{e}	4.00^{d}	3.64^{e}	0.67^{e}	0.52^{f}	0.37^{e}	7.91^{d}	7.28^{e}	6.70^{f}
N	0.03^{bc}	0.04^{bc}	0.04^{cd}	5.33^{e}	4.45^{d}	3.95^{de}	0.75^{d}	0.57^{e}	0.45^{e}	8.38^{cd}	8.07^{d}	7.57^{e}
NPK	0.03^{b}	0.04^{b}	0.04^{bc}	5.87^{d}	5.25^{c}	4.20^{d}	0.83^{c}	0.63^{d}	0.47^{d}	9.06^{c}	8.96^{c}	8.35^{d}
FYM	0.04^{a}	0.04^{ab}	0.05^{ab}	7.00^{c}	6.06^{b}	4.78^{c}	0.93^{b}	0.73^{c}	0.54^{c}	10.49^{b}	9.93^{b}	9.04^{c}
N+FYM	0.04^{a}	0.04^{a}	0.05^{ab}	7.43^{b}	7.16^{a}	5.34^{b}	0.96^{b}	0.81^{b}	0.60^{b}	11.37^{ab}	10.13^{b}	9.56^{b}
NPK+FYM	0.04^{a}	0.06^{a}	0.06^{a}	7.92^{a}	7.43^{a}	6.01^{a}	1.07^{a}	0.92^{a}	0.68^{a}	12.15^{a}	11.02^{a}	10.20^{a}
Mean	0.04^{b}	0.04^{b}	0.05^{a}	6.42^{a}	5.72^{b}	4.65^{c}	0.87^{a}	0.70^{b}	0.52^{c}	9.89^{a}	9.23^{ab}	8.57^{c}

Different superscript indicates significant differences at $P < 0.05$ between different treatment combinations.

NPK) and combined fertilization treatments (FYM, N + FYM and NPK + FYM). However, when compared to CK, WSC increased by ~12, 11 and 20% under NPK and by ~2, 18 and 28% to 27, 23 and 40% under FYM treatment alone or combined FYM and mineral fertilizers under all three soil depths.

Walkley & Black C (WBC)

The WBC content under different treatments varied significantly in all three soil depths and it was in the range 4.97–7.92, 4.00–7.43 and 3.64–6.01 g kg^{-1}, respectively ($P < 0.05$) with an average value of WBC was 6.42, 5.72 and 4.65 g kg^{-1} (~59 to 70% of total soil C), respectively, and it followed the ordered NPK + FYM > N + FYM > NPK > N $\geq$ CK. NPK + FYM treated plot revealed biggest accumulation of WBC, although in the untreated plot witnessed lowermost, it was observed that the plots under the fertilization with NPK contained higher WBC than unbalanced fertilization and CK in all the three soil layers (Table 2). Treatment NPK + FYM had ~59% (0–15 cm), 85% (15–30 cm) and 65% (30–45 cm soil depth) significantly ($P < 0.05$) higher WBC as compared to CK. Plots with NPK + FYM and N + FYM in subsurface soil (15–30 cm depth) and N and CK in all the soil layers were not significantly different.

$KMnO_4$-oxidizable C ($KMnO_4$-C)

Results showed that the $KMnO_4$-C concentration significantly varied among the treatments ranging from 0.67 to 1.07 g kg^{-1} (0–15 cm), 0.52 to 0.92 g kg^{-1} (15–30 cm) and 0.37 to 0.68 g kg^{-1} (30–45 cm depths) with an average values of ~0.87, 0.70 and 0.52 g kg^{-1}. Significantly higher values were recorded with FYM + NPK compared to only mineral fertilization (NPK, N and CK). Significantly higher concentration of $KMnO_4$-C was observed with the application of NPK + FYM and it was ~60, 77 and 84% higher than CK followed by N + FYM and FYM under 0–15, 15–30 and 30–45 cm said depths, respectively (Table 2).

Soil carbon storage

Results showed that the SOC was significantly ($P < 0.05$) influenced by all the treatments combinations compared to CK in different soil depths (Table 3). Significantly highest change in SOC was observed under the plot receiving NPK + FYM followed by N + FYM, FYM and NPK all the soil depths. At 0–45 cm, plots with the application of NPK + FYM, N + FYM and FYM had ~88, 59 and 39% higher change in SOC as compared to NPK plots, respectively (Table 3). The plots with NPK had higher SOC storage over N and CK in all the soil depths. However, the application of organic and inorganic treated plots increased carbon storage over N + FYM except in 0–15 cm, FYM, NPK, N and CK in all soil depths when compared with the initial SOC storage (Table 3) at 0–15, 15–30 and 30–45 cm depths under CK, NPK, and NPK + FYM increased SOC ~5, 18 and 50%, ~16, 40 and 64%, respectively. Nevertheless, the total carbon storage (in 0–45 cm) under NPK + FYM (62.35 Mg C ha^{-1}) treated plot, it was ~42, 21 and 11% higher than CK, NPK and FYM, respectively (Fig. 3a and Table 3).

Nitrogen Pools

Soil total nitrogen (TN)

The contribution towards TN from the organic sources with and without chemical fertilizers (NPK

Table 3. Carbon and nitrogen storage of different soil depths as affected by long-term organic and inorganic fertilization. SOC = soil organic C, and SN = soil total N.

Treatments	SOC storage ($Mg\ C\ ha^{-1}$)			SN storage ($Mg\ N\ ha^{-1}$)		
	-----Soil layer (cm)-----					
	0–15	15–30	30–45	0–15	15–30	30–45
CK	15.76^{c}	14.54^{e}	13.49^{e}	1.22^{d}	1.14^{e}	1.04^{e}
N	16.49^{c}	15.98^{d}	14.99^{d}	1.42^{c}	1.36^{d}	1.19^{d}
NPK	17.65^{bc}	17.54^{c}	16.41^{c}	1.50^{c}	1.42^{c}	1.28^{c}
FYM	20.00^{ab}	19.08^{b}	17.39^{b}	1.56^{bc}	1.47^{bc}	1.37^{b}
N + FYM	21.29^{a}	19.18^{b}	18.27^{b}	1.70^{ab}	1.55^{ab}	1.46^{a}
NPK + FYM	22.46^{a}	20.58^{a}	19.32^{a}	1.79^{a}	1.67^{a}	1.53^{a}
Mean	18.94^{a}	17.82^{ab}	16.65^{b}	1.53^{a}	1.42^{b}	1.32^{b}

Different superscript indicates significant differences at $P < 0.05$ between different treatment combinations.

+ FYM, N + FYM and FYM), was relatively higher in all the three soil depth as compared to NPK, N and CK. The results showed that similar to SOC pattern, significantly highest ($P < 0.05$) TN was observed in NPK + FYM (0.97, 0.89 and 0.81 g kg^{-1}) followed by N + FYM (0.91, 0.82 and 0.77 g kg^{-1}) and FYM (0.82, 0.77 and 0.72 g kg^{-1}) in 0-15, 15–30 and 30–45 cm depths, respectively (Table 4). However, higher TN was recorded in surface layer (0–15 cm) as compared to rest of the soil depths (15–30 and 30–45 cm).

$KMnO_4$ extractable N ($KMnO_4$-N)

In plots receiving FYM along with recommended dose of NPK produced higher amount of $KMnO_4$-N in soil over unfertilized control plot (Table 4). The $KMnO_4$-N content in 0-15 cm soil depth was ~32% higher in NPK + FYM plots followed by ~22% higher with N + FYM and ~18% higher with NPK as compared to CK plots. Similar trends were also observed in lower depths (15–30 and 30–45 cm) but no significant difference was observed between NPK + FYM and N + FYM treated plots.

Soil nitrogen storage

Results clearly indicated that highest total SN storage was reported with NPK + FYM followed by N + FYM, FYM, NPK and N $\geq$ CK in all soil layers (Fig. 3b). Plot receiving NPK + FYM had significantly ~47, 46 and 47% higher total SN storage as compared to unfertilized plots under 0–15, 15–30 and 30–45 cm soil depth, respectively (Table 3). However, the overall total SN storage

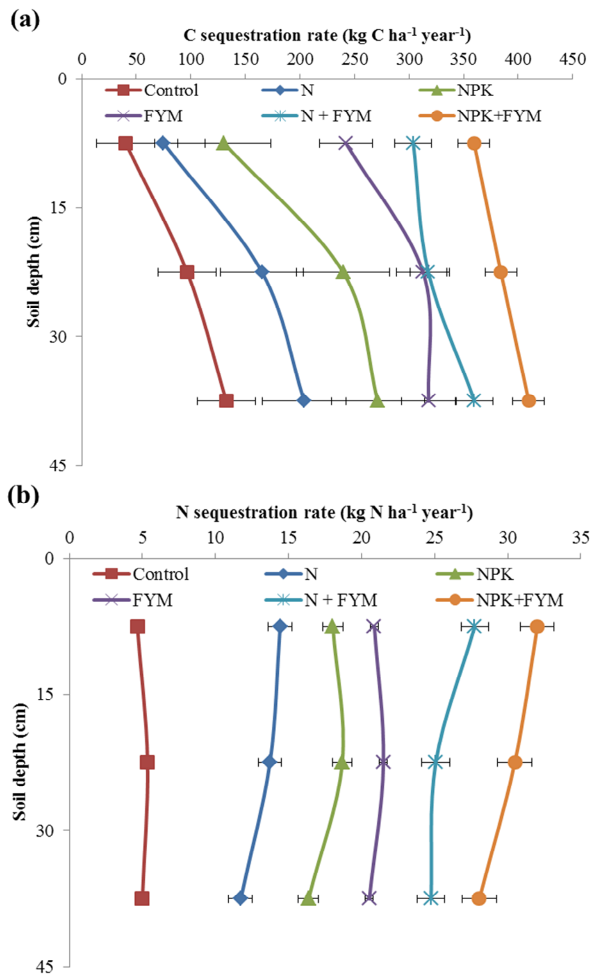

Fig. 3. Depth distribution of (a) C and, (b) N sequestration rate as affected by 21-years long-term organic and inorganic fertilization.

Table 4. Nitrogen pools in different soil depths as affected by long-term organic and inorganic fertilization. $KMnO_4$-N = available soil N, and TN = total soil N.

Treatments	$KMnO_4$-N			TN		
	------------- g kg^{-1} -----------soil layers (cm)---------------					
	0–15	15–30	30–45	0–15	15–30	30–45
CK	0.12^{e}	0.12^{d}	0.11^{d}	0.61^{d}	0.57^{e}	0.52^{f}
N	0.13^{de}	0.13^{cd}	0.12^{cd}	0.72^{c}	0.66^{d}	0.60^{e}
NPK	0.14^{bc}	0.14^{bc}	0.13^{b}	0.77^{bc}	0.72^{c}	0.65^{d}
FYM	0.14^{cd}	0.13^{cd}	0.13^{bc}	0.82^{b}	0.77^{c}	0.72^{c}
N + FYM	0.15^{b}	0.15^{ab}	0.14^{a}	0.91^{a}	0.82^{b}	0.77^{b}
NPK + FYM	0.16^{a}	0.16^{a}	.015^{a}	0.97^{a}	0.89^{a}	0.81^{a}
Mean	0.14^{a}	0.14^{b}	0.13^{b}	0.80^{a}	0.74^{ab}	0.69^{b}

Different superscript indicates significant differences at $P < 0.05$ between different treatment combinations.

(0–45 cm soil depth) under NPK (4.21 Mg N ha^{-1}), it stayed (+24%) higher as compared to CK plots (3.40 Mg N ha^{-1}). Control plots was reported ~12 and 19% lower total SN storage as compared to N + FYM and NPK + FYM treatments, respectively. Similar to SOC storage, TN storage also decreased significantly with soil depth.

A significantly positive linear relationship between TOC and the total N to the soils was observed over the years under 0–15 (y = 0.0671x + 0.1366; R^2 = 0.78), 15-30 (y = 0.0751x + 0.0473; R^2 = 0.8503) and 30–45 cm (y = 0.0794x - 0.0023; R^2 = 0.9341; $P < 0.01$) (Table 5) soil depths.

Discussion

This 21-year long-term field study was performed to evaluate whether a change in carbon and nitrogen storage pattern in soybean-wheat cropping system (SW) could enhance carbon and nitrogen accumulation in soybean and wheat, which could increase the productivity in SW. In past reports, researchers have revealed that increased carbon and nitrogen storage in NPK + FYM of soybean and wheat in SW compared to other cropping system (Singh *et al*. 2017). However, the observations of this experiment revealed that the carbon and nitrogen storage of soybean and wheat was significantly higher in NPK + FYM than other treatment combination.

The current long-term field experiment demonstrates that treatment NPK + 10 t ha^{-1} FYM facilitated the higher storage of CN in SW, which resulted in higher productivity. Significantly an average of all treatments lowest pH was observed with surface, subsurface and deeper surface soil layers (Fig. 2a). Reduction in soil pH might be due to continuous application of nitrogenous fertilizer caused acidification process by producing H^+ ions (Qiu *et al*. 2016).

Plot with NPK + FYM application resulted into significantly lowest bulk density followed by N + FYM, FYM, NPK, N and CK in all three soil depths. Nevertheless, bulk density with the application of NPK + FYM and N + FYM was non-significantly influenced at various soil depths (Table 1 and Fig. 2b). It might be due to integrated use of FYM and mineral fertilizer had lowered bulk density as compared to sole application of chemical fertilizer (Rahman *et al*. 2016). Results clearly indicated that decreased in bulk density with FYM treated plot due to higher concentration of carbon. In present investigation it was observed that irrespective of the treatments soil bulk density increased non-significantly while total porosity decreased with all the three soil depths 0–15, 15–30 and 30–45 cm (Singh *et al*. 2017).

Effect of mineral fertilizers either alone or in combination with organic manure showed higher total SOC and TN concentration over unfertilized control plot after harvest of both crops (Table 2). In general judicious application of FYM and mineral fertilizers resulted higher SOM content under LTFE (Singh *et al*. 2017). WSC is considered as the most active cycling SOC pool (Ghani *et al*. 2003). Application of FYM significantly increased the WSC content in soil might be due to the fact that WSC was supposed to be derived from humus (Kalbitz *et al*. 2000) which significantly ($P < 0.05$) increased by application of FYM. Plot receiving CK and N treatments showed significantly lower content of WSC as compared to balanced fertilization in all soil layers (Srinivas *et al*. 2015). WSC increased significantly with increase in soil

Table 5. Pearson correlation of soil properties (** correlation is significant at the 0.01 level; * correlation is significant at the 0.05 level).

Soil parameters	Pearson's correlation coefficients (r)						
	pH	BD	TOC	WBC	$KMnO_4$-C	WSC	TN
	0–15 cm soil depth						
BD	-0.39						
TOC	0.47*	-0.86**					
WBC	0.58**	-0.80**	0.87**				
$KMnO_4$-C	0.47*	-0.82**	0.87**	0.92**			
WSC	0.32	-0.82**	0.82**	0.70**	0.69**		
TN	0.32	-0.82**	0.88**	0.86**	0.87**	0.71**	
$KMnO_4$-N	0.17	-0.66**	0.69**	0.74**	0.82**	0.48*	0.74**
	15–30 cm soil depth						
BD	-0.37						
TOC	0.38	-0.91**					
WBC	0.47*	-0.88**	0.91**				
$KMnO_4$-C	0.45*	-0.83**	0.89**	0.91**			
WSC	0.56**	-0.74**	0.81**	0.86**	0.85**		
TN	0.38	-0.86**	0.92**	0.94**	0.93**	0.88**	
$KMnO_4$-N	0.06	-0.66**	0.76**	0.75**	0.73**	0.61**	0.73**
	30–45 cm soil depth						
BD	-0.59**						
TOC	0.44*	-0.83**					
WBC	0.52**	-0.81**	0.92**				
$KMnO_4$-C	0.51*	-0.77**	0.93**	0.93**			
WSC	0.45*	-0.65**	0.85**	0.77**	0.88**		
TN	0.50*	-0.79**	0.96**	0.92**	0.94**	0.86**	
$KMnO_4$-N	0.33	-0.65**	0.86**	0.82**	0.88**	0.74**	0.86**

depth but the said soil depth 0–15 cm was at par with 15–30 cm (Table 2). In long-run, the quantity of organic sources is the main factor influencing the amount and composition of WSC (Meena & Sharma 2016). WBC also reported in similar trend might be due to the reason that the imbalanced fertilization did not contribute significantly regarding enhancement of WBC (Das *et al*. 2016).

These results suggested that WBC and $KMnO_4$-C significantly decreased with increasing soil depth (Table 2). This might be due to less concentration of TOC in deeper soil layers (Das *et al*. 2016). Significantly higher amount of $KMnO_4$-C with the NPK + FYM treated plots as compared to CK plot might be outstanding to the larger input (Yang *et al*. 2012). Results showed that significantly highest change in SOC was observed under the plot receiving NPK + FYM followed by N + FYM, FYM and NPK all the soil depths (Table 3). Data noticeably indicated that highest total SN storage was reported with NPK + FYM followed by N + FYM, FYM, NPK and N $\geq$ CK in all soil layers (Fig. 3b). This might be due to the combined application of FYM and NPK which significantly increased C and N storage in agricultural soils (Qiu *et al*. 2016). Plots with NPK + FYM had significantly higher SOC storage than NPK treated plots and the direct application of organic matter through FYM (Dou *et al*. 2016; Manna *et al*. 2017).

Conclusions

Our results have given new insights into the nature of some restoration of soil C, N and their fractions relationships and demonstrate how nutrient management by combined application of organic and inorganic sources is important in sustaining the soil productivity of Indian mid-Himalayan. We concluded that, combined use of organic and mineral fertilizers NPK + FYM (120–26.33 kg ha^{-1} + 10 Mg ha^{-1}) resulted in higher C and N sequestration of SW in the long-run than individual source. However, FYM (10 Mg ha^{-1}) resulted in more reduction of bulk density and higher total porosity, and maintained significantly at par with NPK + FYM. Our study has great relevance to Himalayan countries like India where long-term application of NPK + FYM appear most efficient management system in the sub-temperate climate under irrigated conditions.

References

Blair, G. J., R. D. B. Lefroy & L. Lisle. 1995. Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. *Australian Journal of Agricultural Research* **46:** 1459–1466.

Choudhary, M., S. C. Panday, V. S. Meena, S. Singh, R. P. Yadav, D. Mahanta, T. Mondal, P. K. Mishra J. K. Bisht & A. Pattanayak. 2018. Long-term effects of organic manure and inorganic fertilization on sustainability and chemical soil quality indicators of soybean-wheat cropping system in the Indian mid-Himalayas. *Agriculture, Ecosystems & Environment* **257:** 38–46.

Das, D., B. S. Dwivedi, V. K. Singh, S. P. Datta, M. C. Meena, D. Chakraborty, K. K. Bandyopadhyay, R. Kumar & R. P. Mishra. 2016. Long-term effects of fertilisers and organic sources on soil organic carbon fractions under a rice-wheat system in the Indo-Gangetic Plains of north-west India. *Soil Research* **55**: 296–308.

Dou, X., P. He, X. Cheng & W. Zhou. 2016. Long-term fertilization alters chemically-separated soil organic carbon pools: Based on stable C isotope analyses. *Scientific Reports* **6**: 19061.

Ghani, A., M. Dexter & K. W. Perrott. 2003. Hot-water extractable carbon in soils: a sensitive measurement for determining impacts of fertilisation, grazing and cultivation. *Soil Biology and Biochemistry* **35:** 1231–1243.

Ghosh, B. N., V. S. Meena, N. M. Alam, P. Dogra, R. Bhattacharyya, N. K. Sharma & P. K. Mishra. 2016. Impact of conservation practices on soil aggregation and the carbon management index after seven years of maize-wheat cropping system in the Indian Himalayas. *Agriculture, Ecosystems & Environment* **216:** 247–257.

He, Y. T., W. J. Zhang, M. G. Xu, X. G. Tong, F. X. Sun, J. Z. Wang, S. M. Huang, P. Zhu & X. H. He. 2015. Long-term combined chemical and manure fertilizations increase soil organic carbon and total nitrogen in aggregate fractions at three typical cropland soils in China. *Science of the Total Environment* **532**: 635–644.

Jackson, M. L. 1973. *Soil Chemical Analysis*. Prentice Hall of India Pvt. Ltd., New Delhi, India.

Jha, P., B. L. Lakaria, A. K. Biswas, R. Saha, P. Mahapatra, D. K. Sahi, R. H. Wanjari, R. Lal, M. Singh, A. S. Rao & B. K. Agrawal. 2014. Effects of carbon input on soil carbon stability and nitrogen dynamics. *Agriculture, Ecosystems & Environment* **189:** 36–42.

Kalbitz, K., S. Solinger, J. H. Park, B. Michalzik & E. Matzner. 2000. Controls on the dynamics of dissolved organic matter in soils: a review. *Soil Science* **165:** 277–304.

Lal, R., J. M. Kimble, R. F. Follett & C. V. Cole. 1998. *The Potential of US Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*. Ann Arbor Press, Chelsea, MI.

Ling, N., Y. Sun & J. Ma. 2014. Response of the bacterial diversity and soil enzyme activity in particle-size fractions of Mollisol after different fertilization in a long-term experiment. *Biology and Fertility of Soils* **50:** 901–911.

Manna, M. C., M. Singh, R. H. Wanjari, A. Mandal & A. K. Patra. 2017. Carbon sequestration: nutrient management. *Encyclopedia of Soil Science*, 3rd edition. DOI: 10.1081/E-ESS3-120052914.

Meena, H. M. & R. P. Sharma. 2016. Long-term effect of fertilizers and amendments on different fractions of organic matter in an acid Alfisol. *Communications in Soil Science and Plant Analysis* **47**: 1430–1440.

Nelson, D. W. & L. E. Sommers. 1996. Total carbon, organic carbon, and organic matter. *In*: A. L. Page, *et al. (Eds.). Methods of Soil Analysis, Part 2*. 2nd edition. American Society of Agronomy, Inc., Madison, WI, Agronomy. **9**: 961–1010.

Qiu, S., H. Gao, P. Zhu, Y. Hou, S. Zhao, X. Rong, Y. Zhang, P. He, P. Christie & W. Zhou. 2016. Changes in soil carbon and nitrogen pools in a Mollisol after long-term fallow or application of chemical fertilizers, straw or manures. *Soil and Tillage Research* **163:** 255–265.

Rahman, F., M. M. Rahman, G. K. M. Rahman, M. A. Saleque, A. T. M. Sakhawat Hossain & M. G. Miah. 2016. Effect of organic and inorganic fertilizers and rice straw on carbon sequestration and soil fertility under a rice-rice cropping pattern. *Carbon Management* **7**: 41–53.

Sharma, N. K., R. J. Singh, D. Mandal, A. Kumar, N. M. Alam & S. Keesstra. 2017. Increasing farmer's income and reducing soil erosion using intercropping in rainfed maize-wheat rotation of Himalaya, India. *Agriculture, Ecosystems & Environment* **247:** 43–53.

Shi, Y., X. Zhao, X. Gao, S. Zhang & P. Wu. 2016. The effects of long-term fertiliser applications on soil organic carbon and hydraulic properties of a loess soil in China. *Land Degradation and Development* **27:** 60–67.

Singh, R. J., B. N. Ghosh, N. K. Sharma, S. Patra, K. S. Dadhwal, V. S. Meena, J. S. Deshwal & P. K. Mishra. 2017. Effect of seven years of nutrient supplementation through organic and inorganic sources on productivity, soil and water conservation, and soil fertility changes of maize-wheat rotation in north-western Indian Himalayas. *Agriculture, Ecosystems & Environment* **249:** 177–186.

Srinivas, D., M. B. Lakshmi & P. Bhattacharyya. 2015. Carbon pools and associated soil enzymatic activities as influenced by long-term application of fertilizers and manure in lowland rice soil. *Journal of Indian Society of Soil Science* **63:** 310–319.

Walkley, A. & I. A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of chromic acid titration method. *Soil Science* **37:** 29–38.

Wang, Y., C. Wu, N. Hu, M. Xu & Z. L. Wang. 2015. 23-year manure and fertilizer application increases soil organic carbon sequestration of a rice-barley cropping system. *Biology and Fertility of Soils* **51:** 583–591.

Yang, X. Y., W. D. Ren, B. H. Sun, & S. L. Zhang. 2012. Effects of contrasting soil management regimes on total and labile soil organic carbon fractions in a loess soil in China. *Geoderma* **177-178**: 49–56.

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