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Carbon sequestration and soil carbon pools in a rice–wheat cropping system: Effect of long-term use of inorganic fertilizers and organic manure

B.S. Brar *, Kamalbir Singh, G.S. Dheri, Balwinder-Kumar

Department of Soil Science, Punjab Agricultural University, Ludhiana 141004, India

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ABSTRACT

Agricultural soil is a potential sink for atmospheric carbon as soil organic carbon. The carbon sequestration is affected by cropping system and management practices adopted. Rice–wheat is a dominant cropping system in the Indo-Gangetic plains. Previous studies done by different research workers revealed both its positive as well as negative impacts on carbon sequestration. The objective of this study was to determine C sequestration after nine year's rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping under an ongoing experiment at Punjab Agricultural University, Ludhiana, Punjab (India). This study was based on five treatments (100%N, 100%NP, 100%NPK, 100%NPK + FYM and the control). In the surface soil layer (0–15 cm), soil organic carbon (SOC) increased from the initial status of 2.42 to 3.26 g kg^{-1} in the control, which significantly increased with the application of 100%NPK (4.11 g kg^{-1}) and 100%NPK + FYM (4.55 g kg^{-1}). The rice–wheat cropping even without any fertilization (control) contributed toward carbon sequestration (1.94 Mg C ha^{-1}) with soil organic carbon pools and carbon sequestration rate of 7.84 Mg C ha^{-1} and 0.22 Mg C ha^{-1} yr^{-1}, respectively. The soil organic carbon pools, carbon sequestration and rate of carbon sequestration as observed in treatment of balanced fertilization (100%NPK) were significantly increased from 9.19 to 9.99 Mg C ha^{-1}, 3.30 to 4.10 Mg C ha^{-1} and 0.37 to 0.46 Mg C ha^{-1} yr^{-1}, respectively when farmyard manure was applied in conjunction with 100%NPK. The application of 100%NPK and 100%NPK + FYM significantly increased the soil labile carbon (1378 and 1578 mg kg^{-1}, respectively), water soluble carbon (35.3 and 37.2 mg kg^{-1}, respectively) and water soluble carbohydrates (526 and 538 mg kg^{-1}, respectively) as compared to the control, where the corresponding values were 898, 16.8 and 464 mg kg^{-1}. The content of water stable aggregates organic carbon also increased with fertilization especially in combination with farmyard manure, whereas bulk density of soil was significantly reduced in the treatment of 100%NPK (1.49 Mg m^{-3}) and 100%NPK + FYM (1.46 Mg m^{-3}) over the control (1.60 Mg m^{-3}). The fertilizer treatments (100%N, 100%NP and 100%NPK) made a positive influence on soil organic carbon content in subsurface layers (15–60 cm) also and it was more so in the treatment of 100%NPK + FYM as compared to the control, although contents did not differ significantly. Balanced fertilization (100%NPK) with and without FYM significantly improved the labile C content of soil (up to depth of 60 cm) over the control. Balanced fertilization in combination with FYM significantly increased the water soluble carbon content of soil in comparison to the control (up to depth of 60 cm). Bulk density of sub surface soil (15–60 cm) was reduced in all the treatments as compared to the control although the treatment effect was non-significant. The rice–wheat cropping sequence thus, showed the potential of mitigating atmospheric carbon load through its sequestration and integrated nutrient management may further enhance this potential.

1. Introduction

Agriculture sector in India in 2007 contributed green house gas (GHG) emissions to the tune of 334.41 × 10^6 Mg of CO_2 equivalent with net emissions of 1727.71 × 10^6 Mg of CO_2 equivalent and gross emissions of 1904.73 × 10^6 Mg of CO_2 equivalent in the country and ranked 3rd next to energy (58%) and industry (22%) sectors (INCCA, 2010). Agricultural soil has dual nature as it also serves as a potential sink for atmospheric carbon as soil organic carbon (SOC), which contributes to improve productivity and quality (Rudrappa et al., 2006; Kundu et al., 2007). Soil, an important medium of global C cycle has twice the capacity to store C compared to the atmosphere (Davidson et al., 2000). Dynamics of organic C storage in agricultural soils affects global climatic change

* Corresponding author. Tel.: +91 161 2401960x317; fax: +91 161 2409257.
E-mail address: bsbrar1957@yahoo.co.in (B.S. Brar).

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and crop productivity (Lal et al., 1995; Li et al., 2007). The awareness of greenhouse gas emissions and concerns about the global warming have led to an increased interest in sequestering C in soils (Banger et al., 2009; Follett, 2001). It has been estimated that about 1100–1600 Pg C is sequestered in soils worldwide (Izaurralde et al., 2000). This represents more than twice the amount of C in vegetation (560 Pg) and in the troposphere (750 Pg). It is estimated that about 40–80 Pg of C can be sequestered in soils over the next 50–100 yr through sustainable management (Houghton et al., 1996). Carbon sequestration potential is influenced by many factors such as climate and soil conditions (Miller et al., 2004; Chabbi et al., 2009), cropping systems (Jagadamma and Lal, 2010), managements including tillage (Ogle et al., 2005) and fertilization (Bhattacharyya et al., 2007). A relatively faster rate of decomposition is induced by the continuous warmth in tropical agro-ecosystems, as a result high equilibrium levels of organic matter are difficult to achieve. In these conditions, large annual rates of organic inputs are needed to maintain an adequate labile SOC pool in comparison to cooler climates where soils have more organic carbon because of slower mineralization rates. Moreover, there is need to identify and adopt the best management practices to maintain or improve SOC levels particularly in the tropical regions where soils are low in organic C and production systems are inherently low in soil fertility (Mandal et al., 2005).

The common recommended management practices leading to improve soil C sequestration under integrated nutrient management include the use of manures, compost, crop residues and biosolids, mulch farming, conversation tillage, agro-forestry, diverse cropping systems and cover crops (Lal, 2004). All these practices have the potential to alter C storage capacity of agricultural soil (Halvorson et al., 2002; Russell et al., 2005). The addition of fertilizer on a regular basis leads to an increase in SOC, soil microbial biomass and also alters soil C & N dynamics (Smith et al., 1994). Soil organic carbon is reported to increase by the continuous application of different combinations of N, P and K, whereas it decreased in unfertilized soils (Yadav et al., 1998). According to Su et al. (2006), integrated use of FYM and fertilizers either maintained or improved SOC. The beneficial effect of incorporation of crops residues is more as compared to its burning or removal (Beri et al., 1995). The use of FYM/GM along with incorporation with crop residues has been found to be even more beneficial (Singh et al., 2007). The incorporation of organic manures and crop residues to soil on long-term basis helps in C sequestration, but the rate of C sequestration can vary with the type and nature of organic manure. The rate of change in SOM in agricultural soils is very slow and can take decade to centuries (Stevenson, 1994). The change in SOC fractions like labile carbon, water soluble carbon, and microbial biomass C can be promptly influenced by changes in C inputs (Bolinder et al., 1999). Labile C is the fraction of total C that declines faster and is restored faster and is sensitive to best management practices (Tirol-Padre and Ladha, 2004).

Rice–wheat is a dominant cropping system and it occupies 13.5 million hectare in the Indo-Gangetic Plains (IGP) of Bangladesh, India, Nepal, Pakistan and 10.3 million hectare in China (Ladha et al., 2000). It covers 78% of the gross cropped area of the Punjab, a state of Northern-India (Benbi and Brar, 2009). There are reports in the literature that show both negative and positive impacts of rice–wheat cropping system on carbon sequestration. A 25 years soil testing report of Punjab compiled by Benbi and Brar (2009) emphasized the positive role of intensive agriculture to improve SOC status in the state by 38% (2.9 g kg^{-1} during 1981–1982 to 4.0 g kg^{-1} during 2005–2006). On the contrary, Bhandari et al. (2002) and Regmi et al. (2002) reported the negative effect of rice–wheat cropping system on SOC and soil productivity. Thus a further investigation is needed to understand the real effect of rice–wheat cropping system on SOC fractions and C sequestration. Long-term fertilizer experiments are vital tools to assess impacts of cropping system on sustainable use indicators such as soil quality. Therefore, the present study was done under a nine years old experiment on rice–wheat cropping system to assess the long-term effect of fertilizers and FYM on SOC pools and C sequestration in semi arid region of northern part of India.

2. Materials and methods

2.1. Site description

This study was conducted as a part of an ongoing long-term fertilizer experiment (established since 1999) under rice–wheat cropping system at Research Farm, Department of Soil Science, Punjab Agricultural University, Ludhiana (30°56′N, 75°52′E and 274 msl), Punjab India. This region belongs to C_4 climate zone characterized by hot air conditions. At the start of experiment, the loamy sand soil tested alkaline in reaction (pH 8.3, EC 0.20 dS m^{-1}), low in soil organic carbon (2.1 g kg^{-1} soil) and available N (85.4 kg ha^{-1}) and available K (95.0 kg ha^{-1}), whereas it was medium in available P (12.5 kg ha^{-1}).

2.2. Experimental design

This experiment comprises of 12 fertilization treatments in plot size of 108 m^2 (12 m × 9 m) replicated thrice in a randomized block design. These treatments are 100%NPK (T_1), 150% NPK (T_2), 100%NPK (+S) (T_3), 100%NP (T_4), 100%N (T_5), 100%NK (P to wheat only) (T_6), 100%NPK + Straw (T_7), 50%NPK + FYM (T_8), 100%NPK + FYM (T_9), 50%NPK + GM (T_{10}), 100%NPK + GM (T_{11}) and control (T_{12}). This paper reports the results on the basis of selected five treatments (T_1 = 100%NPK, T_4 = 100%NP, T_5 = 100%N, T_9 = 100%NPK + FYM and T_{12} = Control). Urea, di-ammonium phosphate (DAP) and Muriate of potash (MOP) were used to supply N, P and K, respectively. The farmyard manure at 15 Mg ha^{-1} was applied annually before rice transplanting. On an average, 15 Mg of FYM contained 350 g C kg^{-1}, 5 g N kg^{-1}, 2.5 g P kg^{-1}, 15 g K kg^{-1} and its annual application supplied 5250 kg C ha^{-1}, 75 kg N ha^{-1}, 37.5 kg P ha^{-1}, 225 kg K ha^{-1} to rice–wheat system. The rice and wheat crops were cultivated as per agronomic practices recommended under irrigated condition by Punjab Agricultural University, Ludhiana. The full dose of P and K was applied at the time of transplanting and sowing of rice and wheat respectively. In rice, N was applied in three split doses (1/3rd dose at transplanting, 1/3rd dose after 3 weeks of transplanting and another 1/3rd dose after 6 weeks of transplanting). In wheat ½ of the N was applied at the time of sowing and remaining ½ of N was broadcasted at the time of 1st irrigation.

2.3. Soil sampling and analysis

Soil samples were collected by boring at 4 random places with the help of post hole auger from all the plots at four soil depths (0–15, 15–30, 30–45 and 45–60 cm) after the harvesting of wheat in 2008. Soil core sampler (each core had an inner diameter of 7 cm and length of 4.5 cm) was used to take the sample for the determination of bulk density (Db). Soil samples were air dried in shade. Less than 2 mm size fraction of soil samples were used for determining different fractions of carbon, while 5–8 mm soil fraction was used for the determining water stable aggregates.

The rapid titration method using 1 N $K_2Cr_2O_7$ solution as described by Walkley and Black (1934) was followed for the determination of SOC.

Labile carbon (LC) was determined by $KMnO_4$ oxidation method (Blair et al., 1995). Three gram soil sample was treated with 25 ml of 33 mM $KMnO_4$ and was shaken for 24 h on a reciprocal shaker. After centrifuging at 2000 rpm for 5 min, the samples were filtered through a Whatman No. 1 filter paper. A corresponding blank without soil was also prepared in the same manner. The absorbance of filtrate from samples and blank aliquot was measured at 565 nm on a double beam spectrophotometer. The concentration of $KMnO_4$ from samples and blank was determined using standard calibration curve, obtained by plotting $KMnO_4$ concentration against absorbance at 565 nm.

Water soluble carbon (WSC) was determined using the method as described by McGill et al. (1986). Ten gram soil was taken in centrifuge tube and 20 ml of distilled water was added. The tubes were centrifuged for 1 h at 5000 rpm and the supernatant aliquot was filtered. Ten ml of the filtrate was treated with 5 ml of 0.07 N $K_2Cr_2O_7$, 10 ml of 98% H_2SO_4 and 5 ml of 88% H_3PO_4 and the mixture was digested at 150 °C for 30 min. Cooled samples were titrated with a solution of 0.01 N ferrous ammonium sulphate (FAS) in 0.4 N H_2SO_4 using diphenylamine as an indicator. The WSC was calculated by the following relation:

$$\%\text{WSC} = (\text{B} - \text{S}) \times 0.01 \times 0.003 \times \frac{100}{10}$$

where 'B' is ml of 0.01 N FAS used in the blank and 'S' is ml of 0.01 N FAS used in soil sample.

Water soluble carbohydrates were determined using the method developed by Chebhire and Mundie (1966). Ten gram soil was treated with 50 ml of 24 N H_2SO_4 and was digested on a hot plate at 100 °C for 10–16 h. The filtrate was then precipitated with 6 N NaOH (5 ml) for neutralization and centrifuged for 10 min at 1500 rpm. To 5 ml of aliquot, 10 ml of 0.2% anthrone was added. The intensity of green color was read at 625 nm on the spectrophotometer. The unknown values were calculated on basis of standard curve and compared with anthrone and expressed as mg kg^{-1} soil.

Water stable aggregate size distribution was determined by wet sieving method as described by Yoder (1936). Air dried soil clods of size 5–8 mm were spread uniformly on the top most sieve of a nest of sieves having pore diameter 2, 1, 0.5, 0.25 and 0.11 mm. The nest of sieves was oscillated up and down by a pulley arrangement for 30 min at a frequency of 30 cycles per minute in salt free water. The water stable aggregates of different sizes were collected from the respective sieves separately after oven drying the sieves at 50 °C. Oven dried soil aggregates of different size fractions were ground with pestle and mortar to <0.25 mm size and water stable aggregates associated organic carbon (WSOC) was determined by rapid titration method (Walkley and Black, 1934).

Soil bulk density was determined by collecting undisturbed soil samples of known weight in the metallic cores of known volume (internal diameter of 7.0 cm and length of 4.5 cm). These soil samples were oven dried at 105 °C for 24 h to take the dry weight of soil samples (Blake and Hartge, 1986). The bulk density of undisturbed soil samples was calculated using the equation:

$$D_b = \frac{W_s}{V_t}$$

where 'D_b' is bulk density of soil (Mg m^{-3}), 'W_s' is weight of soil (g) and 'V_t' is the volume of soil sample (cm^3).

Soil organic pools were calculated as per the following equation:

$$\begin{aligned}\text{SOC pool (Mg ha}^{-1}) = {} & \text{SOC concentration } (\%) \\ & \times \text{ soil depth (m)} \\ & \times \text{ bulk density (Mg m}^{-3}) \\ & \times 104 \text{ m}^2 \text{ ha}^{-1} \times 10^{-2}\end{aligned}$$

The carbon sequestration was determined by subtracting the value of C pools at start of the experiment (1999) from the value of C pools in year 2008. The ratio of carbon sequestration over C initial (1999) was calculated. The annual rate of C sequestration was calculated by ratio of changes in C pools over total number of years.

The data for different soil carbon fractions and sequestration were analyzed using a Randomized Block Design (RBD) with Duncan's Multiple Range Test at 5% level of significance for comparing the means. Statistical analysis was performed by a window-based SPSS program.

3. Results and discussion

3.1. Soil organic carbon

Soil organic carbon content was lowest in the control and maximum in treatment of 100%NPK + FYM (Table 1). At a soil depth of 0–5 cm, an application of 100%N, 100%NP and 100%NPK significantly increased the SOC content by 13.2, 17.1 and 30.0% over the control, respectively. Such a beneficial effect of long-term use of chemical fertilizers has also been reported by Campbell and Zentner (1993). However, the SOC content in 0–5 cm layer 100%NPK + FYM treatment (5.07 g kg^{-1}) was significantly higher over the 100%NPK dose alone. Similar was the trend in 5–10 cm layer. The effect of balanced nutrient application (100%NPK) with and without organic manure (FYM) on SOC content was significant over all other treatments in surface soil layer (up to 0–15 cm layer). Similar results have also been reported in literature (Clark et al., 1998; Padre et al., 2007; Kaur et al., 2008). The build up of SOC content was more in surface layer due to more addition of root biomass, root exudates and plant biomass and it decreased with increase in depth irrespective of fertilizer treatments. Similar results were also reported by Sharma et al. (1992) and Kaur et al. (2008). The variation in SOC content at different soil depths due to farmyard manure and fertilizer's application may be attributed to the accumulation of varying amounts of root biomass, root exudates and plant residues left in respective soil layers (Sharma et al., 1992; Brar and Pasricha, 1998; Padre et al., 2007).

3.2. Labile carbon

In surface soil layer (0–15 cm), the labile carbon content was increased significantly by 24.1, 42.3, 53.5 and 75.7% with an application of 100%N, 100%NP, 100%NPK and 100%NPK + FYM, respectively over the control (Table 2). The addition of FYM along with 100%NPK significantly improved labile carbon content (14.5%) of surface layer (0–15 cm) over the 100%NPK treatment. Similar trend was observed at different depth intervals (0–60 cm) among different treatments. The maximum labile carbon content was observed at surface layer which may be attributed to addition of crop residue and microbial activity. The increase in labile carbon content with application of N may be ascribed to the priming effect of applied inorganic N on fresh organic material in the soil, which

Table 1
Effect of long-term use of organic manure and inorganic fertilizers on soil organic carbon (g kg^{-1}) under rice–wheat cropping system.

Treatment	Depth (cm)					
	0–5	5–10	10–15	15–30	30–45	45–60
Control	3.33a	3.27a	3.17a	2.70a	2.53ab	2.43a
100%N	3.77b	3.70b	3.13a	2.87a	2.70ab	2.63a
100%NP	3.90b	3.77b	3.13a	2.77a	2.73ab	2.57a
100%NPK	4.33c	4.23c	3.77b	2.90a	2.87ab	2.60a
100%NPK + FYM	5.07d	4.70d	3.87b	3.10a	2.80ab	2.73a

Values within a column, followed by different letters are significantly different at $p < 0.05$ by Duncan's multiple range test.

Table 2
Effect of long-term use of inorganic fertilizers and organic manure on labile C ($mg\,g^{-1}$) under rice–wheat cropping system.

Treatment	Depth (cm)			
	0–15	15–30	30–45	45–60
Control	898a	824a	752a	644a
100%N	1114b	1024b	934b	692b
100%NP	1278c	1122c	996c	812c
100%NPK	1378d	1176d	1022c	898d
100%NPK + FYM	1578e	1390e	1222d	992e

Values within a column, followed by different letters are significantly different at $p < 0.05$ by Duncan's multiple range test.

Table 3
Effect of long-term use of inorganic fertilizers and organic manure on Water soluble carbon ($mg\,kg^{-1}$) under rice–wheat cropping system.

Treatment	Depth (cm)			
	0–15	15–30	30–45	45–60
Control	16.8a	13.6a	12.8a	12.3a
100%N	18.2a	14.7ab	13.8ab	13.2ab
100%NP	26.7b	22.4abc	20.9abc	19.7ab
100%NPK	35.3c	29.6bc	27.2bc	26.1ab
100%NPK + FYM	37.2c	31.3c	28.4c	27.6b

Values within a column, followed by different letters are significantly different at $p < 0.05$ by Duncan's multiple range test.

stimulates the microbial activity resulting in the decomposition of soil organic matter. The depth-wise distribution of labile carbon content showed a decreasing trend with increase in soil depth in each treatment. Thus, the continuous cropping over the years without fertilizer application (i.e. control) resulted in a slight increase in labile carbon content of soil. However, the buildup was considerable in fertilizers treatments and maximum in FYM amended plots. Similar results were reported by Tirol-Padre and Ladha (2004) and Rudrappa et al. (2005).

3.3. Water soluble carbon

Application of balanced (100%NPK) fertilizers with and without FYM resulted in higher content of water soluble carbon (WSC) in soil (0–60 cm) in comparison to the control (Table 3). In the surface soil (0–15 cm), the treatment of 100%N increased the WSC content by 8.3% as compared to the control. The application of 100%NP and 100%NPK significantly improved WSC content by 58.9 and 110.1% respectively, over the control. The maximum value of WSC content was observed with integrated use of inorganic and organic fertilizer (100%NPK + FYM) and it was comparable to 100%NPK treatment.

In 15–30 cm soil layer, the WSC content increased significantly by 8.1 and 64.7% with 100%N and 100%NP dose respectively in comparison to the control. The balanced fertilizer dose (100%NPK) either alone or in combination with FYM resulted in significant increase in WSC content compared to the control. The similar trend was followed at a depth of 30–45 cm. The application of FYM along with 100%NPK significantly increased the WSC even at 45–60 cm, which indicated the importance of integrated use of organic manure and inorganic fertilizers. The depth-wise distribution of WSC showed a decreasing trend in each treatment. The higher WSC content in surface layer might be due to addition of plant residues and microbial activity. The increase in WSC content with application of N fertilizers could be as a result of the priming effect of applied inorganic N on fresh organic material in the soil, which stimulates the microbial activity helping in the decomposition of SOM with rapid release of the WSC fraction (Yagi et al., 2005). The beneficial effects of FYM application under rice–wheat cropping system on WSC content were also reported by Manna et al. (2006).

3.4. Water stable aggregates organic carbon

In soil (0–15 cm), water stable aggregates organic carbon (WSAC) content was maximum among 0.50–0.25 mm size fractions followed by 0.25–0.11 mm size fractions >2.00 mm size fractions >1.00–0.50 mm size fractions >2.00–1.00 mm size fractions (Fig. 1). Among 0.50–0.25 and 1.00–0.50 mm size fractions, balanced fertilizers (100%NPK) with and without FYM significantly increased water stable aggregates organic carbon contents as compared to the other treatments, whereas in case of 0.25–0.11 and 2.00–1.00 size fractions water stable aggregates organic carbon contents under 100%NPK and 100%NPK + FYM both being at par with each other, were significantly higher over other treatments. Thus, long-term use of FYM along with 100%NPK proved to be most beneficial treatment as microbial action on FYM resulted in the formation of organo-mineral complexes leading to aggregation of soil particles, which further influenced soil C storage and dynamics (Elliot and Coleman, 1988). These results were consistent with the findings of Gerzabek et al. (2001).

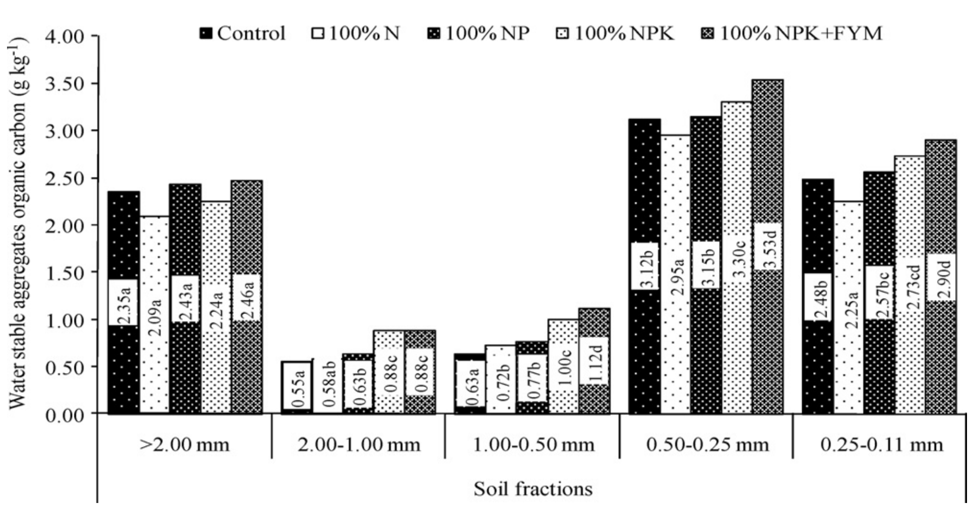


Fig. 1. Effect of long-term use of organic manure (FYM) and inorganic fertilizers on water stable aggregates organic carbon ($g\,kg^{-1}$) in soil (0–15 cm) under rice–wheat cropping system. The vertical bars with values followed by different letters indicate significant difference ($p < 0.05$) according to Duncan's multiple range test.

Table 4
Effect of long-term use of inorganic fertilizers and organic manure on water soluble carbohydrates (mg kg^{-1}) under rice–wheat cropping system.

Treatment	Depth (cm)			
	0–15	15–30	30–45	45–60
Control	464a	372a	338a	320a
100%N	479ab	376ab	344a	326ab
100%NP	496ab	408abc	372ab	348ab
100%NPK	526b	438bc	396ab	368ab
100%NPK + FYM	538b	446c	412b	386b

Values within a column, followed by different letters are significantly different at $p < 0.05$ by Duncan's multiple range test.

Table 5
Effect of long-term use of inorganic fertilizers and organic manure on bulk density (Mg m^{-3}) under rice–wheat cropping system.

Treatment	Depth (cm)					
	0–5	5–10	10–15	15–30	30–45	45–60
Control	1.58de	1.59d	1.64cd	1.70a	1.81a	1.84a
100%N	1.48cd	1.50c	1.60bc	1.69a	1.77a	1.82a
100%NP	1.46c	1.48bc	1.55bc	1.65a	1.70a	1.79a
100%NPK	1.46b	1.47b	1.54ab	1.67a	1.73a	1.80a
100%NPK + FYM	1.42a	1.44a	1.52a	1.65a	1.71a	1.76a

Values within a column, followed by different letters are significantly different at $p < 0.05$ by Duncan's multiple range test.

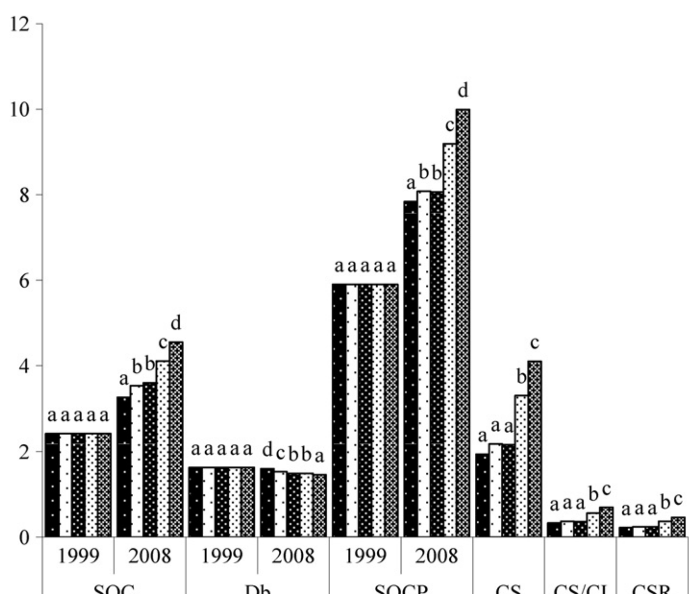
3.5. Water soluble carbohydrates

The water soluble carbohydrates content of soil (0–15 cm) in 100%N and 100%NP treatments was higher by 3.2 and 6.9% over the control (Table 4). The balanced fertilizer (100%NPK) dose significantly improved the water soluble carbohydrates (526 mg kg^{-1}) over the control indicating that balanced use of fertilizers resulted in better establishment of root system of plants (Banwasi and Bajpai, 2001) and also increased microbial activity in soil. The FYM along with 100%NPK increased the water soluble carbohydrates over the 100%NPK application alone, although the contents did not differ significantly.

In sub surface soil layer (15–30 cm), water soluble carbohydrates in 100%N, 100%NP and 100%NPK were 1.1, 9.7 and 17.7% higher over the control, respectively. The balanced fertilizers (100%NPK) dose with and without FYM resulted in significantly higher water soluble carbohydrates content in comparison to the control. The different combinations of fertilizers resulted in higher water soluble carbohydrates content at soil depth of 30–60 cm over the control however this increase was non-significant except FYM treatment. As a whole, distribution of water soluble carbohydrates showed a decreasing trend in its contents with increase in depth. Thus, integrated use of FYM and 100%NPK proved more beneficial as also reported by other workers (Izquierdo et al., 2005; Tejada et al., 2006; Kaur et al., 2008).

3.6. Bulk density

The bulk density of soil decreased with fertilization. This decreased was non-significant with imbalanced fertilizer application. However, balance fertilizer application (100%NPK) integrated with organic manure (FYM) proved best among all the treatments which significantly decreased the bulk density of surface soil (0–15 cm) over the imbalanced fertilizer treatments (Table 5). At lower soil depths, the effect of fertilization on bulk density was non-significant. The bulk density exhibited an increasing trend with increase in soil depth (0–60 cm) in respective treatments. The decrease in bulk density over the years could be attributed to the addition of root and plant biomass and to the conversion of some micro-pores into macro-pores due to cementing action of organic



	1999 SOC	2008 SOC	1999 Db	2008 Db	1999 SOCP	2008 SOCP	CS	CS/CI	CSR
Control	2.42	3.26	1.63	1.60	5.90	7.84	1.94	0.33	0.22
100% N	2.42	3.53	1.63	1.53	5.90	8.08	2.18	0.37	0.24
100% NP	2.42	3.60	1.63	1.49	5.90	8.06	2.16	0.37	0.24
100% NPK	2.42	4.11	1.63	1.49	5.90	9.19	3.30	0.56	0.37
100% NPK+FYM	2.42	4.55	1.63	1.46	5.90	9.99	4.10	0.69	0.46

Fig. 2. Carbon sequestration (0–15 cm soil depth) after 9 year's application of inorganic fertilizer and organic manure in a rice–wheat cropping system. Different letters (a, b and c) on vertical bars for particular year indicate significant difference ($p < 0.05$) according to Duncan's multiple range test. The soil organic carbon (g kg^{-1}), bulk density (Mg m^{-3}), soil organic carbon pools (Mg C ha^{-1}), carbon sequestration (Mg C ha^{-1}), carbon sequestration/carbon initial and carbon sequestration rate (Mg C ha^{-1} yr^{-1}) are denoted as SOC, Db, SOCP, CS, CS/CI and CSR, respectively.

acids and polysaccharides formed during the decomposition of organic residues by higher microbial activities. These results were similar to those reported by several other researchers (Sharma et al., 1987; Babhulkar et al., 2000; Prasad and Sinha, 2000; Agbede et al., 2008; Rasool et al., 2008; Bhattacharyya et al., 2004).

3.7. Carbon balance and turnover rate

After 9 years of cultivation (2008), rice–wheat cropping system even without any fertilization (i.e. control) contributed toward C sequestration (Fig. 2). In comparison to the time of start of the experiment (1999), SOC content of the soil was improved by 34.7 in the control, whereas it increased by 69.8 and 88.0% in treatments of 100%NPK dose and 100%NPK + FYM, respectively. The application of 100%N and 100%NP significantly increased SOC content over the control although both these treatments did not differ significantly in SOC content. The balanced fertilizers (100%NPK) dose with and without FYM significantly improved the SOC content of soil as compared to other treatments, which may be attributed to the increased plant biomass addition. During 2008, the SOC pools increased by 32.9% in the control, whereas treatments of 100%NPK dose and 100%NPK + FYM led to an increase in SOC pools by 55.8 and 69.3%, respectively. In similarity to the trend as observed for SOC content, the SOC pools in the treatments of 100%N and 100%NP were significantly higher over the control although both these treatments did not differ significantly. An application of balanced fertilizers (100%NPK) dose with and without FYM significantly improved the SOC pools as compared to other treatments.

The rice–wheat cropping even without any fertilization (control) contributed toward carbon sequestration (1.94 Mg C ha^{-1}). It was increased by 12.4% in the treatment of 100%N when compared to the control. Balanced application of fertilizers (100%NPK) significantly increased the carbon sequestration over the control, 100%N and 100%NP. The farmyard manure along with balanced chemical fertilizers (100%NPK) proved most useful as it significantly increased the carbon sequestration over all other treatments including 100%NPK dose alone.

The application of 100%N alone increased the ratio of carbon sequestration over carbon initial by 12.1% over the control (Fig. 2). The addition of 100%P along with 100%N showed no effect. Balanced fertilizers (100%NPK) dose significantly improved this ratio in comparison to the control, 100%N and 100%NP. The treatment of FYM + 100%NPK proved to be most beneficial as it was significantly superior even over balanced fertilizers (100%NPK) alone. Similar trend was observed in the case of carbon sequestration rate, which increased by 9.1% with application of 100%N. Application of 100%P showed no effect. The treatment of 100%NPK significantly improved the carbon sequestration rate over the control and 100%N. However, FYM in addition to NPK resulted in significantly higher carbon sequestration rate over all the other treatments. This might be attributed to greater amount of organic input with higher lignin content (FYM) resulting in a greater accumulation per unit of C input (Stevenson, 1965; Paustian et al., 1992). Benbi and Brar (2009) on the basis of soil data for 25 years also reported that intensive cultivation of an exhaustive rice–wheat system unexpectedly improved C sequestration and organic carbon status on a regional scale.

4. Conclusions

This study was done as both positive and negative impacts of rice–wheat system have been reported on carbon sequestration by different research workers. In this study the positive impact of long-term rice–wheat cropping was observed. The continuous adoption of this cropping system even without any fertilizer application (control) contributed toward C sequestration (1.94 Mg C ha^{-1}), which further increased to 3.30 and 4.10 Mg C ha^{-1} in treatments of 100%NPK and 100%NPK + FYM, respectively. The SOC pools significantly increased from 7.84 Mg C ha^{-1} in the control to 9.19 and 9.99 Mg C ha^{-1} with 100%NPK dose and 100%NPK + FYM, respectively. The application of 100%NPK + FYM significantly increased the soil organic carbon, soil labile carbon as compared to other treatments (control, 100%N, 100%NP and 100%NPK). The balanced use of chemical fertilizers (100%NPK) with and without farmyard manure significantly increased water soluble carbohydrates over control. The beneficial effect of chemical fertilizers with and without FYM was more in the surface (0–15 cm) soil layer. The integrated use of farmyard manure and inorganic fertilizers was most promising for improvement of soil organic carbon, soil carbon pools and carbon sequestration.

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