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Long-term effect of different integrated nutrient management on soil organic carbon and its fractions and sustainability of rice–wheat system in Indo Gangetic Plains of India

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A B S T R A C T

Rice–wheat rotation is the most important cropping system of the Indo-Gangetic Plains (IGP) and is responsible for the food security of the region. The effect of different integrated nutrient management practices on soil organic carbon (SOC) stocks and its fractions, SOC sequestration potential as well as the sustainability of the rice–wheat system were evaluated in long term experiments at different agro-climatic zones of IGP. Application of NPK either through inorganic fertilizers or through combination of inorganic fertilizer and organics such as farm yard manure (FYM) or crop residue or green manure improved the SOC, particulate organic carbon (POC), microbial biomass carbon (MBC) concentration and their sequestration rate. Application of 50% NPK + 50% N through FYM in rice and 100% NPK in wheat, sequestered 0.39, 0.50, 0.51 and 0.62 Mg C ha^{-1} yr^{-1} over control (no N–P–K fertilizers or organics), respectively at Ludhiana, Kanpur, Sabour and Kalyani using the mass of SOC in the control treatment as reference point. Soil carbon sequestration with response to application of fertilizer partially substituted (50% on N basis) with organics were higher in Kalyani and Sabour lying in humid climate than Ludhiana and Kanpur lying in semiarid climate. The rice yield recorded a significant declining trend in Ludhiana and Kanpur where as the yield trend was stable at Sabour and Kalyani under unfertilized control. The system productivity in N–P–K fertilized plots and NPK along with organics showed either an increasing trend or remained stable at all locations during last two and half decades of the experiment.

1. Introduction

Following the unprecedented expansion and intensification of agriculture in India, there is clear evidence of a decline in the soil organic carbon (SOC) contents in many soils as a consequence; while on the other hand it has been reported that good farming practices such as balanced fertilization and addition of crop residues either maintains or results build up or depletion of SOC stock (Swarup et al., 2000; Kong et al., 2005). The process of decline of soil organic matter is accelerated by the process of nutrient depletion (Himes, 1998; Lal, 2002), soil erosion and other forces of land degradation (Lal, 1999). The benefits of soil organic carbon are linked closely to the fact that it acts as a storehouse for nutrients, is a source of soil fertility, and contributes to soil aeration, thereby reducing soil compaction. Other benefits are related to the improvement of infiltration rates and the increase in storage capacity for water. Furthermore, it acts as an energy source for soil microorganisms. Irrespective of its potential benefits to productivity and profitability, organic carbon might be sequestered by vegetation and soils, as a possible way of reducing the rate of CO_2 enrichment of atmosphere and moderate the global climate change. Soils, and managed agricultural soils in particular, represent a potentially significant low-to no cost sink for greenhouse gases (GHGs) (Lal, 2004a; Pacala and Socolow, 2004). The potential of agriculture (excluding bioenergy) to absorb large quantities of atmospheric CO_2 through soil carbon sequestration which has strong synergy with sustainable agriculture is widely being put forward as one of the mitigating options for climate change (Lal, 2002; Post et al., 2004). Thus, one of the more promising ways to reduce the rate of rise in atmospheric CO_2 is to encourage management policies that promote C sequestration in vegetation and ultimately in soils (Idso and Idso, 2002). The SOC concentration of most soils in India is less than 10 g kg^{-1}, and is generally less than 5 g kg^{-1}. Because of the low clay contents, the SOC concentration

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is especially low in alluvial soils of the Indo-Gangetic Plains (IGP), coarse-textured soils of southern India, and arid zone soils of north-western India (Dhir et al., 1991). These soils have been cultivated for centuries, and often with low off-farm input, based on systems that involve removal of crop residue and dung for fuel and other purposes. Consequently, SOC concentration of most soils is low. The prevalent low levels of SOC concentrations are attributed to soil-mining practices of excessive tillage, imbalance in fertilizer use, little or no crop residue returned to the soil, and soil degradation (Lal, 2004b). The most agricultural soils can store more carbon and even a modest increase in carbon stocks across the large land areas used for agriculture would represent a significant GHG mitigation by decreasing the rate of enrichment of atmospheric CO_2. Nevertheless there are much uncertainty and debate on the total potential of soils to store additional carbon, the rate at which soils can store carbon, the permanence of this carbon sink, and how best to monitor changes in soil carbon stocks (Sanderman et al., 2010).

In India, the importance of organic matter addition was considered so important that numerous studies with organic manures were conducted. The primary purpose was to determine their nutrient equivalence in comparison to chemical fertilizers. Despite the fact that organic manures contain almost all the essential plant nutrients and produce other non-nutrient benefits also, their value was principally assessed in terms of N only (Katyal, 1993; Tandon, 1997). In long term experiments, it has been observed that intensive rice-based systems is showing symptoms of 'fatigue', witnessed by stagnating or declining yields (Ram, 1998; Dawe et al., 2000; Duxbury et al., 2000; Ladha et al., 2003). One of the major reasons put forward for such stagnation in yield is the decline in soil organic matter (SOM) quality and quantity (Dawe et al., 2000; Yadav et al., 2000; Ladha et al., 2003). Long term studies have shown that practices like improved fertilizer management, manuring and compost application, residue incorporation, crop rotation, green manuring, reduced tillage, adjusting irrigation method and restoration of waste land enhanced soil carbon build up and storage (Kimble et al., 2002). These practices not only promote sustainable agriculture but also mitigate the impact of climate change through both carbon sequestration and minimized emissions of GHGs. A single land use or management practice will not be effective at sequestering C in all regions (Lal et al., 1998). The cropping systems and the management practices that could provide C input higher than the above critical level are likely to sustain the SOC level and maintain good soil health in the subtropical regions of the Indian subcontinent (Mandal et al., 2007). The present study focuses on long-term dynamics of carbon in the rice–wheat cropping system under different agro climatic zones of IGP. The objectives of this study are to assess the long-term impacts of nutrient management practices on (i) yield trend of rice, wheat and sustainable yield indices; (ii) SOC and SOC fractions, their sequestration rate, and (iii) the relationship among sustainable yield indices, SOC and its fractions in rice–wheat cropping system.

2. Materials and method

2.1. Site descriptions

The long-term field experiments were initiated in 1980s at Ludhiana, Kanpur, Sabour and Kalyani falling in Trans Gangetic Plains (TGP), Upper Gangetic Plains (UGP), Middle Gangetic Plains (MGP) and Lower Gangetic Plains (LGP), respectively extending from 21°45′N to 31°00′N latitude and from 74°15′E to 91°30′E longitude representing a total area of 43.7 M ha, i.e. 13% of the total area of the country (Fig. 1). The details about year of start, geographical coordinates, climatic conditions for the sites were presented in Table 1 and basic soil properties analysed for sand, silt and clay (international pipette method), OC (Walkley and Black method), available N (alkaline $KMNO_4$ method), 0.5 M $NaHCO_3$ (pH 8.5) extractable P and 1 N NH_4 OAc–extractable K following Page et al. (1982) are listed Table 2.

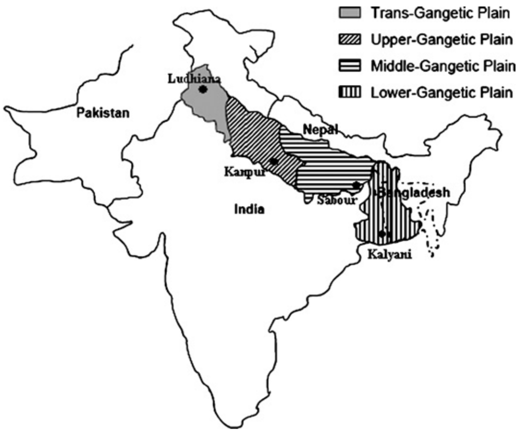

Fig. 1. Map of India (not to the scale) showing the Indo-Gangetic Plains and the locations of the long-term experiment on rice–wheat system.

2.2. Cropping practices

The treatments represented different combinations of inorganic and organic sources of nutrients to rice and wheat. In rice, the full recommended levels of N, P, and K were supplemented with N through FYM, crop residue (wheat straw in Ludhiana, Kanpur and Sabour and paddy straw in Kalyani), and sesbania (*Sesbania sesban* (L.) Merr.), a leguminous green manure (GM) so that the 100% recommended N dose was available to the rice crop. The wheat did not receive any organic sources of nutrients but received N–P–K fertilizer. The experiment included two crops per year, rice (July–October) and wheat (November–April), with 12 treatments which were laid out in a randomized design and replicated thrice. Of the 12 treatments, five selected for the present study were: (i) no N–P–K fertilizers or organics (control), (ii) 100% N–P–K in rice and wheat (NPK), (iii) 50% N–P–K + 50% N through FYM in rice, 100% N–P–K in wheat (NPK + FYM), (iv)) 50% N–P–K + 50% N through crop residue (paddy straw in Kalyani and wheat straw in rest three places) in rice, 100% N–P–K in wheat (NPK +CR), (v)) 50% N–P–K + 50% N through green manuring in rice, 100% N–P–K in wheat (NPK + GM). The 100% N–P–K dose used in rice (wheat) was 120:30:30 (120:60:30) kg $N:P_2O_5:K_2O$ ha^{-1} in Ludhiana, 120:60:60 (80:30:0) kg $N:P_2O_5:K_2O$ ha^{-1} in Kanpur, 80:40:20 (100:50:25) kg $N:P_2O_5:K_2O$ ha^{-1} in Sabour and 120:60:40 (100:60:40) kg $N:P_2O_5:K_2O$ ha^{-1} in Kalyani, respectively. During June and July, the land was plowed, puddled and leveled. Rice crop was transplanted (@ two seedlings $hill^{-1}$) in the puddled lowland field at 20-cm × 15-cm spacing. For green manuring, an appropriate amount of aboveground biomass of sesbania was chopped into 5–10-cm pieces, uniformly spread into the plots and incorporated into the puddled soil with a power tiller a day before transplanting of rice. Calculated amounts of well-decomposed FYM and crop residue (CR) were manually spread uniformly and incorporated into the moist soil 2 weeks before transplanting of rice. The N content (quantity applied) of FYM, CR and GM used in the experiments over the years were 0.50–0.82% (7.3–12 t ha^{-1}), 0.65–0.68% (8.8–9.2 t ha^{-1}) and 1.7–2.4% (2.5–3.5 t ha^{-1}), respectively. After the rice was harvested in the last week of October, land preparation (plowing and laddering) was done and wheat was sown in the second week of November with a spacing of 20 cm between rows, and harvested in April. All P and K and a half dose of N were drilled at sowing. The remaining N was top-dressed 21 days after

Table 1
Geographical coordinates and climatological data of experimental sites.

Location	Year of start of experiment	Latitude	Longitude	Altitude (m)	Precipitation (mm yr^{-1})	Mean temperature	
						June–October	November–April
Ludhiana	1983	30°56′N	75°52′E	247	500	28.84	17.27
Kanpur	1984	26°58′N	80°34′E	129	818	29.42	19.95
Sabour	1984	25°14′N	87°04′E	43	1358	29.61	24.14
Kalyani	1986	23°00′N	89°00′E	11	1480	29.01	23.42

Table 2
Basic soil properties and available nutrients at the start of the long term experiment.

Location	Soil type	Sand (%)	Silt (%)	Clay (%)	pH	Organic carbon (g kg^{-1})	Available nutrients (mg kg^{-1})		
							N	P	K
Ludhiana	Typic-Ustochrept	54.0	28.0	18.0	8.1	3.1	65	5.1	46
Kanpur	Udic-Ustrochrepts	47.0	35.0	18.0	8.0	2.9	83	6.3	82
Sabour	Udic-Ustrochepts.	50.0	22.0	28.0	8.1	4.6	n.d.[a]	4.5	58
Kalyani	Aeric-Haplaquept	20.5	29.5	50.0	7.2	9.2	45	7.3	36

[a] n.d.: not determined.

sowing. Other recommended practices such as weeding, irrigation and plant protection measures were followed. The wheat crop was harvested when 90% of ear-heads were fully matured. The rice and wheat yields were reported at 14% grain moisture content.

2.3. Soil sampling

Soil samples from each replicated plot were collected randomly from three spots with the help of a core sampler (10 cm internal diameter and 15 cm height) after the harvest of wheat crop in the year 2009. The soil cores were collected from 0 to 15, 15 to 30, 30 to 45 and 45 to 60 cm soil depth. One composite sample representing each replication was prepared by mixing two cores of respective soil depth. Immediately after collection, the soil samples were brought to the laboratory and stored in a refrigerator for measurement of cumulative carbon mineralized (C_{min}) and microbial biomass carbon (MBC). A subset of soil samples was air dried and passed through a 2 mm sieve for determination of pH, SOC and particulate organic carbon (POC). The third core sample was used for the estimation of bulk density.

2.4. Soil analysis

The soil pH was measured in soil:water suspension (1:2). The electrical conductivity (ECe) was determined in soil saturation extract. The bulk density of soil was measured using core sampler method as suggested by Veihmeyer and Hendrickson (1948).

2.5. Soil organic carbon

Soil organic carbon was determined by wet digestion with potassium dichromate along with 3:2 H_2SO_4:85% H_3PO_4 digestion mixture in a digestion block set at 120 °C for 2 h (Snyder and Trofymow, 1984). A pre-treatment with 3 ml of 1 N HCl g^{-1} of soil was used for removal of carbonate and bicarbonate. By using the bulk density value the SOC for each soil layer was calculated and expressed as Mg ha^{-1}.

2.6. Particulate organic carbon

Particulate organic matter (POM) was separated from 2 mm soil following the method described by Camberdella and Elliott (1992). Briefly a 10 g sub-sample of soil was dispersed in 100 ml 0.5% sodium hexa-metaphosphate solution by shaking for 15 h on a reciprocal shaker. The soil suspension was poured over a 0.05 mm screen. All material remaining on the screen, defined as the particulate organic fraction within a sand matrix, was transferred to a glass beaker and weighed after oven-drying at 60 °C for 24 h. The particulate organic carbon in POM was determined following the method of Snyder and Trofymow (1984).

2.7. Soil microbial biomass carbon

Microbial biomass carbon was determined according to the $CHCl_3$ fumigation–extraction method in field-moist samples (Vance et al., 1987). Fumigated and non-fumigated samples were incubated during 24 h at 25 °C at constant moisture content. Microbial C was extracted from both fumigated and non-fumigated samples with 0.5 M K_2SO_4 and digested in the presence of potassium persulphate ($K_2S_2O_8$) and 0.025 M H_2SO_4 in a digestion block at 120 °C for 2 h. The amount of CO_2–C thus evolved was estimated by following the method of Snyder and Trofymow (1984). Microbial C was calculated by subtracting the extracted C in unfumigated samples from that measured in fumigated samples and dividing it by a K_c value of 0.45 (Joergensen, 1996). The values of MBC were represented in μg g^{-1} dry soil.

2.8. Carbon mineralization

Aerobic incubation in the laboratory was used to estimate potential C mineralization. Samples of 100 g fresh soil at 60% water holding capacity (WHC) were placed in a 1 L air tight jar along with a vial containing 0.1 N NaOH to trap evolved CO_2 (Zibilski, 1994) and incubated for 30 days at 28 °C. The alkali was replaced twice a week during the first two weeks, followed by once a week for the rest of the incubation period. The unspent alkali was titrated back with standard HCl to estimate the CO_2–C evolved from soil.

2.9. Sustainable yield index

The sustainable yield index (SYI suggested by Singh et al., 1990) is defined as

$$\text{SYI} = \frac{Y - \text{sd}}{Y_{\text{max}}} \qquad (1)$$

where SYI is sustainable yield index, Y is the average yield of rice and wheat over years and sd is the standard deviation and Y_{max} is the observed maximum yield in the experiment over the years of cultivation. Similarly sustainable yield index of the system (rice–wheat) was worked out using the Rice Equivalent Yield (REY) in place of Y and REY_{max} is the observed maximum REY in the experiment over the years of cultivation. Equivalent yield is calculated in terms rice using the following formula

$$\mathrm{REY} = \frac{\sum Yi \cdot Pi}{P_{(p)}} \tag{2}$$

where REY denotes rice equivalent yield; Yi = yield of different crops; Pi = price of wheat and $P(p)$ = price of rice (constant base price of 1990 was used for both the crops).

2.10. Statistical analysis

The significant difference among the means of SOC and their fractions, sequestration rates of different treatments within and among the locations were analysed by Duncan's Multiple Range Test (Gomez and Gomez, 1984) using SAS v 9.2. Multivariate correlation matrix analysis was performed for the SYI of rice, wheat and the system, soil organic carbon fractions and bulk density to determine their strength of relationship. The parametric test was done to know the presence of linear trend by examining the relationship between time (experimentation period in years) and the variable of interest *viz.*, yield of rice, wheat and system productivity (Y) using a least squares linear regression

$$Y = a + bt \tag{3}$$

where Y is the grain yield (t ha^{-1}) of rice or wheat or REY, a is the constant, b is the slope or magnitude of yield trend (percent change in yields per year), and t is the time (experimentation period in years).

3. Results and discussion

3.1. Rice and wheat yield trends

Application of NPK, either through inorganic fertilizers or in combination with organic manures/crop residue/green manure, significantly increased the yields of rice and wheat over control at all locations. For yields averaged over years, the comparison of treatments revealed that the percent yield increase in treated plots over control ranged from 150 to 216, 135 to 180, 202 to 229 and 167 to 198% in rice and 220 to 257, 271 to 294, 291 to 335 and 228 to 271% in wheat at Ludhiana, Kanpur, Sabour and Kalyani, respectively. This clearly indicated the importance of application of adequate quantity of nutrients in recommended doses with or without partial substitution of organics for sustaining the productivity of rice–wheat system in the IGP. Yadav et al. (2000) also reported that continuous rice–wheat cropping in IGP without addition of adequate nutrients resulting in yield decline, while favourable effect of organic manures along with inorganic fertilizers have been reported for sustaining rice–wheat productivity (Hegde and Dwivedi, 1992; Singh et al., 1994).

The yield data used for time series analysis (Figs. 2–5) revealed that though there was no management change in the long term experiments during 1994–1997, yield peaks were observed at Kanpur and to some extent at Sabour. In order to avoid the influence of these yield peaks on the trend, the procedure of Dawe et al. (2000) was followed and yield data from 1998–1999 to 2008–2009 was used for trend analysis in case of Kanpur and Sabour (Figs. 3 and 4) while the entire dataset was used in case of Ludhiana and Kalyani (Figs. 2 and 5). The rice yield recorded a significant declining trend (P = 0.05) in control and NPK treatments at Kanpur; in control, NPK and NPK + CR treatments at Ludhiana. However, working on the yield data in NPK treatment from 1973 to 1998, Yadav et al. (2000) reported a significant increase in yield trend of rice at Kanpur. Significantly increasing trend in rice yield was observed at Saboure and Kalyani in treatments having NPK or NPK + FYM/crop residue/green manure (Table 3, Figs. 4 and 5). The higher grain yield of rice in combined application of nutrients through inorganic and organic sources might be due to availability of nutrients throughout the growth period at Sabour and Kalyani.

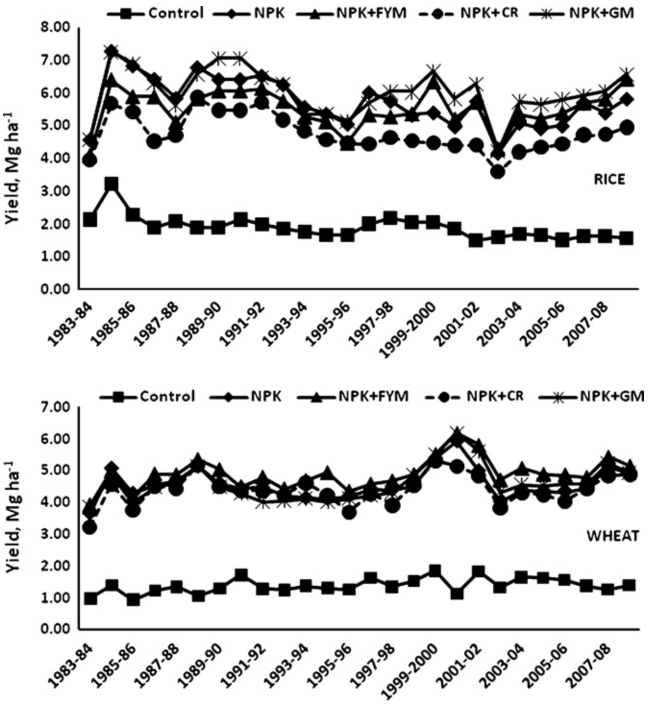

Fig. 2. Trends in rice and wheat yield in a long-term rice–wheat system under various integrated nutrient management treatments at Ludhiana.

The trends in wheat yields of unfertilized (control) plots were negative at Kanpur and Kalyani and positive at Ludhiana and Sabour. However, the trend was significant only at Ludhiana. There was significant increase in wheat yield trends at Sabour in the plots applied with fertilizer and/or organics while at Ludhiana it was significant only in NPK + FYM and NPK + GM applied plots. However, at Kalyani and Kanpur the yield trend of wheat under these treatments were not significant. Trend analysis revealed that in unfertilized plots, system productivity showed a negative trend but

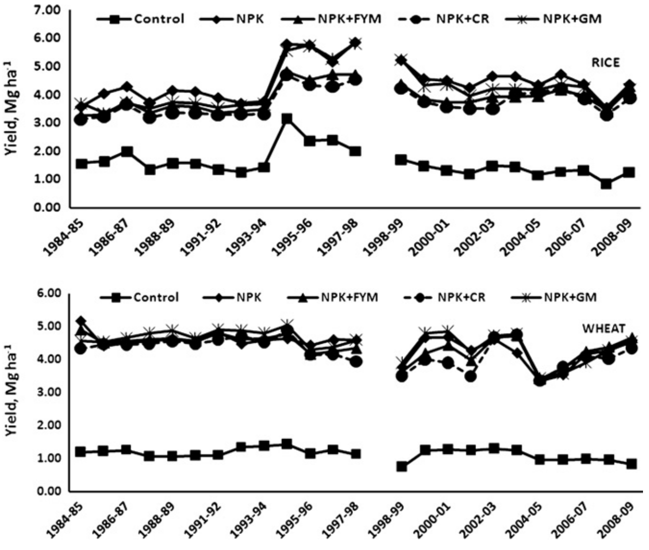

Fig. 3. Trends in rice and wheat yield in a long-term rice–wheat system under various integrated nutrient management treatments at Kanpur (yield data from 1998–1999 to 2008–2009 only used in trend analysis).

Table 3
Long term yield trend parameters of rice, wheat and rice equivalent yield (REY) under different integrated nutrient management system in Indo-Gangetic Plains.

Treatments	Ludhiana		Kanpur		Saboure		Kalyani	
	t-statistic	*b*-value	*t*-statistic	*b*-value	*t*-statistic	*b*-value	*t*-statistic	*b*-value
Rice								
Control	−4.333**	−0.030	−2.738*	−0.044	−2.22	−0.018	−0.364	−0.003
NPK	−3.292**	−0.056	−2.264*	−0.075	3.157*	0.063	2.186*	0.031
NPK + FYM	−0.074	−0.001	−0.072	−0.002	2.434*	0.078	2.558*	0.036
NPK+ CR	−2.522*	−0.033	−0.187	−0.006	3.129*	0.088	2.957**	0.047
NPK + GM	−1.119	−0.021	−2.247	−0.076	2.647*	0.093	2.55*	0.038
Wheat								
Control	2.628*	0.016	−1.166	−0.021	0.160	0.001	−0.444	−0.005
NPK	1.025	0.013	−0.337	−0.015	3.999**	0.092	1.35	0.023
NPK + FYM	2.306*	0.028	0.729	0.032	4.451**	0.120	1.131	0.019
NPK+ CR	1.275	0.015	0.842	0.037	3.585**	0.097	1.035	0.020
NPK + GM	2.124*	0.030	−0.783	−0.038	4.906**	0.123	1.31	0.025
REY								
Control	−0.453	−0.005	−2.110	−0.044	−0.503	−0.006	−0.330	−0.005
NPK	−0.295	−0.009	0.448	0.038	4.359**	0.240	2.779*	0.081
NPK + FYM	2.121*	0.062	2.040	0.169	4.700**	0.301	2.862**	0.080
NPK+ CR	0.511	0.014	2.451*	0.162	4.587**	0.275	3.006**	0.093
NPK + GM	1.29	0.044	0.062	0.005	4.650**	0.312	3.128**	0.091

t-statistic; *b*-value (slope i.e., percent change in yields per year) were computed from linear regression.

* Significant at $P = 0.05$.

** Significant at $P = 0.01$.

not significant while in NPK fertilized plots and NPK along with organics showed either an increasing trend or remained stable at all locations during last two and half decades of the experiment (Table 3). The declining yield trend in the unfertilized plots in IGP may be attributed to a decline in SOC and the associated reduction in nutrient supply. Thus, the rice–wheat system productivity can be maintained or increased by application of recommended N–P–K or N–P–K partially substituted with organic manures/crop residues/green manure.

3.2. Sustainable yield index

The SYI for rice and wheat presented in Table 4 revealed that SYI was greater for wheat than for rice at Kanpur in all treatments while at Sabour, Kalyani and Ludhiana, SYI for rice was greater than wheat, indicating that rice yields are more sustainable than those of wheat at these locations. Among various treatments analysed, NPK + FYM and NPK + GM sustained the rice–wheat system yield more than other treatments at all four locations.

3.3. Bulk density

Bulk density of soil increased from the surface to the subsurface soil layer irrespective of treatments and locations. Among the treatments, application of N–P–K along with organics has resulted in significantly lower bulk density compared to control

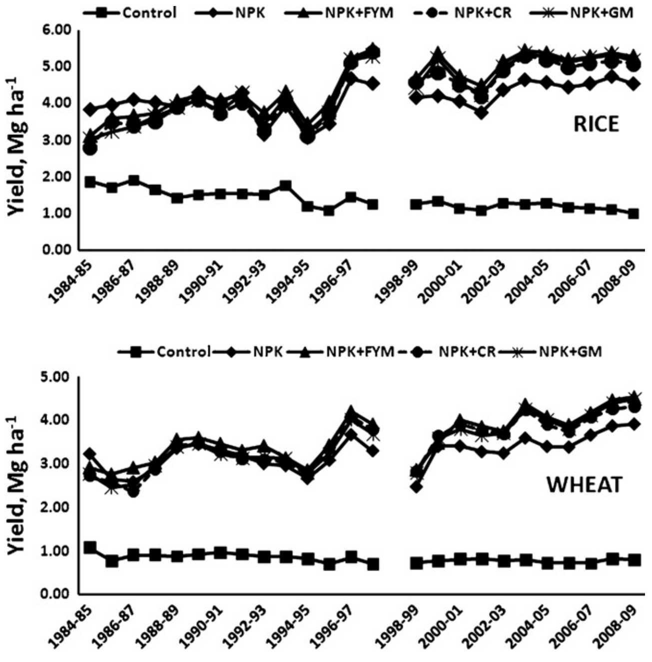

Fig. 4. Trends in rice and wheat yield in a long-term rice–wheat system under various integrated nutrient management treatments at Sabour (yield data from 1998–1999 to 2008–2009 only used in trend analysis).

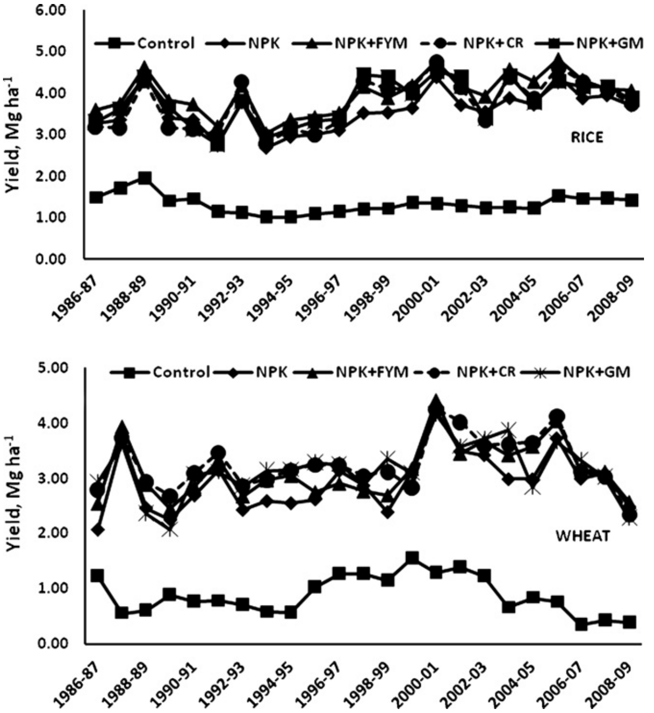

Fig. 5. Trends in rice and wheat yield in a long-term rice–wheat system under various integrated nutrient management treatments at Kalyani.

Table 4
Long sustainable yield indices of rice (Rice SYI), wheat (Wheat SYI) and rice–wheat system (System SYI) under different integrated nutrient management system in Indo-Gangetic Plains.

Parameters	Ludhiana			Kanpur			Sabour			Kalyani		
	Rice SYI	Wheat SYI	System SYI	Rice SYI	Wheat SYI	System SYI	Rice SYI	Wheat SYI	System SYI	Rice SYI	Wheat SYI	System SYI
Control	0.23	0.20	0.22	0.19	0.20	0.21	0.20	0.16	0.16	0.23	0.11	0.20
NPK	0.73	0.70	0.70	0.60	0.79	0.75	0.63	0.62	0.56	0.64	0.50	0.62
NPK + FYM	0.72	0.76	0.72	0.59	0.79	0.74	0.69	0.67	0.63	0.73	0.56	0.69
NPK+ CR	0.62	0.67	0.64	0.57	0.76	0.71	0.64	0.63	0.60	0.65	0.57	0.68
NPK + GM	0.76	0.70	0.72	0.59	0.79	0.75	0.65	0.64	0.60	0.67	0.56	0.68

at 0–15 and 15–30 cm soil depth in Sabour while all other locations recorded at par soil bulk density at all soil depths (Table 5). With respect to locations, the control treatment (0–15 cm soil depth) in Sabour recorded higher bulk density (1.56 Mg m^{-3}) than in Ludhiana (1.44 Mg m^{-3}) and Kalyani (1.42 Mg m^{-3}) while in Kanpur it was 1.47 Mg m^{-3}.

3.4. Soil organic carbon

Continuous application of NPK for 23–26 yr in rice–wheat system has resulted in significantly higher SOC over control in 0–15 cm soil depth at all the four locations. Intensive rice–wheat system in IGP without application of fertilizers (control) resulted in reduction (22 and 35% decrease) of SOC concentration over initial value at Sabour and Kalyani, respectively whereas at Ludhiana and Kanpur it has more or less maintained the SOC level (Table 5). As initial SOC concentration was comparatively higher at Sabour and Kalyani than other two sites under study, it would be hard to maintain SOC contents without fertilization and/or organic matter addition in Sabour and Kalyani. However, because of very low initial value, the SOC concentration in the control plot was maintained at Ludhiana and Kanpur despite declining yield trend. Abrol et al. (2000) have attributed the declining trend in crop productivity of the rice-based cropping system in IGP to the declining C stock in soil. The application of recommended dose of N–P–K resulted in increased SOC in surface soil over the initial level at all places except at Kalyani where a slight reduction was recorded. The higher stubble and root biomass retention commensurating with higher yield in the N–P–K fertilized plot might have improved the SOC in surface soil at all sites except at Kalyani where initial SOC value was comparatively higher than others. However, compared to unmanured/unfertilized control, the fields receiving recommended N–P–K fertilizer resulted higher SOC concentration in surface soil at all the places. Similar trend was observed up to 15–30 cm soil at Ludhiana and up to 30–45 cm soil at all other places. Results of other long-term experiments have also shown that with optimum application of inorganic fertilizers, the SOC content has either been increased (Purakayastha et al., 2008a; Zhang et al., 2009) or maintained/slightly increased over the years (Biswas and Benbi, 1997).

Substitution of 50% N through FYM or CR or GM to rice has improved SOC significantly over NPK treated plots at all the locations. The addition of FYM, CR, and GM complemented with N–P–K increased the organic carbon content of soil over that achieved with N–P–K alone, due to additive effect of N–P–K and organics and interaction between them. A similar buildup of SOC due to cropping with the application of chemical fertilizer combined with manure (Rudrappa et al., 2006), paddy straw (Verma and Bhagat, 1992), and green manure (Yadav et al., 2000) was also reported from long-term experiments. Bharambe and Tomar (2004) reported an increase in organic carbon content in a rice–wheat system when

Table 5
Soil organic carbon (SOC, g kg^{-1}) concentration and bulk density (BD, Mg m^{-3}) in different integrated nutrient management system under different agro-climatic situation in Indo-Gangetic Plains. (Means with the same lower case letter are not significantly different in a column in same depth.)

Particulars	Ludhiana		Kanpur		Sabour		Kalyani	
	SOC	BD	SOC	BD	SOC	BD	SOC	BD
	0–15 cm							
Control	3.0^{d}	1.44^{a}	3.7^{c}	1.47^{a}	3.6^{c}	1.56^{a}	6.0^{d}	1.42^{a}
NPK	5.1^{c}	1.41^{a}	5.5^{b}	1.42^{a}	5.6^{b}	1.46^{ab}	8.4^{c}	1.37^{a}
NPK + FYM	6.8^{a}	1.35^{a}	6.3^{a}	1.41^{a}	7.7^{a}	1.38^{b}	9.9^{a}	1.35^{a}
NPK + CR	6.1^{b}	1.38^{a}	6.5^{a}	1.41^{a}	7.5^{a}	1.36^{b}	9.6^{ab}	1.36^{a}
NPK + GM	5.9^{b}	1.39^{a}	6.1^{a}	1.40^{a}	7.4^{a}	1.40^{b}	9.0^{b}	1.38^{a}
	15–30 cm							
Control	2.5^{c}	1.48^{a}	2.2^{c}	1.58^{a}	2.3^{d}	1.58^{a}	3.2^{b}	1.55^{a}
NPK	3.2^{b}	1.43^{a}	3.2^{b}	1.55^{a}	3.1^{c}	1.50^{ab}	3.2^{b}	1.52^{a}
NPK + FYM	3.5^{a}	1.41^{a}	3.4^{a}	1.54^{a}	3.8^{a}	1.48^{ab}	5.5^{a}	1.5^{a}
NPK+ CR	3.3^{ab}	1.42^{a}	3.6^{a}	1.54^{a}	3.6^{ab}	1.46^{b}	5.4^{a}	1.50^{a}
NPK + GM	3.2^{b}	1.43^{a}	3.1^{b}	1.53^{a}	3.5^{b}	1.46^{b}	5.1^{a}	1.53^{a}
	30–45 cm							
Control	2.0^{b}	1.54^{a}	1.5^{d}	1.61^{a}	2.0^{d}	1.55^{a}	2.3^{b}	1.56^{a}
NPK	2.0^{b}	1.50^{a}	1.9^{c}	1.62^{a}	2.3^{c}	1.52^{a}	3.0^{a}	1.51^{a}
NPK + FYM	2.2^{a}	1.48^{a}	2.5^{a}	1.61^{a}	2.8^{a}	1.52^{a}	3.1^{a}	1.50^{a}
NPK+ CR	2.2^{a}	1.49^{a}	2.4^{a}	1.58^{a}	2.6^{b}	1.53^{a}	3.1^{a}	1.50^{a}
NPK + GM	2.1^{ab}	1.49^{a}	2.2^{b}	1.63^{a}	2.5^{b}	1.52^{a}	3.1^{a}	1.52^{a}
	45–60 cm							
Control	1.5^{c}	1.55^{a}	1.0^{c}	1.66^{a}	1.7^{b}	1.57^{a}	2.1^{b}	1.49^{a}
NPK	1.7^{b}	1.54^{a}	1.2^{b}	1.58^{a}	1.7^{b}	1.50^{a}	2.2^{b}	1.49^{a}
NPK + FYM	1.9^{a}	1.50^{a}	1.3^{a}	1.58^{a}	2.0^{a}	1.55^{a}	2.5^{a}	1.46^{a}
NPK+ CR	1.9^{a}	1.51^{a}	1.3^{a}	1.59^{a}	1.7^{b}	1.56^{a}	2.5^{a}	1.47^{a}
NPK + GM	1.5^{c}	1.52^{a}	1.0^{c}	1.57^{a}	1.7^{b}	1.55^{a}	2.1^{b}	1.52^{a}

FYM: farm yard manure; CR: crop residue; GM: green manure.

inorganic fertilizers were applied along with FYM. Many long-term experiments have shown that both chemical fertilizer and manure application increased the SOC content in the soil, but the increases in SOC were much higher with organic manure (Christensen, 1996; Smith et al., 1997; Aoyama and Kumakura, 2001). In the surface soil (0–15 cm), NPK + FYM recorded significantly higher concentration of SOC (6.8 g kg^{-1}) over all other treatments at Ludhiana. The SOC concentration of surface soil in NPK + FYM, NPK + CR and NPK + GM were at par at Kanpur and Sabour while NPK + FYM and NPK + CR treatments at Kalyani were at par.

Substitution of 50% N through FYM or CR or GM to rice improved SOC significantly when compared with initial SOC values at Ludhiana, Kanpur and Sabour. In case of Kalyani, substitution of 50% N through FYM or CR has improved the SOC over the initial level, though the magnitude of increase was less compared to other three sites. Due to high initial SOC and continued application of organic manure at Kalyani, soil carbon accumulation may have reached close to saturation point and hence become less responsive to increased carbon inputs. This can be explained by the fact that every soil has its own C carrying capacity, therefore in spite of addition of large amount of C might not increase soil C proportionately (Purakayastha et al., 2008a). Many long-term field experiments exhibit a proportional relationship between C inputs and soil C content across treatments (Larson et al., 1972; Paustian et al., 1997), some experiments in high C soils show little or no increase in soil C content with two to three fold increases in C inputs (Campbell et al., 1991; Paustian et al., 1997; Solberg et al., 1997).

Though the average SOC concentration decreased with soil depth, the FYM + NPK and NPK + CR treatments resulted in significant increase in SOC even in 45–60 cm soil layer over all other treatments across the locations, whereas at Sabour FYM + NPK even resulted significant increase in SOC over NPK + CR treatments, whereas at other locations they were at par. The decrease in SOC concentration with soil depth is well documented (Liu et al., 2003; Brady and Weil, 2000).

Across the different agro-climatic zones of IGP, higher SOC content was observed in Kalyani (LGP) followed by Sabour (MGP), Kanpur (UGP) and Ludiana (TGP), respectively. The higher SOC content in Kalyani and Sabour over Ludhiana and Kanpur was due to higher clay content in the soil, low land situation, reduced conditions due to incomplete drainage and humid climate in the former two places. Organic matter decomposition proceeds faster in sandy than in clayey soils (Katyal, 2001), while the rate of soil organic matter decomposition is lessened in lowland rice fields, apparently due to excessively reduced conditions (Watanabe, 1984). Because of the lack of oxygen under submerged conditions even a modest oxygen demand for microbial activity cannot be met if large pores are filled with water, resulting in a decreased rate of decomposition (Jenkinson, 1988). Therefore, there is an incomplete decomposition of organic materials and decreased humification of organic matter under submerged conditions, resulting in net accumulation of organic matter in soils (Sahrawat, 2004).

Using the mass of SOC in the control treatment as reference point and number of years of interventions we estimated the sequestration rate (rate of net SOC increase), which varied from 0.231 to 0.332 t ha^{-1} yr^{-1} in N–P–K treated plot under continuous rice–wheat cropping system in the different agro-climatic zones of IGP (Fig. 6). Among the treatments, NPK + FYM recorded significantly higher sequestration rate over all other treatments across all the agro-climatic zones except at Kalyani and Kanpur where the sequestration rate between NPK + FYM and NPK + CR were at par. Response of SOC to carbon input has been controversial (e.g. Campbell et al., 2007; Purakayastha et al., 2008b). Our study indicates that applications of N–P–K fertilizer with or without organics can sequester carbon in soils at all the sites of IGP. Hao et al. (2008) reported that applications of combinated inorganic fertilizers (i.e. the N–P and N–P–K fertilization) with or without manure can sequester carbon in soils at most of the sites of Northern China. The soil carbon sequestration rates vary from 0.08 to 0.98 t ha^{-1} yr^{-1} in IGP under the NPK, NPK + FYM, NPK + CR and NPK + GM treatments, which are comparable to those from other studies (Akselsson et al., 2005; Causarano et al., 2008; Kundu et al., 2007; Hien et al., 2006; Kroodsma and Field, 2006).

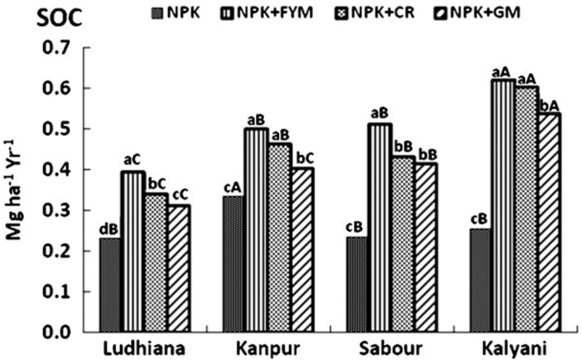

Fig. 6. Soil organic carbon sequestration (Mg ha^{-1} yr^{-1}) in different integrated nutrient management system over the control under different agro-climatic situation in Indo-Gangetic Plains. (Means with the same lower case letters are not significantly different in different treatments at same centre, means with the same uppercase letters are not significantly different in a treatment at different centres.)

The net change in rate of SOC was highest at Kalyani and lowest at Ludhiana for all the treatments except NPK, for which Kanpur recorded highest net increase in SOC while Ludhiana recorded the lowest. The soil carbon sequestration with response to application of fertilizer complemented with organics were higher in Kalyani and Sabour lying in humid climate than Ludhiana and Kanpur lying in semiarid climate. Though the magnitude of increase in SOC at Kalyani and Sabour was less compared to Ludhiana and Kanpur, the increased sequestration rate at the former two places is due to faster SOC depletion in control plots compared to the latter two places. While budgeting C stocks in different eco-regions of Asia, Bronson et al. (1998) indicated a possible conservation or even increase in C stock in soil in the lowland tropics, despite high temperature prevalent throughout the years, which favours rapid mineralization of C. They opined that this was due to the relatively slow rate of soil C mineralization under anaerobiosis and also the large C inputs from nonvascular plants (photosynthetic algal communities) in the soil–flood water ecosystem. Soils rich in clay may have more potential to sequester carbon than those rich in sandy and silt in the similar climate zone, due to the physical protection of mineral on SOC (Matus et al., 2008) which also partly explained the higher SOC sequestration rate at Kalyani having higher clay percent.

3.5. Particulate organic carbon

In absence of initial POC data of the experimental site, we compared the POC data of the treatments with the control alone. Similar to SOC trend, continuous application of N–P–K in rice–wheat system resulted significantly higher POC over control at 0–15 cm soil depth in all the four locations. Application of FYM along with N–P–K (NPK + FYM) resulted in a significant positive built up of POC over NPK at different locations at all soil depths (Table 6). Similarly, substitution of 50% N through CR or GM to rice also recorded significantly higher POC concentration over NPK at all locations in 0–15 and 15–30 cm soil depths only. The increase in POC in fertilized plot was mainly being due to increased yield trend in this treatment over past years. The additional amounts of organic C input from organics in the treatments received NPK along with organics further enhanced the POC contents in these treatments. The main source of POC in this study was mainly the left over root

Table 6
Particulate organic carbon (POC, $\mu g\,g^{-1}$) concentration in different integrated nutrient management system under different agro-climatic situation in Indo-Gangetic plains. (Means with the same lower case letter are not significantly different in a column in same depth.)

Particulars	Particulate organic carbon ($\mu g\,g^{-1}$)			
	Ludhiana	Kanpur	Sabour	Kalyani
	0–15 cm			
Control	335.5^{d}	399.6^{d}	379.0^{d}	625.0^{e}
NPK	655.4^{c}	698.5^{c}	706.9^{c}	1046.3^{d}
NPK + FYM	1025.3^{a}	938.7^{a}	1116.9^{a}	1434.1^{a}
NPK+ CR	888.9^{b}	916.5^{a}	1063.6^{ab}	1334.4^{b}
NPK + GM	837.8^{b}	854.0^{b}	1038.8^{b}	1243.4^{c}
	15–30 cm			
Control	240.1^{d}	192.1^{d}	222.7^{d}	304.0^{c}
NPK	330.8^{c}	323.2^{c}	306.0^{c}	330.5^{c}
NPK + FYM	431.3^{a}	432.0^{a}	413.8^{a}	643.1^{a}
NPK+ CR	386.8^{b}	410.4^{a}	381.8^{b}	604.8^{b}
NPK + GM	362.3^{b}	350.3^{b}	329.3^{c}	590.0^{b}
	30–45 cm			
Control	173.6^{d}	117.5^{d}	174.2^{c}	201.8^{b}
NPK	188.0^{c}	181.5^{c}	192.0^{ab}	286.1^{a}
NPK + FYM	211.2^{a}	242.5^{a}	203.7^{a}	304.8^{a}
NPK+ CR	206.4^{ab}	230.4^{a}	192.0^{ab}	301.7^{a}
NPK + GM	194.8^{bc}	211.2^{b}	185.3^{bc}	292.8^{a}
	45–60 cm			
Control	126.2^{c}	85.9^{c}	147.1^{c}	176.8^{d}
NPK	155.1^{b}	112.8^{b}	164.4^{b}	207.1^{c}
NPK + FYM	175.8^{a}	124.8^{a}	187.2^{a}	237.7^{ab}
NPK+ CR	180.5^{a}	123.5^{a}	165.3^{b}	242.5^{a}
NPK + GM	180.5^{a}	123.5^{a}	157.7^{bc}	223.3^{b}

FYM: farm yard manure; CR: crop residue; GM: green manure.

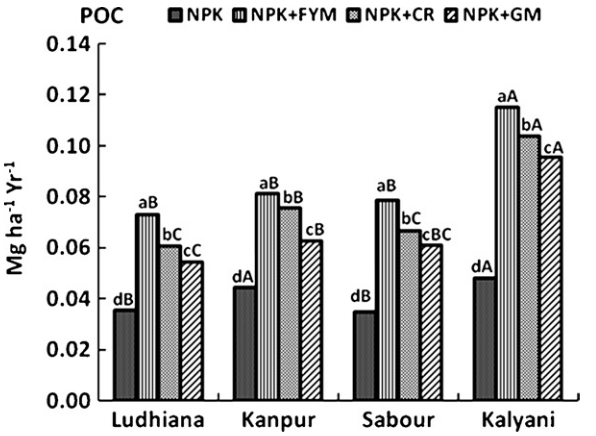

Fig. 7. Particulate organic carbon sequestration ($Mg\,ha^{-1}\,yr^{-1}$) in different integrated nutrient management system over the control under different agro-climatic situation in Indo-Gangetic Plains. (Means with the same lower case letters are not significantly different in different treatments at same centre, means with the same uppercase letters are not significantly different in a treatment at different centres.)

biomass and increased microbial biomass debris. It is suggested that the greater biochemical recalcitrance of root litter (Puget and Drinkwater, 2001) might have also increased the POC contents in soil depending upon the root biomass produced.

The POC content of the soil in all the treatments at Kalyani was significantly higher over the soils under the same treatment at all other locations. In the surface soil (0–15 cm), NPK + FYM recorded significantly higher concentration of POC (1025.3 and 1434.1 $\mu g\,g^{-1}$) over all other treatments at Ludhiana and Kalyani while the POC concentration in NPK + FYM and NPK + CR were at par and significantly higher than NPK and control at Kanpur and Sobour. Across all the agro climatic zones, the sequestration rate of POC in all the four treatments followed the order NPK + FYM > NPK + CR > NPK + GM > NPK (Fig. 7). Kalyani recorded highest POC sequestration rate in NPK + FYM (0.115 $Mg\,ha^{-1}\,yr^{-1}$) followed by NPK + CR (0.104 $Mg\,ha^{-1}\,yr^{-1}$) and NPK + GM (0.096 $Mg\,ha^{-1}\,yr^{-1}$). In NPK treated plot, the POC sequestration rate was in the order of Kalyani ≈ Kanpur > Ludhiana ≈ Sabour.

3.6. *Microbial biomass carbon*

Distinct difference of MBC content was observed among different treatments and at different depths in a long term rice–wheat system. Continuous application of FYM along with N–P–K (NPK + FYM) resulted in a significantly higher soil MBC over NPK at all four locations (Table 7). The MBC content of plots which received CR along with NPK (NPK + CR) was at par with NPK + FYM at all places except Ludhiana. However, the MBC content of surface soil in NPK + GM treatments was significantly lower than NPK + FYM at Ludhiana, Sabour and Kalyani except Kanpur where it was at par. The MBC content of surface soil in NPK + GM plots was at par with NPK + CR at all places except at Kalyani where it was significantly lower. It is reported that MBC responded to number of management practices e.g., addition of manures, synthetic fertilizers and residue incorporation (Schjønning et al., 2002). Across the location highest MBC contents in surface soil were recorded at Kalyani and lowest at Ludhiana. The highest MBC content of 515.4 $\mu g\,g^{-1}$ at surface soil (0–15 cm)1 was observed in NPK plots at Kalyani. It is known that the microbial fraction of clay soils is often greater than it is in sandy soils due to the protective effect of clays on microbial biomass (Jenkinson and Ladd, 1981; Wardle, 1992; Theng and Orchard, 1995; Sparling, 1997). This explains the high MBC content at the Kalyani site which had the highest clay content. The soil MBC content expressed as percent of SOC was highest at Kalyani followed by Kanpur, Sabour and Ludhiana respectively. The rate of change in MBC concentration in NPK + FYM was significantly higher across all the locations except at Kanpur, where it was at par with NPK + CR (Fig. 8). With respect to MBC sequestration rate, NPK + CR

Table 7
Microbial biomass carbon (MBC, $\mu g\,g^{-1}$) concentration in different integrated nutrient management system under different agro-climatic situation in Indo-Gangetic plains. (Means with the same lower case letter are not significantly different in a column in same depth.)

Particulars	Microbial biomass carbon ($\mu g\,g^{-1}$)			
	Ludhiana	Kanpur	Sabour	Kalyani
	0–15 cm			
Control	100.7^{d}	128.1^{c}	119.1^{d}	288.3^{c}
NPK	174.1^{c}	215.8^{b}	199.7^{c}	425.7^{b}
NPK + FYM	264.8^{a}	308.1^{a}	298.4^{a}	515.4^{a}
NPK+ CR	232.9^{b}	309.1^{a}	284.7^{ab}	486.5^{a}
NPK + GM	218.3^{b}	298.0^{a}	274.5^{b}	455.0^{b}
	15–30 cm			
Control	80.9^{c}	67.4^{d}	76.6^{d}	109.6^{d}
NPK	107.1^{b}	113.0^{c}	105.8^{c}	135.0^{c}
NPK + FYM	127.7^{a}	131.8^{a}	145.2^{a}	235.4^{a}
NPK+ CR	120.3^{a}	126.7^{a}	130.2^{b}	225.3^{ab}
NPK + GM	110.3^{b}	116.0^{b}	122.2^{b}	220.4^{b}
	30–45 cm			
Control	54.6^{d}	44.9^{e}	59.4^{c}	69.2^{d}
NPK	60.0^{c}	76.9^{d}	61.0^{c}	102.6^{c}
NPK + FYM	74.8^{a}	108.5^{a}	92.5^{a}	124.0^{a}
NPK+ CR	71.0^{ab}	100.3^{b}	83.5^{b}	118.0^{ab}
NPK + GM	67.7^{b}	87.3^{c}	80.7^{b}	115.8^{b}
	45–60 cm			
Control	39.2^{b}	32.2^{b}	48.6^{b}	60.0^{b}
NPK	47.9^{b}	40.2^{a}	50.5^{b}	65.4^{a}
NPK + FYM	59.2^{a}	40.9^{a}	60.1^{a}	72.4^{a}
NPK+ CR	60.8^{a}	42.1^{a}	54.2^{ab}	72.2^{a}
NPK + GM	57.0^{a}	40.4^{a}	54.9^{ab}	73.1^{a}

FYM: farm yard manure; CR: crop residue; GM: green manure.

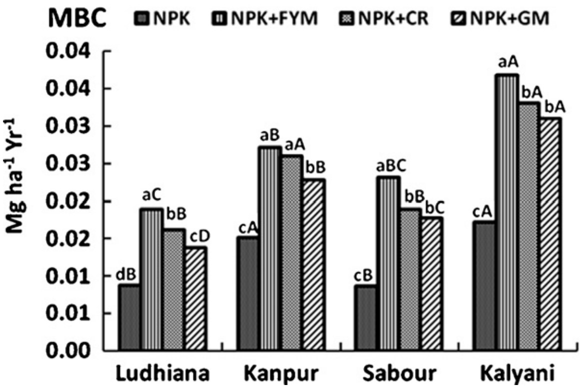

Fig. 8. Microbial biomass carbon sequestration (Mg ha^{-1} yr^{-1}) in different integrated nutrient management system over the control under different agro-climatic situation in Indo-Gangetic Plains. (Means with the same lower case letters are not significantly different in different treatments at same centre, means with the same uppercase letters are not significantly different in a treatment at different centres.)

performed significantly better than NPK + GM at Ludhiana and Kanpur. Hopkins and Shiel (1996) observed that the microbial biomass was considerably greater in soils receiving FYM along with NPK fertilizer than in plots receiving merely NPK fertilizer. Also, Ocio et al. (1991) have demonstrated rapid and significant increases in microbial biomass following straw inputs in field conditions.

Table 8
Mineralizable carbon ($C_{\min}$, μg g^{-1}) concentration in different integrated nutrient management system under different agroclimatic situation in Indo-Gangetic plains. (Means with the same lower case letter are not significantly different in a column in same depth.)

Particulars	Mineralizable carbon (μg g^{-1})			
	Ludhiana	Kanpur	Sabour	Kalyani
	0–15 cm			
Control	274.5^{d}	344.1^{d}	344.3^{d}	558.9^{d}
NPK	537.6^{c}	578.5^{c}	585.3^{c}	895.6^{c}
NPK + FYM	767.3^{a}	718.2^{a}	853.0^{a}	1127.5^{a}
NPK+ CR	649.8^{b}	721.5^{a}	808.8^{ab}	1065.6^{a}
NPK + GM	607.7^{b}	664.9^{b}	775.4^{b}	982.1^{b}
	15–30 cm			
Control	210.5^{c}	174.2^{c}	211.3^{c}	281.6^{d}
NPK	308.2^{b}	300.4^{b}	288.3^{b}	314.3^{c}
NPK + FYM	347.8^{a}	332.9^{a}	339.3^{a}	549.4^{a}
NPK+ CR	325.5^{b}	322.8^{ab}	327.4^{a}	529.2^{ab}
NPK + GM	312.5^{b}	303.8^{b}	292.5^{b}	502.7^{b}
	30–45 cm			
Control	145.5^{c}	100.3^{c}	150.5^{c}	176.3^{b}
NPK	179.5^{b}	173.8^{b}	181.2^{b}	271.2^{a}
NPK + FYM	202.6^{a}	210.2^{a}	195.7^{a}	286.4^{a}
NPK+ CR	198.4^{a}	201.5^{a}	184.8^{ab}	287.0^{a}
NPK + GM	190.2^{ab}	202.4^{a}	181.5^{b}	280.6^{a}
	45–60 cm			
Control	102.5^{c}	71.4^{c}	112.3^{c}	150.6^{c}
NPK	145.5^{b}	103.2^{b}	153.8^{b}	187.5^{b}
NPK + FYM	169.1^{a}	117.0^{a}	178.6^{a}	220.5^{a}
NPK+ CR	165.5^{a}	113.2^{a}	151.2^{b}	217.8^{a}
NPK + GM	162.8^{a}	111.4^{a}	143.4^{b}	201.4^{b}

3.7. Mineralizable organic carbon

Significantly higher $C_{\min}$ content was recorded in a continuous N–P–K applied plots over control at all soil depths in all the four locations in the IGP (Table 8). The treatments where partial substitution of N were made from organic sources, significantly higher $C_{\min}$ was recorded both over NPK treated plots and control at surface soil (0–15 cm). The higher value of $C_{\min}$ content in the N–P–K fertilizer with organic amendments treatments may be attributed to the good supply of labile C substrate in those treatments (Majumder et al., 2008). Partial substitution of N through GM and CR resulted at par $C_{\min}$ content at Ludhiana and Sabour. However partial substitution of N through either FYM or CR resulted at par $C_{\min}$ content in the surface soil except at Ludhiana (TGP), where FYM treated plots recorded significantly higher $C_{\min}$ than the plots treated with CR. At all the sites NPK + FYM recorded significantly higher $C_{\min}$ than NPK +GM. The differences in $C_{\min}$ content among different treatments continually reduced towards lower depths. The FYM and CR having higher C:N ratio is less resistant to decomposition, in our study addition of inorganic N (50% of recommended dose) along with these materials reduced the C:N ratio and enhanced its decomposability. This explain the higher $C_{\min}$ value in FYM treated plots at all the sites and CR treated plots at some sites over GM treated plots. The time required for organisms to lower the C:N ratio of the organic residues to the level for optimum mineralization depend on many factors including climate, application rate and microbial activity (Stevenson and Cole, 1999). The residue which have high C:N ratios results in low decomposition rate and high SOC concentrations in agricultural soils (Martens, 2000; Russell et al., 2005). Other researchers have indicated that neither the N concentration in the SOM nor the N availability in the soil directly influences the C decomposition rate (Hobbie and Vitousek, 2000), suggesting that C:N ratio is not the only chemical property that directly controls C decomposition

3.8. Correlation

A correlation matrix developed among sustainable yield index of rice (Rice SYI), sustainable yield index of wheat (Wheat SYI) and system sustainable yield index (System SYI), SOC and SOC fractions and bulk density showed that across the agro-climatic zones of IGP, increase in SOC, POC, $C_{\min}$ and MBC content was significantly ($P = 0.05$) related to increase in Rice SYI and System SYI while Wheat SYI was positively and significantly related to POC and $C_{\min}$ (Table 9). It has been reported that MBC is regarded as one of the most sensitive indicators of the sustainability of the management systems. There were also significant correlations among

Table 9
Correlation matrix for sustainable yield indices, SOC and its fractions and bulk density.

Parameters	Rice SYI	Wheat SYI	System SYI	SOC	POC	MBC	$C_{\min}$	BD
Rice SYI	1.00							
Wheat SYI	0.86*	1.00						
System SYI	0.93*	0.96*	1.00					
SOC	0.67*	0.40	0.59*	1.00				
POC	0.76*	0.53*	0.70*	0.97*	1.00			
MBC	0.52*	0.28	0.51*	0.95*	0.91*	1.00		
$C_{\min}$	0.71*	0.46*	0.65*	0.99*	0.99*	0.95*	1.00	
BD	−0.74*	−0.56*	−0.70*	−0.77*	−0.81*	−0.69*	−0.78*	1.00

SOC: soil organic carbon; POC: particulate organic carbon; MBC: microbial biomass carbon; $C_{\min}$: mineralizable carbon; BD: bulk density.

[*] Significant at $P = 0.05$.

SOC and its fractions in the soil which indicate the existence of a dynamic equilibrium among them. This means that depletion or enrichment in one would shift the equilibrium and affect the size of the others. This suggests the importance of these pools of SOC in influencing crop yield, possibly through maintaining better soil quality. However, the soil bulk density exhibited a significant negative relationship with SOC and its fractions and with all the three sustainability indices.

However, the very low value for yields and low SOC in control treatments might have made the correlation function significant. Hence we treated the NPK treatment as base line instead of control treatment in the correlation study. It was found that there was no significant correlation between SOC with Rice SYI and System SYI. However, it showed a negative correlation with Wheat SYI, which seems to be unrealistic. The reason may be due to the high value of SOC and low yield of wheat recorded at Kalyani because of its non-favourable agro climatic conditions. When the data for Kalyani was also excluded from the correlation study, it was found that SOC was not having significant correlations with Rice SYI, Wheat SYI and System SYI. It is assumed that very low variations of SOC among the experimental sites might have contributed for this non-significant relationship. Hence no definite conclusion can be arrived at using the correlation study. Hence, there is a need for such type of study involving wide range of SOC level on long term fertilizer experiment at specific locations.

4. Conclusions

The study indicated that application of recommended dose of N–P–K either through inorganic fertilization or through inorganic fertilizer N–P–K with 50% of nitrogen substituted by FYM or crop residue or green manure to rice and N–P–K to wheat improved the SOC, POC, MBC concentration, total SOC stocks and their sequestration rate. The SOC concentration and its sequestration were higher with the treatment applied with N–P–K partially substituted (50% on N basis) with organics than N–P–K application. Soil carbon sequestration with response to application of fertilizer partially substituted (50% on N basis) with organics were higher in Kalyani (LGP) and Sabour (MGP) lying in humid climate than Ludhiana (TGP) and Kanpur (UGP) lying in semiarid climate. The rice yield recorded a significant declining trend in TGP and UGP where as the yield trend was stable at MGP and LGP under unfertilized control. Application of recommended dose of N–P–K or N–P–K partially substituted with organics has increased or maintained the system productivity. It is therefore important that the recommended fertilization either through inorganic fertilizer alone or in combination with manures, crop residue and green manuring has to be promoted in order to maintain long-term rice–wheat system productivity. Nevertheless, there is a need for more quantitative assessment of the carbon sequestration potential of agricultural soils of IGP under different management practices for different soil types, climates and agricultural systems by supporting existing long term cropping system trial sites and the establishment of new ones where appropriate; quantifying interactions of SOC sequestration with soil emissions of GHGs and developing soil carbon models that can account for locally relevant agricultural management practices.

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References

Abrol, I.P., Bronson, K.F., Duxbury, J.M., Gupta, R.K., 2000. Long-term soil fertility experiments in rice–wheat cropping systems. In: Rice–Wheat Consortium Paper Series 6, New Delhi, p. 171.

Akselsson, C., Berg, B., Meentemeyer, V., Westling, O., 2005. Carbon sequestration rates in organic layers of boreal and temperate forest soils—Sweden as a case study. Global Ecol. Biogeogr. 14, 77–84, doi:10.1111/j.1466-822X.2004.00133.x.

Aoyama, M., Kumakura, N., 2001. Quantitative and qualitative changes of organic matter in an ando soil induced by mineral fertilizer and cattle manure application for 20 years. Soil Sci. Plant Nutr. 47, 241–252.

Bharambe, A.P., Tomar, A., 2004. Direct and residual effect of FYM and inorganic nutrients on rice–wheat cropping system in vertisol. PKV Res. J. 28, 47–52.

Biswas, C.R., Benbi, D.K., 1997. Sustainable yield trends of irrigated maize and wheat in a long-term experiment on loamy sand in semiarid India. Nutr. Cycl. Agroecosyst. 46, 225–234, doi:10.1007/BF00420557.

Brady, N.C., Weil, R.R., 2000. Elements of the Nature and Properties of Soils. Prentice-Hall, Inc., Upper Saddle River, New Jersey.

Bronson, K.F., Cassman, K.G., Wassmann, R., Olk, D.C., Noordwijk, M., van Garrity, D.P., 1998. Soil carbon dynamics in different cropping systems in principal eco-regions of Asia. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soil. CRC, Boca Raton, NY, pp. 35–57.

Camberdella, C.A., Elliott, E.T., 1992. Particulate soil organic matter across grassland cultivation sequence. Soil Sci. Soc Am. J. 56, 777–783, doi:10.3923/ijss.2010.1.10.

Campbell, C.A., Bowren, K.E., Schnitzer, M., Zentner, R.P., Townley-Smity, L., 1991. Effect of crop rotations and fertilization on soil biochemical properties in a thick Black Chernozem. Can. J. Soil Sci. 71, 377–387.

Campbell, C.A., VandenBygaart, A.J., Grant, B.B., Zentner, R.P., McConkey, B.G., Lemke, R.L., Gregorich, E.G., Fernandez, M.R., 2007. Quantifying carbon sequestration in a conventionally tilled crop rotation study in southwestern Saskatchewan. Can. J. Soil Sci. 87, 23–38, doi:10.4141/S06-015.

Causarano, H.J., Doraiswarny, P.C., McCarty, G.W., Hatfield, J.L., Milak, S., Stern, A.J., 2008. Epic modeling of soil organic carbon sequestration in croplands of Lowa. J. Environ. Qual. 37, 1345–1353, doi:10.2134/jeq2007.0277.

Christensen, B.T., 1996. The Askov long-term experiments on animal manure and mineral fertilizers. In: Powlson, D.S., Smith, P., Smith, J.U. (Eds.), Evaluation of Soil Organic Matter: Models Using Existing Datasets NATO, ASI, vol. 138. Springer, Heidelberg, pp. 301–312.

Dawe, D., Dobermann, A., Moya, P., Abdulrachman, S., Singh, B., Lal, P., Li, S.Y., Lin, B., Panaullah, G., Sariam, O., Singh, Y., Swarup, A., Tan, P.S., Zhen, Q.X., 2000. How widespread are yield declines in long-term rice experiments in Asia? Field Crops Res. 66, 175–193, doi:10.1016/S0378-4290%2800%2900075-7.

Dhir, R.P., Chaudhary, M.R., Nath, J., Somani, L.L., 1991. Constraints of sandy soils of arid and adjoining areas of Western and Northern India and their management. In: Biswas, T.D. (Ed.), Soil-Related Constraints in Crop Production, vol. 15. Indian Soc. Soil Sci., Bull., New Delhi, India, pp. 52–69.

Duxbury, J.M., Abrol, I.P., Gupta, R.K., Bronson, K.F.,2000. Analysis of long-term soil fertility experiments with rice–wheat rotations in South Asia. In: Long-Term Soil Fertility Experiments with Rice–Wheat Rotations in South Asia. Rice–Wheat Consortium Pap. Ser. no. 6. Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, pp. 7–22.

Gomez, A.K., Gomez, A.A., 1984. Statistical Procedures for Agricultural Research, 2nd ed. John Wiley & Sons, New York, pp. 180–209.

Hao, X.H., Liu, S.L., Wu, J.S., Hu, R.G., Tong, C.L., Su, Y.Y., 2008. Effect of long-term application of inorganic fertilizer and organic amendments on soil organic matter and microbial biomass in three subtropical paddy soils. Nutr. Cycl. Agroecosyst. 81, 17–24, doi:10.1007/s10705-007-9145-z.

Hegde, D.M., Dwivedi, B.S., 1992. Nutrient management in rice wheat cropping system in India. Fertil. News 37, 27–41.

Hien, E., Ganry, F., Oliver, R., 2006. Carbon sequestration in a savannah soil in southwestern Burkina as affected by cropping and cultural practices. Arid Land Res. Manag. 20, 133–146, doi:10.1080/15324980500546007.

Himes, F.L., 1998. Nitrogen, sulfur, and phosphorus and the sequestering of carbon. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Soil Processes and the Carbon Cycle. CRC Press, Boca Raton, FL, pp. 315–319.

Hobbie, S.E., Vitousek, P.M., 2000. Nutrient regulation of decomposition in Hawaiian montane forests: do the same nutrients limit production and decomposition? Ecology 81, 1867–1877.

Hopkins, D.W., Shiel, R.S., 1996. Size and activity of soil microbial communities in long-term experimental grassland plots treated with manure and inorganic fertilizers. Biol. Fertil. Soils 22, 66–70, doi:10.1007/BF00384434.

Idso, S.B., Idso, K.E., 2002. Global Warming, Carbon Sequestration to Mitigate. Encyclop. Soil Sci., Marcel Dekker, New York, pp. 612–614.

Jenkinson, D.S., Ladd, J.N., 1981. Microbial biomass in soil: measurement and turnover. In: Paul, E.A., Ladd, J.N. (Eds.), Soil Biochemistry, vol. 5. Mercel, New York, pp. 415–471.

Jenkinson, D.S., 1988. Soil organic matter and its dynamics. In: Wild, A. (Ed.), Russell's Soil Conditions and Plant Growth. , 11th ed. Longman Group UK Limited, pp. 564–607.

Joergensen, R.G., 1996. The fumigation–extraction method to estimate soil microbial biomass: calibration of the kEC value. Soil Biol. Biochem. 28, 25–31, doi:10.1016/0038-0717.(95)00102-6.

Katyal, J.C., 1993. Integrated nutrient management and supply: an overview. Proc. Indian Nat. Sci. Acad. 59, 161–172.

Katyal, V.V., 2001. Conservation of organic carbon in relation to crop productivity, yield stability and soil fertility under rice (*Oryza sativa*)–wheat (*Triticum aestivum*) cropping system. Indian J. Agronomy 46, 1–4.

Kimble, J.M., Lal, R., Follett, R.R., 2002. Agricultural practices and policy options for carbon sequestration: what we know and where we need to go. In: Kimbel, J.M., Lal, R., Follett, R.F. (Eds.), Agricultural Practices and Policies for Carbon Sequestration in Soil. Lewis, New York, p. 512.

Kong, Y.Y., Angela, S.J., Bryant, C., Denish, D.F., Kessel, C.V., 2005. The relationship between carbon input, aggregation andsoil organic carbon stabilization in sustainable cropping systems. Soil Sci. Soc. Am J. 69, 1078–1085, doi:10.2136/sssaj2004.0215.

Kroodsma, D.A., Field, C.B., 2006. Carbon sequestration in California agriculture, 1980–2000. Ecol. Appl. 16, 1975–1985, doi:10.1890/10510761%282006%29016%5B1975%3ACSICA%5D2.0.CO%3B2.

Kundu, S., Bhattacharyya, R., Prakash, V., Ghosh, B.N., Gupta, H.S., 2007. Carbon sequestration and relationship between carbon addition and storage under rainfed soybean wheat rotation in a sandy loam soil of the Indian Himalayas. Soil Till. Res. 92, 87–95, doi:10.1016/j.still.2006.01.009.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K., Hobbs, P.R., 2003. How extensive are yield declines in long-term rice–wheat experiments in Asia? Field Crops Res. 81, 159–180, doi:10.1016/S0378-4290%2802%2900219-8.

Lal, R., 1999. Soil management and restoration for C sequestration to mitigate the greenhouse effect. Prog. Environ. Sci. 1, 307–326.

Lal, R., 2002. Carbon sequestration in drylands. Ann. Arid Lands 38, 1–11.

Lal, R., 2004a. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623–1627, doi:10.1126/science.1097396.

Lal, R., 2004b. Soil carbon sequestration in India. Climatic Change 65, 277–296.

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

Larson, W.E., Clapp, C.E., Pierre, W.H., Morachan, Y.B., 1972. Effects of increasing amounts of organic residues on continuous maize: II. Organic carbon, nitrogen, phosphorus, and sulfur. Agron. J. 64, 204–208, doi:10.2134/agronj1972.00021962006400020023x.

Liu, X.B., Han, X.Z., Herbert, S.J., Xing, B., 2003. Dynamics of soil organic carbon under different agricultural management systems in the black soil of China. Commun. Soil Sci. Plant Anal. 34, 973–984, doi:10.1081/CSS-120019103.

Mandal, B., Majumder, B., Bandopadhyay, P.K., Hazra, G.C., Gangopadhyay, A., Samantaroy, R.N., Misra, A.K., Chowdhuri, J., Saha, M.N., Kundu, S., 2007. The potential of cropping systems and soil amendments for carbon sequestration in soils under long-term experiments in subtropical India. Global Change Biol. 13, 357–369, doi:10.1111/j.1365-2486.2006.01309.x.

Majumder, B., Mandal, B., Bandyopadhyay, P.K., Gangopadhyay, A., Mani, P.K., Kundu, A.L., Mazumder, D., 2008. Organic amendments influence soil organic carbon pools and rice–wheat productivity. Soil Sci. Soc. Am. J. 72, 775–785.

Martens, D.A., 2000. Plant residue biochemistry regulates soil carbon cycling and carbon sequestration. Soil Biol. Biochem. 32, 361–369.

Matus, F.J., Lusk, C.H., Maire, C.R., 2008. Effects of soil texture, carbon input rates, and litter quality on free organic matter and nitrogen mineralization in Chilean rain forest and agricultural soils. Commun. Soil Sci. Plan. 39, 187–201, doi:10.1080/00103620701759137.

Ocio, J.A., Martinez, J., Brookes, P.C., 1991. Contribution of straw derived N to total microbial biomass N following incorporation of cereal straw to soil. Soil Biol. Biochem. 23, 655–659, doi:10.1016/0038-0717%2891%2990079-Y.

Pacala, S., Socolow, R., 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science 305, 968–972, doi:10.1126/science.1100103.

Page, A.L., Millar, R.H., Keeney, D.R., 1982. Methods of Soil Analysis, Part 2. Am. Soc. Agron. Inc./Soil Sci. Soc. Am. Inc., Madison WI, USA.

Paustian, K., Collins, H.P., Paul, E.A., 1997. Management controls on soil carbon. In: Paul, E.A. (Ed.), Soil Organic Matter in Temperate Agroecosystems. CRC Press, Boca Raton, FL, pp. 15–49.

Post, W.M., Izarurralde, R.C., Jastrow, J.D., McCarl, B.A., Amonette, J.E., Bailey, V.L., Jardien, P.M., West, T.O., Zhou, J., 2004. Enhancement of carbon sequestration in U.S. Soils Biosci. 54, 895–908, doi:10.1641/0006-3568%282004%29054%5B0895%3AEOCSIU%5D2.0.CO%3B2.

Puget, P., Drinkwater, L.E., 2001. Short-term dynamics of root-and shoot-derived carbon from a leguminous green manure. Soil Sci. Soc. Am. J. 65, 771–779, doi:10.2136/sssaj2001.653771x.

Purakayastha, T.J., Rudrappa, L., Singh, D., Swarup, A., Bhadraray, S., 2008a. Long-term impact of fertilizers on soil organic carbon pools and sequestration rates in maize–wheat–cowpea cropping system. Geoderma 144, 370–378, doi:10.1016/j.geoderma.2007.12.006.

Purakayastha, T.J., Huggins, D.R., Smith, J.L., 2008b. Carbon sequestration in native prairie, perennial grass, no-tilled and cultivated Palouse silt loam. Soil Sci. Soc. Am. J. 72, 534–540, doi:10.2136/sssaj2005.0369.

Ram, N., 1998. Effect of continuous fertilizer use on soil fertility and productivity of a mollisol. In: Swarup, A., Reddy, D.D., Prasad, R.N. (Eds.), Long-Term Soil Fertility Management through Integrated Plant Nutrient Supply. Indian Institute of Soil Science, Bhopal, pp. 229–237.

Rudrappa, L., Purakayastha, T.J., Singh, Dhyan, Bhadraray, S., 2006. Long-term manuring and fertilization effects on soil organic carbon pools in a typic haplustept of semi-arid sub-tropical India. Soil Tillage Res. 88, 180–192, doi:10.1016/j.still.2005.05.008.

Russell, A.E., Laird, D.A., Parkin, T.B., Mallarino, A.P., 2005. Impact of nitrogen fertilization and cropping system on carbon sequestration in Midwestern mollisols. Soil Sci. Soc. Am. J. 69, 413–422.

Sahrawat, K.L., 2004. Organic matter accumulation in submerged soils. Adv. Agron. 81, 169–201, doi:10.1016/S0065-2113%2803%2981004-0.

Sanderman, J., Farquharson, R., Baldock, J., 2010. Soil carbon sequestration potential: a review for Australian agriculture. A Report Prepared for Department of Climate Change and Energy Efficiency, p. 89.

Schjønning, P., Elmholt, S., Munkholm, L.J., Debosz, K., 2002. Soil quality aspects of humid sandy loams as influenced by organic and conventional long-term management. Agric. Ecosyst. Environ. 88, 195–214, doi:10.1016/S0167-8809%2801%2900161-X.

Singh, R.P., Das, S.K., Bhaskara Rao, U.M., Narayana Reddy, M., 1990. Sustainability Index Under Different Management. Annu. Rep. Central Res. Inst. for Dryland Agric, Hyderabad, India.

Singh, Y., Singh, B., Khera, T.S., Meelu, O.P., 1994. Integrated management of green manure, farmyard manure, and nitrogen fertilizer in a rice ± wheat rotation in north-western India. Arid Soil Res. Rehab. 8, 199–205.

Smith, P., Powlson, S.D.S., Glendining, M.J., Smith, J.U., 1997. Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. Global Change Biol. 3, 67–79, doi:10.1046/j.1365-2486.1997.00055.x.

Snyder, D., Trofymow, J.A., 1984. Rapid accurate wet oxidation diffusion procedure for determining organic and inorganic carbon in plant and soil samples. Comm. Soil Sci. Plant Anal. 15, 1587–1597, doi:10.1080/00103628409367499.

Solberg, E.D., Nyborg, M., Izaurralde, R.C., Malhi, S.S., Janzen, H.H., Molina-Ayala, M., 1997. Carbon Storage in soils under continuous cereal grain cropping: N fertilizer and straw. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, FL, pp. 235–254.

Sparling, G.P., 1997. Soil microbial biomass activity and nutrient cycling as indicators of soil health. In: Pankhurst, C.E., et al. (Eds.), Biological Indicators of Soil Health. CAB International, Wallingford, pp. 97–119.

Stevenson, F.J., Cole, M.A., 1999. The internal cycle of nitrogen in soil. In: Cycles of Soil Carbon, Nitrogen, Phosphorus, Sulfur, Micronutrients. John Wiley and Sons, Inc., New York, pp. 191–229.

Swarup, A., Manna, M.C., Singh, G.B., 2000. Impact of land use and management practiced on organic carbon dynamics in soils of India. In: Lal. (Ed.), Advances in Soil Science Global Climate Change and Tropical Ecosystem. CRC Lewis, Boca Raton, FL, pp. 261–281.

Tandon, H.L.S., 1997. Organic residues: an assessment of potential supplies their contribution to agricultural productivity and policy issues for Indian agriculture from 2000 to 2025. In: Kanwar, I.S., Katyal, S.C. (Eds.), Plant Nutrient Needs, Supply, Efficiency and Policy Issues: 2000–2025. National Academy of Agricultural Sciences, New Delhi, India.

Theng, B.K.G., Orchard, V.A., 1995. Interactions of clays with microorganisms and bacterial survival in soil: a physicochemical perspective. In: Huang, P.M., et, al. (Eds.), Environmental Impact of Soil Component Interactions, vol. II. CRC Lewis, Boca Raton, FL, pp. 123–143.

Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass. Soil Biol. Biochem. 19, 703–707, doi:10.1016/0038-0717%2887%2990052-6.

Veihmeyer, F.J., Hendrickson, A.H., 1948. Soil density and root penetration. Soil Sci. 65, 487–493, doi:10.1097/00010694-194806000-00006.

Verma, T.S., Bhagat, R.M., 1992. Impact of rice straw management practices on yield, nitrogen uptake and soil properties in a wheat–rice rotation in northern India. Fert. Res. 33, 97–106.

Wardle, D.A., 1992. A comparative assessment of factors which influence microbial biomass carbon and nitrogen levels in soil. Biol. Rev. 67, 321–358, doi:10.1111/j.1469-185X.1992.tb00728.x.

Watanabe, I., 1984. Anaerobic decomposition of organic matter. In: Organic Matter and Rice. International Rice Research Institute, Manila, Philippines, pp. 2377–258.

Yadav, R.L., Dwivedi, B.S., Pandey, P.S., 2000. Rice–wheat cropping system assessment of sustainability under green manuring and chemical fertilizer inputs. Field Crops Res. 65, 15–30, doi:10.1016/S0378-4290%2899%2900066-0.

Zhang, W., Xu, M., Wang, B., Wang, X.J., 2009. Soil organic carbon, total nitrogen and grain yields under long-term fertilizations in the upland red soil of southern china. Nutr. Cycl. Agroecosyst. 84, 59–69, doi:10.1007/s10705-008-9226-7.

Zibilski, L.M., 1994. Carbon mineralization. In: Bingham, J.M., Mickelson, S.H. (Eds.), Methods of Soil Analysis, Part 2. Microbiological and Biochemical Properties, SSSA, Book Series No. 5. ASA, SSSA, Madison, WI, pp. 853–863.