Expl Agric. (2012), volume 48 (4), pp. 473–487 © *Cambridge University Press 2012*
doi:10.1017/S0014479712000130

LONG-TERM EFFECT OF PULSES AND NUTRIENT MANAGEMENT ON SOIL ORGANIC CARBON DYNAMICS AND SUSTAINABILITY ON AN INCEPTISOL OF INDO-GANGETIC PLAINS OF INDIA

By P. K. GHOSH, M. S. VENKATESH†, K. K. HAZRA *and*
NARENDRA KUMAR

Division of Crop Production, Indian Institute of Pulses Research, Kanpur,
Uttar Pradesh 208 024, India

(*Accepted 1 March 2012; First published online 18 April 2012*)

SUMMARY

Continuous cultivation of rice–wheat cropping system in the Indo-Gangetic plains is under threat with decline in soil organic carbon (SOC), total factor productivity and overall sustainability. Pulses, an important component of crop diversification, are known to improve soil quality through their unique ability of biological N_2 fixation, leaf litter fall and deep root system. Therefore, the effect of inclusion of pulses in the puddled rice system under organic and inorganic amendments on SOC pool and its management indices were evaluated in a long-term experiment after seven cropping cycles. The results indicated that inclusion of pulses in the rice-based system improved the SOC content, being greater in surface soil (0–20 cm) and declining with soil depth. Among the four carbon fractions determined, less labile carbon fraction ($C\mathit{frac}_3$) was the dominant fraction in the puddled rice system, particularly under organic treatments, indicating that it is possible to maintain organic carbon for longer time in this system. The rice–wheat–mung bean system resulted in 6% increase in SOC and 85% increase in soil microbial biomass carbon as compared with the conventional rice–wheat system. Application of crop residues, farm yard manure (5 t ha^{-1}) and biofertilisers had greater amount of carbon fractions and carbon management index (CMI) over control and the recommended inorganic (NPKSZnB) treatment in the soil surface, particularly in the system where pulses are included. Interestingly, in the puddled rice system, passive carbon pool is more in surface soil than deeper layers. The relative proportion of active carbon pool in surface layer (0–20 cm) to subsurface layer (20–40 cm) was highest in rice–wheat–rice–chickpea (1.14:1) followed by rice–wheat–mung bean (1.07:1) and lowest in the rice–wheat system (0.69:1). Replacing wheat with chickpea either completely or during alternate year in the conventional rice–wheat system also had positive impact on SOC restoration and CMI. Therefore, inclusion of pulses in the rice-based cropping system and organic nutrient management practices had significant impact on maintaining SOC in an Inceptisol of the Indo-Gangetic plains of India.

INTRODUCTION

The rice–wheat cropping system occupies about 13.5 million ha in the Indo-Gangetic Plains of South Asia and provides food for 400 million people (Ladha *et al.*, 2003). During the last one decade, the rice–wheat system has started showing the signs of stress with production of fatigue and deterioration of soil health (Timsina and Connor, 2001; Yadav *et al.*, 1998). This is especially true for areas where a continuous rice–wheat rotation predominates and system diversity is low (Fujisaka *et al.*, 1994). In many such areas, yields have started declining (Hobbs and Morris 1996; Yadav, 1998) mainly due

---

†Corresponding author. Email: msvbhat@rediffmail.com

to changes in biochemical and physical comparisons of organic matter and gradual decline in the supply of soil nutrients causing macro and micro nutrient imbalances on account of inappropriate fertiliser application (Ladha *et al.*, 2000; Shukla *et al.*, 2004; Timsina and Connor, 2001), and compaction of subsoil layers (Balloli *et al.*, 2000; Ladha *et al.*, 2003). Organic matter is a critical component of soils under the rice–wheat cropping system providing organic substrate for nutrient release and playing a critical role in maintenance of soil structure, water holding capacity and reduction in erosion. Many studies indicate strong positive relationship between the amount of carbon incorporated into soil, either from crop residues or from external sources such as manure, and the content of total soil organic carbon (SOC) (Havlin *et al.*, 1990). Restoration and build-up of organic carbon is a big challenge under intensive production system for tropical, subtropical arid and semi-arid regions where soils are inherently low in organic carbon.

Total organic carbon (TOC) in soil is composed of several fractions. These fractions include large number of organic compounds that are broadly grouped as labile pool and passive pool. The labile pool primarily composes microbial biomass carbon, while the passive pool is a complex material resistant to decomposition, often called humus, and is associated with clay in the soil. Labile pool is more readily lost from the soil than others (Mandal *et al.*, 2008). The relative proportion of these various fractions in soil determines soil quality and its susceptibility to rapid mineralisation and is therefore a critical determinant of soil carbon dynamics. Ghosh *et al.* (2010) reported that conventional cultivation had the lowest TOC content (148 t ha^{-1}), whereas NPK + farm yard manure (FYM)-amended soils had the largest TOC (207 t ha^{-1}). The highest proportion of the labile carbon was observed under fallow whereas the proportion of non-labile carbon fraction was more under NPK + FYM. Long-term experiments have also added much to our understanding of the complex issue of carbon sequestration in soil and particularly the quantification and prediction of carbon sink potential of arable soils (Rogasik *et al.*, 2004). In spite of the existence of large number of long-term experiments that can provide relevant data pertaining to soil management, few studies integrate the total SOC pool and carbon lability into carbon management index (CMI) as a way to assess the capacity of management systems to promote soil quality.

Pulses or food legumes because of their ability for atmospheric nitrogen fixation, leaf shedding ability and higher belowground biomass add significant amount of organic carbon to soil (Ganeshamurthy, 2009). Singh and Sandhu (1980) and Newaj and Yadav (1994) also reported that organic carbon content of soils increased over the initial level due to inclusion of pulses in the cereal-based cropping systems. Our hypothesis is that inclusion of pulses in the lowland puddled rice-based cropping system using organic and inorganic sources of nutrients for a long period may have an impact on the dynamics of different pools of SOC, and thus the quality of soil. Long-term fertility experiments would be more useful to determine the effects of cropping systems, soil and crop residue management etc. on the quantitative and mechanistic changes in SOC (Leigh and Johnstone, 1994). Effects of the pulse-based cropping system on soil carbon dynamics have not been fully quantified in the Indo-Gangetic alluvial plain region. In the present study, we examined the soils of a long-term fertility experiment under the lowland rice-based cropping system on an Inceptisol of the north-eastern Indo-Gangetic Plain zone of India (Kanpur) after seven-year cropping cycles with respect to soil carbon pool and carbon management indices.

MATERIALS AND METHODS

Description of field experiment

The data reported here were generated from a long-term fertility experiment at main research farm of Indian Institute of Pulses Research (IIPR), Kanpur, India (26° 27′ N, 80° 14′ E and 152.4 m above **mean sea level** (msl)). The climate is tropical sub-humid, receives annual rainfall of 722 mm and mean annual maximum and minimum temperature is 33.0 °C and 20.0 °C, respectively. The soils of experimental site comes under taxonomical class *typic ustochrept* with sandy loam texture having pH 8.1, bulk density 1.43 g cm^{-3} and with low organic carbon content (2.8 g cm^{-3}) at the time of initiation of the experiment.

Experimental design and treatments

The long-term trial was initiated during kharif 2003 to determine the effect of different cropping systems, viz. (1) rice–wheat (RW), (2) rice–chickpea (RC), (3) rice–wheat–mung bean (RWMb) and (4) rice–wheat–rice–chickpea (RWRC) (alternate year), and three fertility levels, viz. (1) control (2) inorganic (NPKSZnB) and (3) organic (crop residues + biofertilisers + FYM @ 5 t/ha). Pant Dhan 12 (rice), PBW 343 (wheat), KWR-108 (chickpea) and cv. Samrat (mung bean) were the genotypes used in the experiment.

Sowing and harvesting periods of each crop in different cropping systems are presented in Figure 1. The experiment was under seventh year of crop rotation when the soil was sampled. The treatment was laid out in a split plot design with three replications. Fertilisers N, P_2O_5 and K_2O (kg ha^{-1}) were applied in the form of urea, diammonium phosphate and muriate of potash (KCl) at the following rates: rice and wheat (120–60–40), chickpea and mung bean (20–60–20). Sulphur was applied in the form of gypsum @ 20 kg ha^{-1}, zinc as $ZnSO_4$ @ 25 kg ha^{-1} and boron as borax @ 10 kg ha^{-1}. Well-decomposed FYM was spread uniformly at the rate of 5 t ha^{-1} one month before transplanting of rice, which provided 28, 9, 26, and 448 kg ha^{-1} of N, P_2O_5, K_2O and C, respectively. Full amount of dry crop residues in a system were chopped using rotatory machine, uniformly spread, mixed with soil and allowed to decompose before sowing. Biofertilisers (*Azotobacter* for cereals, *Rhizobium* for pulses and phosphate solubilising bacteria, *Bacillus polymyxa*, for both cereals and pulses) were applied @ 20 g kg^{-1} seed (10^7 bacteria g^{-1} culture) through seed treatment of PUSA inoculant (source: microbiology division, Indian Agricultural Research Institute, New Delhi).

Soil sampling and analysis

Soil samples were collected in 2010 from four soil depths (0–20, 20–40, 40–60 and 60–80 cm) from each treatment after harvesting last crop in the crop cycle. The

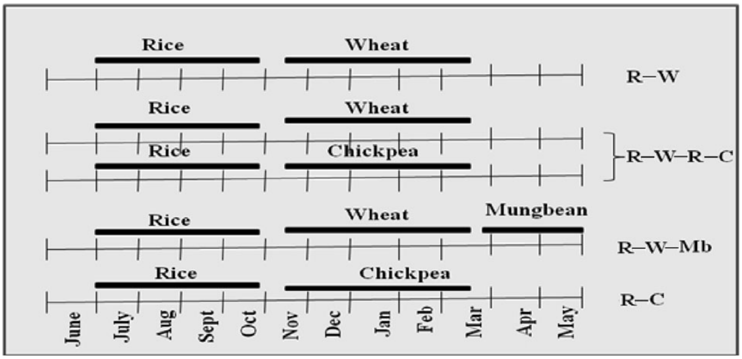

Figure 1. Temporal layout of crop duration under various cropping systems.

samples were air-dried, grounded and passed through a 0.2-mm sieve, stored at room temperature and analysed for oxidisable organic carbon by wet oxidation method (Walkley and Black, 1934). Total organic carbon was calculated using the following formula: oxidisable organic carbon × 1.33 (Hesse, 2002). In surface (0–20 cm) and subsurface (20–40 cm) depths, the fractions of organic carbon present in the soil was estimated through the modified Walkley and Black method as described by Chan *et al.* (2001) using 5, 10, and 20 ml of concentrated H_2SO_4 resulting in three acid aqueous solution ratios, 0.5:1, 1:1 and 2:1 (which corresponded, respectively, to 12 N, 18 N and 24 N of H_2SO_4) (Ghosh *et al.*, 2010). The amount of SOC determined using 5, 10 and 20 ml of concentrated H_2SO_4 when compared with TOC allowed separation of TOC into the following four different fractions of decreasing oxidisability: fraction 1 ($Cfrac_1$), organic carbon oxidisable under 12-N H_2SO_4; fraction 2 ($Cfrac_2$), difference in SOC extracted between 18 N and 12 N H_2SO_4; fraction 3 ($Cfrac_3$), difference in SOC extracted between 18 N and 24 N H_2SO_4 (the 24 N H_2SO_4 is equivalent to the standard Walkley and Black method); and fraction 4 ($Cfrac_4$), residual organic carbon after reaction with 24 N H_2SO_4 when compared with TOC (Nelson and Sommers, 1982).

Active and passive pools

Soil organic carbon oxidised by 12 N H_2SO_4 was designed as very labile pool ($Cfrac_1$) and the difference in SOC oxidised between 18 N and 12 N H_2SO_4 was termed as labile pool ($Cfrac_2$). These two together were designated as active pool of SOC because of their easy oxidisability (by weak 12 N and 18 N H_2SO_4). On the other hand, the passive pool represents the less labile pool ($Cfrac_3$) and the non-labile ($Cfrac_4$) pool of TOC. Summation of these two pools constituted the passive pool of SOC in the experimental soils:

$$\text{Active pool} = Cfrac_1 + Cfrac_2\ \text{(unstable/labile)},$$

$$\text{Passive pool} = Cfrac_3 + Cfrac_4\ \text{(stable/non} - \text{labile or slow pool)}.$$

Carbon management index (CMI)

Step 1. A lability index for SOC was computed using all the three pools (C*frac*$_1$, C*frac*$_2$ and C*frac*$_3$) mentioned above. The C*frac*$_1$, C*frac*$_2$ and C*frac*$_3$ have been designated as very labile, labile and less labile, and are given weightage of 3, 2 and 1, respectively. Subsequently, their actual values were transformed to a proportional amount of TOC and weighed with the weighing factor to get lability index for the organic carbon content in each of the soils under different depths (Blair *et al.*, 1995),

$$\mathrm{LI} = [(\mathrm{C}\mathit{frac}_1/\mathrm{TOC}) \times 3 + (\mathrm{C}\mathit{frac}_2/\mathrm{TOC}) \times 2 + (\mathrm{C}\mathit{frac}_3/\mathrm{TOC}) \times 1].$$

Step 2. Carbon pool index (CPI) was derived using the following formula:

$$\mathrm{CPI} = \text{Sample total C (mg/kg)/reference total C (mg/kg)},$$

where reference total carbon is the total carbon content (mg/kg) of control plots (Blair *et al.*, 1995).

CMI is calculated as follows:

$$\mathrm{CMI} = \mathrm{CPI} \times \mathrm{LI} \times 100.$$

Soil microbial biomass carbon (SMBC)

Microbial biomass carbon was analysed following the chloroform fumigation method. Fifty-gram soil was fumigated for 24 h in a vacuum desiccator using ethanol-free chloroform. After fumigation, chloroform fumes were removed by evacuation. Non-fumigated and fumigated soils (50 g each) were extracted using 200 ml of 0.5 M K_2SO_4 (Vance *et al.*, 1987). The carbon in the chloroform fumigation assay was analysed by wet combustion technique as described by Jenkinson and Powlson (1976),

Soil microbial biomass carbon = $F_c/0.45$,

where F_c = (Organic carbon extracted from 0.5 M K_2SO_4 from fumigated soil–organic carbon extracted from non-fumigated soil).

Statistical analysis

Effects of treatment were evaluated by split plot analysis of variance (ANOVA) with cropping system as main factor and nutrient management as sub-factors. ANOVA was performed using the program SPSS 11.0 for windows. The significance of the treatment effect was determined using *F*-test. When ANOVA indicated that there was a significant value, multiple comparisons of mean value were performed using the least significant difference (LSD) method.

RESULTS

Soil organic carbon

Different cropping systems ($p \leq 0.05$) and nutrient management practices ($p \leq 0.05$) had significant effect on SOC content (Figure 2). Among the cropping systems,

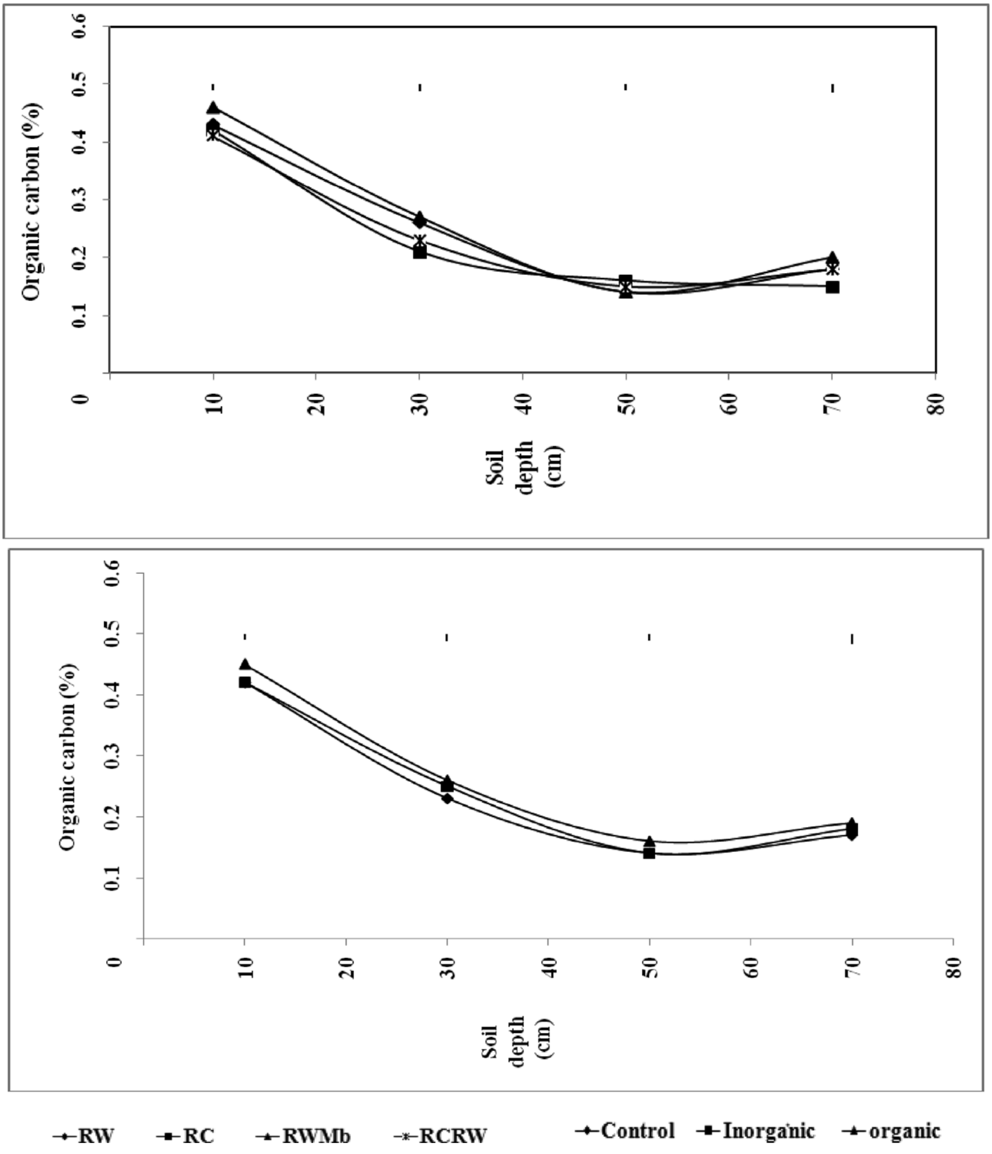

Figure 2. Profile of soil organic carbon content (%) as affected by different cropping systems and nutrient management practices. (RW = rice–wheat; RC = rice–chickpea; RWMb = rice–wheat–mung bean; RWRC = rice–wheat–rice–chickpea; OC = organic carbon). The vertical error bars represent the standard error of means.

rice–wheat–mung bean had the highest SOC content in surface depth, which was 6% higher than the rice–wheat system. Continuous application of organic amendments resulted in the highest increase of SOC content (10.4%) over control. The analysed data detected significant variation in depth-wise distribution of SOC with cropping system and nutrient management practices ($p \leq 0.05$). The SOC content decreased up to 43% at 20–40-cm depth and further 22% at 40–60-cm depth.

Table 1 Cropping system and nutrient management effect on carbon fractions in the experimental soils.

Treatment	$Cfrac_1$ (%)		$Cfrac_2$ (%)		$C\,frac_3$ (%)		$Cfrac_4$ (%)	
Cropping system	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Rice–wheat	0.11	0.12	0.09	0.17	0.23	0.15	0.14	0.08
Rice–chickpea	0.17	0.14	0.10	0.14	0.21	0.13	0.15	0.07
Rice–wheat–mung bean	0.18	0.18	0.11	0.09	0.27	0.07	0.15	0.08
Rice–chickpea–rice–wheat	0.18	0.15	0.13	0.12	0.17	0.12	0.14	0.08
LSD ($p = 0.05$)	0.021	0.019	0.02	NS	0.04	0.01	NS	NS
Nutrient management								
Control	0.13	0.17	0.07	0.12	0.18	0.10	0.15	0.08
Inorganic (NPKSZnB)	0.16	0.14	0.11	0.13	0.23	0.11	0.14	0.08
Organic (crop residues + biofertilisers + FYM)	0.19	0.13	0.13	0.14	0.25	0.14	0.15	0.07
LSD ($p = 0.05$)	0.03	NS	0.02	NS	0.03	0.01	NS	NS

NS = Nonsignificant.

Carbon pools

Inclusion of pulses in the rice-based system increased $Cfrac_1$ both at surface and subsurface layers as compared with the rice–wheat system. Maximum and significant ($p \leq 0.05$) increase in $Cfrac_1$ (64%) at surface depth was observed under both rice–wheat–mung bean and rice–wheat–rice–chickpea systems. On the other hand, at subsurface depth, rice–wheat–mung bean recorded significantly highest $Cfrac_1$ over other cropping systems ($p \leq 0.01$). The effect of cropping system on $Cfrac_2$ was also significant ($p \leq 0.05$) at surface depth. The rice–wheat–rice–chickpea system resulted in greater accumulation of $Cfrac_2$ in surface layer, but at subsurface layer, cropping system effect for this fraction was nonsignificant ($p > 0.05$) (Table 1). Inclusion of mung bean in the rice–wheat system led to significantly ($p \leq 0.01$) higher $Cfrac_3$ as compared with other cropping systems in surface depth. However, at subsurface depth, $Cfrac_3$ was found highest in the rice–wheat system ($p \leq 0.05$). $Cfrac_4$ did not vary significantly ($p > 0.05$) with cropping systems at both soil depths. Application of organic and inorganic amendments had significant effect on distribution of different carbon pool and their share at surface depth ($p \leq 0.05$). Among nutrient management practices, organic treatment (incorporation of crop residue along with FYM and biofertilisers) significantly increased $Cfrac_1$ ($p = 0.001$), $Cfrac_2$ ($p = 0.04$) and $Cfrac_3$ ($p \leq 0.01$) over control and inorganic (NPKSZnB) but not the $Cfrac_4$ ($p = 0.812$). The distribution of different carbon fractions followed the order $Cfrac_3 > Cfrac_1 > Cfrac_4 > Cfrac_2$ in surface depth, whereas it was in the order $Cfrac_1 > Cfrac_2 > Cfrac_3 > Cfrac_4$ at subsurface depth.

The distribution of active and passive pool with soil depth varied significantly with cropping system ($p \leq 0.05$). Relatively higher amount of passive pool was noticed in surface soil than subsurface soil (Figure 3). The relative proportion of active carbon pool in surface to subsurface was highest in the rice–wheat–rice–chickpea system (1.14:1) followed by the rice–wheat–mung bean system (1.07:1), and lowest in the

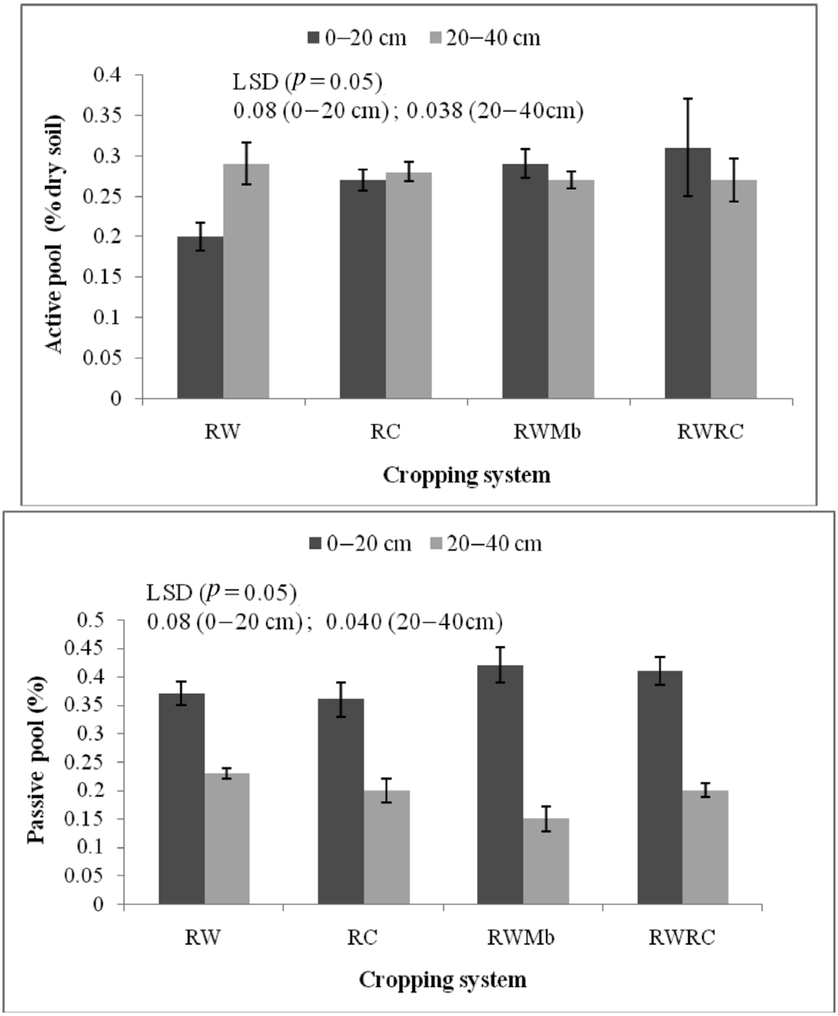

Figure 3. Active pool and passive pool (% dry soil) of soil carbon under different cropping systems and nutrient management practices. (RW = rice–wheat; RC = rice–chickpea; RWMb = rice–wheat–mung bean; RWRC = rice–wheat–rice–chickpea). Vertical error bars represent the corresponding standard error of means.

rice–wheat system (0.69:1). Among nutrient management practices this ratio was relatively more in organic treatment (1.19:1) followed by NPKSZnB (1.00:1) and control (0.69:1). The ratio of passive pool from surface to subsurface was maximum in the rice–wheat–mung bean system (2.63:1) system and minimum in the rice–wheat system (1.61:1). The variation in passive pool of surface to subsurface depth as affected by nutrient management practices was almost comparable.

Soil microbial biomass carbon

There was significantly higher SMBC upon inclusion of pulses in the rice-based system at both soil depths ($p \leq 0.01$). Higher SMBC was recorded in the rice–

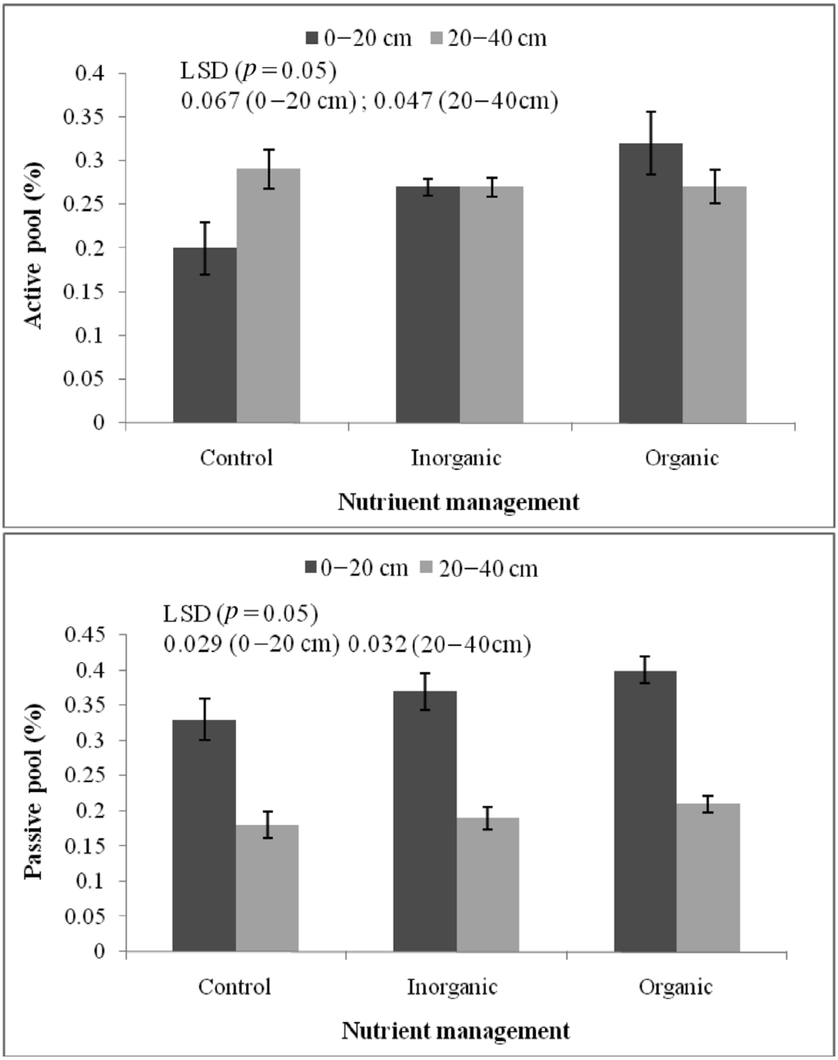

Figure 3. Continued

wheat–mung bean and rice–chickpea systems at surface soil depth (Figure 4). Among nutrient management practices, significantly ($p \leq 0.01$) higher SMBC (38% increase over control) was recorded in organic treatments followed by inorganic treatment in both surface and subsurface depths.

Carbon management index

Inclusion of pulses in the rice-based system increased CMI, although its effect was nonsignificant ($p > 0.05$). Incorporation of crop residue along with application of FYM and biofertiliser was found to improve CMI by 14% over NPKSZnB treatment. Significant interaction effect was detected in nutrient management practices at

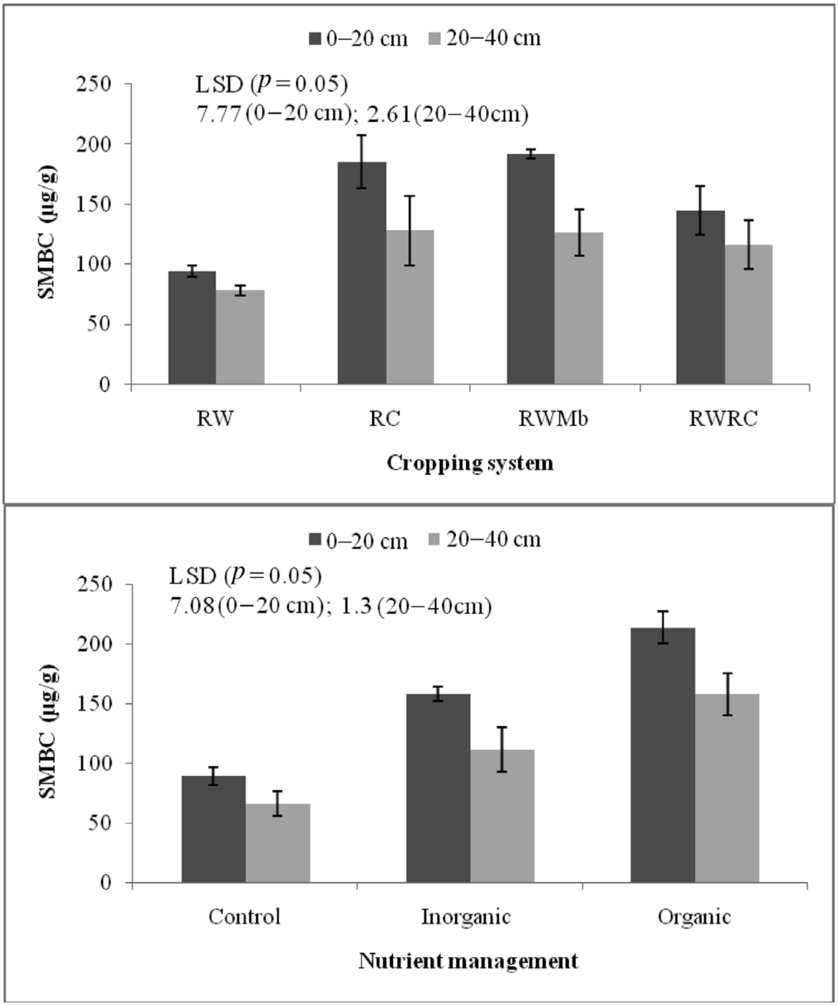

Figure 4. Soil microbial biomass carbon (SMBC) under different cropping systems and nutrient management practices. (RW = rice–wheat; RC = rice–chickpea; RWMb = rice–wheat–mung bean; RWRC = rice–wheat–rice–chickpea). Vertical error bars represent the corresponding standard error of means.

cropping system. Rice–wheat–mung bean showed significantly ($p \leq 0.05$) variable response in CMI with organic and inorganic fertilisation. The interaction of nutrient management at cropping system for CMI was also significant (Figure 5a).

DISCUSSION

Soil organic carbon and its fractions

Our results suggested that crop rotation had considerable effect on the relative proportion of SOC in carbon fraction. The highest increase in SOC content due to inclusion of mung bean in the rice–wheat system was associated with addition of more aboveground biomass of crop residues in this system (Figure 5b). This may

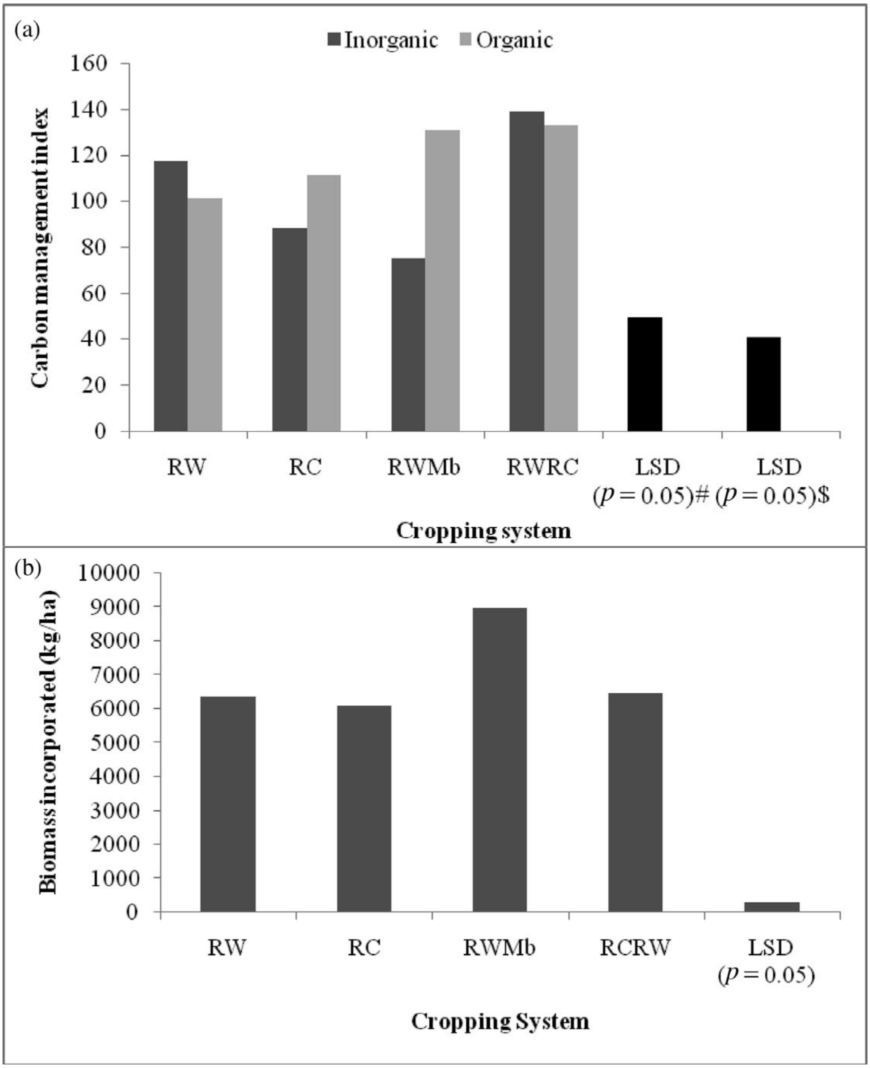

Figure 5. (a) Carbon management index (CMI) in different cropping systems and nutrient management practices (CMI = CPI × lability index; CMI compares the changes that occur in total and labile carbon as a result of agricultural practice with emphasis on changes in labile carbon as opposed to non-labile carbon in SOM; RW = rice–wheat; RC = rice–chickpea; RWMb = rice–wheat–mung bean; RWRC = rice–wheat–rice–chickpea). $^{\#}$LSD ($p = 0.05$) for nutrient management at cropping system (interaction). $^{\$}$LSD ($p = 0.05$) for cropping system at nutrient management (interaction). (b) Annual aboveground biomass of different crops incorporated under different cropping systems. The biomass value represented in the figure is the mean of last four years.

be attributed to the fact that soil organic matter content and their properties are a function of agricultural practices and the kind and amount of plant residues returned to soil (Campbell *et al.*, 1999; Cheshire *et al.*, 1990; Ding *et al.*, 2002). Intensive rice–wheat–mung bean system leads to utilise summer fallow period, which ultimately results in SOC improvement. Earlier studies reported that fallowing reduces SOC by decreasing the amount of non-harvested plant residue returned to the soil (Calegari *et al.*, 2008) whereas increasing the cropping intensity increases SOC (Hutchinson *et al.*, 2007). Increase in SOC in cropping system with pulses as compared with the rice–wheat system could be attributed to addition of more belowground biomass in the form of root (Ganeshamurthy, 2009).

Organic fertiliser treatment resulted in higher increase in SOC as compared with inorganic and control treatment. This increase was likely due to significant increase in carbon input with organic amendments (Gong *et al.*, 2009; Ma *et al.*, 2011; Purakayastha *et al.*, 2008). Powlson *et al.* (1998) at Rothamsted (UK) also reported similar increase in SOC after manure application in long-term experiments. Across all the treatments, relatively higher proportion of carbon fraction was found in surface soil, whereas it was found to decrease with increasing soil depth. This was due to supply and availability of additional mineralisable and readily hydrolysable carbon resulting in higher microbial activity in surface layers (Kaur *et al.*, 2008). Build up of organic carbon is more in surface layer than in lower depth because of more addition of roots and plant biomass in surface layers and lack of nutrient and biological activity in deeper layers, which ultimately constrain the rooting depth (Ingram and Fernandes, 2001; Sharma *et al.*, 1992; Tiwari *et al.*, 1995). Diversification through pulses in the rice-based system resulted in greater accumulation of active and passive pool in surface depth. This finding was highly correlated with soil microbial biomass carbon, which was also higher in surface depth (Figure 4). The higher SMBC observed in the rice–wheat–mung bean system was due to higher quantity and rate of decomposition of crop residues in this system and inclusion of mung bean residues with lower lignin, cellulose and carbon–nitrogen ratio. Irrespective of the cropping system and nutrient management, presence of $Cfrac_3$ was more than other carbon fractions. This could be due to anaerobic conditions prevailing in the lowland ecosystem. Perhaps, this is the reason why passive pool is more in the puddled rice system than active pool. Organic treatment also resulted in increase of more resistant $Cfrac_3$ (Table 1) that might last long and cause a perceptible change in SOC, and further confirmed the dominant role of passive pool in the puddled rice soil. The effect of cropping system on more resistant $Cfrac_4$ was not significant, whereas all other fractions ($Cfrac_1$–$Cfrac_3$) varied significantly due to crop rotation. Lefroy *et al.* (1994) also found similar variation in C*frac*1, C*frac*2 and C*frac*3, which indicated that these fractions were mainly responding to cropping. Consequently, these three fractions have been combined in the derivation of lability index component as outlined by Blair *et al.* (1995). Organic amendments, like crop residues and FYM, are easily mineralised under subtropical conditions. Therefore, their effect was observed on labile fractions of carbon ($Cfrac_1$, $Cfrac_2$ and $Cfrac_3$) only.

Carbon management index

The SOC pool directly influences soil's physical, chemical and biological attributes, as well as the self-organisation capacity of soils (Addiscott, 1995; Blair and Crocker, 2000; Vezzani, 2001). Compared with a single measure such as TOC, CMI can be used as a more sensitive indicator of the rate of change of SOC in response to cropping system and soil management changes (Whitbread *et al.*, 1998). Therefore, the integration of both soil organic carbon pool and carbon lability into CMI, originally proposed by Blair *et al.* (1995), can provide a useful parameter to assess the capacity of management systems to promote soil quality. In our study, legume-based systems showed higher CMI than other systems. Blair and Crocker (2000), Diekow *et al.* (2005) and Blair *et al.* (2006) also reported increase in CMI when legumes were introduced in crop rotations, reinforcing the role of legumes on the addition of photosynthesised carbon in soil. Under organic fertiliser management, significant increase in CMI was noticed over inorganic treatment. This is due to the increase in annual carbon input and the variation in organic matter quality, thus modifying the lability of carbon to oxidised form (Tirol-Padre and Ladha, 2004). The result is similar to that by Blair *et al.* (2006), who reported that manure and manure with inorganic fertiliser significantly increased CMI compared with any other chemical fertiliser treatments in a long-term experiment. Significant variation in CMI in the rice–wheat–mung bean system with nutrient management was attributed to more carbon input provided by crop residues and organic amendments. Gong *et al.* (2009) also reported that 18 years of organic manure addition (alone and in combination with nitrogen fertiliser) was more effective for increasing CMI than chemical fertiliser alone in the maize–wheat system.

CONCLUSION

Inclusion of pulses and nutrient management practices played important role in influencing SOC, carbon fraction and CMI under the rice-based cropping system in Inceptisols. *Cfrac*3 contributed the largest percentage of SOC, which is probably the reason for having more passive pool in the puddled rice system. Among nutrient management treatments, organic fertiliser treatment had greater amount of SOC, C*frac*3, active pool, passive pool, CMI and is considered the best soil management practice in the present study. Among different cropping systems, rice–wheat–mung bean and rice–wheat–rice—chickpea, having higher biomass, maintained greater SOC and CMI under organic management practices, and are considered the ideal system in terms of maintenance of soil health and long-term perspective of system productivity in Inceptisol of the Indo-Gangetic plain of India.

REFERENCES

Addiscott, T. (1995). Entropy and sustainability. *European Journal of Soil Science* 46:161–168.

Balloli, S. S., Ratan, R. K., Garg, R. N., Singh, G. and Krishna Kumari, M. (2000). Soil physical and chemical environment influenced by duration of rice-wheat cropping system. *Journal of Indian Society of Soil Science* 48:75–78.

Blair, N. and Crocker, G. J. (2000). Crop rotation effects on soil carbon and physical fertility of two Australian soils. *Australian Journal of Soil Research* 38:71–84.

Blair, N., Faulkner, R. D., Till, A. R. and Poulton, P. R. (2006). Long-term management impactions on soil C, N and physical fertility. Part I: broadbalk experiment. *Soil and Tillage Research* 91:30–38.

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

Calegari, A., Hargrove, W. L., Rheinheimer, D. D. S., Ralish, R., Tessier, D., Tourdonnet, S. and Guimaraes, M. F. (2008). Impact of long-term no tillage and cropping system management on soil organic carbon in an Oxisol: a model for sustainability. *Agronomy Journal* 100:1013–1019.

Campbell, C. A., Biederbeck, V.O., McConkey, B. G., Curtin, D. and Zentner, R. P. (1999). Soil quality–effect of tillage and fallow frequency. Soil organic matter quality as influenced by tillage and fallow frequency in a silt loam in South-Western Saskatchewan. *Soil Biology and Biochemistry* 31:1–7.

Chan, K. Y., Bowman, A. and Oates, A. (2001). Oxidizible organic carbon fractions and soil quality changes in oxic paleustalf under different pasture leys. *Soil Science* 166:61–67.

Cheshire, M. Y., Christensen, B. T. and Sorensen, L. H. (1990). Labeled and native sugars in particle size fractions from soils incubated with ^{14}C straw for 6 to 18 years. *Soil Science* 41:29–39.

Diekow, J., Mielniczuk, J., Knicker, H., Bayer, C., Dick, D. P. and Kogel-Knabe, I. (2005). Carbon and nitrogen stocks in physical fractions of a subtropical acrisol as influenced by long-term no-till cropping systems and N fertilization. *Plant and Soil* 268:319–328.

Ding, G., Novak, J. M., Amarasiriwardena, D., Hunt, P. G. and Xing, B. (2002). Soil organic matter as affected by tillage management. *Soil Science Society of America Journal* 66:421–429.

Fujisaka, S., Harrington, L. W. and Hobbs, P. R. (1994). Rice-wheat in south Asia: system and long-term priorities established through diagnostic research. *Agricultural System* 46:169–187.

Ganeshamurthy, A. N. (2009). Soil changes following long-term cultivation of pulses. *Journal of Agricultural Science* 147:699–706.

Ghosh, S., Wilson, B. R., Mandal, B., Ghoshal, S. K. and Growns, I. (2010). Changes in soil organic carbon pool in three long-term fertility experiments with different cropping systems and inorganic and organic soil amendments in the eastern cereal belt of India. *Australian Journal of Soil Research* 48:413–420.

Gong, W., Yan, X. Y., Wang, J. Y., Hu, T. X. and Gong, Y. B. (2009). Long-term manuring and fertilization effects on soil organic carbon pools under a wheat–maize cropping system in North China Plain. *Plant and Soil* 314:67–76.

Havlin, J. L., Kissel, D. E., Maddux, L. D., Classen, M. M. and Long, J. H. (1990). Crop rotation and tillage effects on soil organic carbon and nitrogen. *Soil Science Society of America Journal* 54:448–452.

Hesse, P. R. (2002). *A Text Book of Soil Chemical Analysis*. New Delhi, India: CBS.

Hobbs, P. R. and Morris, M. (1996). *Meeting South Asia's Future Requirement from Rice–Wheat Cropping System: Priority Facing Researchers in the Post-Green Revolution Era*. NRG Report No. 96–01 CIMMYT, Mexico DF, 49 pp.

Hutchinson, J. J., Campbell, C. A. and Desjardins, R. L. (2007). Some perspectives on carbon sequestration in agriculture. *Agriculture and Forest Meteorology* 142:288–302.

Ingram, J. S. I. and Fernandes, E. C. M. (2001). Managing carbon sequestration in soils: concept and terminology. *Agriculture, Ecosystems and Environment* 87:111–117.

Jenkinson, D. S. and Powlson, D. S. (1976). The effects of biocidal treatments on metabolism in soil V. A method for measuring soil biomass. *Soil Biology & Biochemistry* 8:209–213.

Kaur, T., Brar, B. S. and Dhillon, N. S. (2008). Soil organic matter dynamics as affected by long-term use of organic and inorganic fertilizers under maize – wheat cropping system. *Nutrient Cycling in Agro-Ecosystems* 81:59–69.

Ladha, J. K., Dawas, D., Pathak, H., Padre, A. T., Yadav, R. L. and Singh, B. (2003). How extensive are yield decline in long-term rice–wheat experiments in Asia. *Field Crop Research* 81:159–180.

Ladha, J. K., Fischer, K. S., Hossain, M., Hobbs, P. R. and Hardy, B. (2000). Improving the productivity and sustainability of rice–wheat system of Indo-Gangetic plains: a synthesis of NARS–IRRI partnership research. *IRRI Discussion Paper* Series No. 40, Manila, Philippines, 31 pp.

Lefroy, R. D. B., Blair, G. J. and Strong, W. M. (1994). Changes in soil organic matter with cropping as measured by organic carbon fractions and ^{13}C natural isotope abundance. *Plant and Soil* 155/156;399–402.

Leigh, R. A. and Johnstone, A. E. (1994). *Long-Term Experiments in Agricultural and Ecological Sciences*. Wallingford, UK: CAB International.

Ma, L., Yang, L. Z., Xia, L. Z., Shen, M. X., Yin, S. X. and Li, Y. D. (2011). Long-term effects of inorganic and organic amendments on organic carbon in a paddy soil of the Taihu Lake Region, China. *Pedosphere* 21:186–196.

Mandal, B., Majumder, B., Bandypadhyay, P. K., Hazra, G. C., Gangopadhyay, A., Santaray, R. N., Misra, A. K., Chaudhury, J., Saha, M. N. and Kundu, S. (2008). Potential of cropping systems and soil amendments for carbon sequestration in soils under long-term experiments in sub-tropical India. *Global Change Biology* 3:357–369.

Nelson, D. W. and Sommers, L. E. (1982). Total carbon, organic carbon, and organic matter. In *Methods of Soil Analysis*, 2nd ed. ASA Monograph 9(2), 539–579 (Ed. A. L. Page). Madison, WI: *American Society of Agronomy*.

Newaj, R. and Yadav, D. S. (1994). Changes in physico-chemical properties of soil under intensive cropping systems. *Indian Journal of Agronomy* 39:373–378.

Powlson, D. S., Smith, P., Cloeman, K., Smith, J. U., Glendining, M. J., Korshens, M. and Franco, U. (1998). A European network of long-term sites for studies on soil organic matter. *Soil and Tillage Research* 47:263–274.

Purakayastha, T. J., Rudrappa, L., Singh, D., Swarup, A. and Bhadraray, S. (2008). Long-term impact of fertilizers on soil organic carbon pools and sequestration rates in maize–wheat–cowpea cropping system. *Geoderma* 144:370–378.

Rogasik, J., Schroetter, S., Funde, U., Schnug, E. and Kurtineez, P. (2004). Long-term fertilizer experiment as a database for calculating carbon sink potential of arable soils. *Archives of Agronomy and Soil Science* 50:11–19.

Sharma, K. N., Bhandari, A. L. and Rana, D. S. (1992). Long-term influence of ingradient of crop technology in pigeonpea–wheat sequence on crop yield and soil fertility changes. *Journal of Research (PAU)* 28:125–131.

Shukla, A. K., Sharma, S. K., Singh, V. K. and Upadhay, N. C. (2004). Rice–wheat system: fertilizer management constraints and their remedial measures. In *Souvenir of National Symposium on Second Generation Problem in Agriculture and its Remedies*, Modipuram, India, 26–27 November, 121–139.

Singh, G. and Sandhu, H.S. (1980). Studies on multiple cropping II. Effect of crop rotation on physical and chemical properties of soils. *Indian Journal of Agronomy* 25:57–67.

Timsina, J. and Connor, D. J. (2001). Productivity and management of rice–wheat cropping systems: issues and challenges. *Field Crop Research* 69:93–132.

Tirol-Padre, A. and Ladha, J. K. (2004). Assessing the reliability of permanganate-oxidizable carbon as an index of soil labile carbon. *Soil Science Society of America Journal* 68:969–978.

Tiwari, R. C., Verma, U. N. and Mishra, A. K. (1995). Effect of long-term cropping system on chemical characteristics of soil properties. *Journal of the Indian Society of Soil Science* 43:278–279.

Vance, E. D., Brookes, P. C. and Jenkinson, D. S. (1987). An extraction method for measuring soil microbial biomass carbon. *Soil Biology and Biochemistry* 19:703–707.

Vezzani, F. M. (2001). *Quality of Soil System in the Agriculture Production*. PhD thesis, Federal University of Rio Grande do Sul, Porto Alegre, 184 pp. (in Portuguese).

Walkley, A. and Black, I. A. (1934). An examination of method for determining organic carbon in soils: effect of variations in digestion conditions and of inorganic soil constituents. *Soil Science* 63:251–263.

Whitbread, A. M., Lefroy, R. D. B. and Blair, G. J. (1998). A survey of the impact of cropping on soil physical and chemical properties in north-western New South Wales. *Australian Journal of Soil Research* 36:669–681.

Yadav, R. L. (1998). Factor productivity trend in rice–wheat cropping system under long-term use of chemical fertilizers. *Experimental Agriculture* 34:1–18.

Yadav, R. L., Dwivedi, B. S., Gangwar, K. S. and Prasad, K. (1998). Overview and prospects for enhancing residual benefits of legumes in rice–wheat cropping system in India. In *Residual Effect of Legumes in Rice and Wheat Cropping system of Indo-Gangetic Plains*, 207–226 (Eds. J. V. D. K. K. Rao, C. Johansen and T. J. Rego) New Delhi, India: Oxford and IBH Publishing Co. Pvt. Ltd.