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Long-Term Effects of Soil Fertility Management on Carbon Sequestration in a Rice–Lentil Cropping System of the Indo-Gangetic Plains

Ch. Srinivasarao*
B. Venkateswarlu
Central Research Institute for Dryland Agriculture
Santoshnagar, Saidabad (P.O)
Hyderabad, 500 059
Andhra Pradesh, India

Rattan Lal
Carbon Management and Sequestration Center
The Ohio State Univ.
Columbus, OH 43210

Anil Kumar Singh
Indian Council of Agricultural Research
Krishi Anusandhan Bhawan (KAB-II)
New Delhi, 110 012, India

K.P.R. Vittal
National Institute for Abiotic Stress Management
Baramati, 413 115
Maharashtra, India

Sumanta Kundu
Central Research Institute for Dryland Agriculture
Santoshnagar, Saidabad (P.O)
Hyderabad, 500 059
Andhra Pradesh, India

S.R. Singh
S.P. Singh
Banaras Hindu Univ.
Varanasi, 221 005
Uttar Pradesh, India

Enrichment of soil organic carbon (SOC) stocks through sequestration of atmospheric CO_2 in agricultural soils is important because of its impacts on soil quality, agronomic production, and adaptation to and mitigation of climate change. In a 21-yr field experiment conducted under subhumid tropical conditions in India, the impacts of crop residue C inputs were assessed for the rice (*Oryza sativa* L.)–lentil (*Lens esculenta* Moench) cropping sequence. These impacts were evaluated in an experiment involving mineral fertilizers and manuring treatments on crop yield sustainability with reference to critical biomass requirements for maintenance of SOC in an Inceptisol. Application of farmyard manure (FYM) without and with mineral fertilizers increased C input and SOC concentration and stock. In comparison with the control, the 100% organic (FYM) treatment had significantly higher profile SOC (27.5 Mg ha^{-1}), and more C build up (55.0%) and C sequestration (6.6 Mg C ha^{-1}) to 1-m depth vis-à-vis the antecedent values in 1986. These parameters were also higher in 100% FYM treatment at a rate providing equivalent amount of the recommended dose of N followed by conjunctive use of FYM and mineral fertilizers. The SOC stock and rate of sequestration were positively correlated with cumulative C input, and with sustainable yield index (SYI) of upland rice and lentil. Higher grain yield (1.95 and 1.04 Mg ha^{-1} of rice and lentil, respectively) was obtained with the application of 50% organic (FYM)+50% recommended dose of fertilizer (RDF). In comparison, higher SOC sequestration rate was measured with the application of 100% organic (FYM). For every Mg increase in SOC stock in the root zone there was 0.16 and 0.18 Mg ha^{-1}yr^{-1} yield increase of rice and lentil, respectively. For maintaining a stable SOC level (zero change due to cropping), a minimum quantity of 2.47 Mg C ha^{-1} yr^{-1} is required for this soil, climate, cropping system, and fertilization treatments. To achieve this quantity of C, 7.1 Mg of biomass is required to be produced every year vs. average rice and lentil yields of 1.6 and 0.7 Mg ha^{-1}, respectively. The sole application of mineral fertilizers at 50 or 100% of the RDF did not maintain the SOC stock. Thus, application of FYM (or other organics) in conjunction with mineral fertilizers is essential to maintaining and enhancing the SOC stock in the rice-based cropping systems.

Abbreviations: BD, bulk density; FYM, farmyard manure; INM, integrated nutrient management;NUE, nitrogen use efficiency; RDF, recommended dose of fertilizer; SOC, soil organic carbon; SOM, soil organic matter; SYI, sustainable yield index.

Research information on rate of enrichment of SOC stocks through sequestration of atmospheric CO_2 in agricultural soils is important because of its impacts on adaptation to and mitigation of climate change, crop productivity, and sustainability. Soil organic matter (SOM) constitutes a signifi-

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*Corresponding author (cherukumalli2011@gmail.com).

cant component of the global terrestrial C pool (Ciampitti et al., 2011; Lal, 2010a). A high SOC concentration can be achieved through the adoption of appropriate crop rotations (Wright and Hons, 2005), integrated soil fertility management (Lal, 2010a; Ciampitti et al., 2011), judicious rates of mineral fertilizers and organic amendments (Schuman et al., 2002; Mandal et al., 2007; Majumder et al., 2008), and conservation tillage methods (Lal, 2009). In arid and semiarid regions, characterized by drought-prone soils of low and depleted SOC stocks, agronomic productivity is strongly influenced by soil quality. Therefore, restoring soil quality and enhancing SOC stocks are essential to improving and sustaining agronomic productivity (Lal, 2006, 2010b, 2010c).

Excessive tillage and extractive farming practices can adversely affect the distribution and stability of soil aggregates, and reduce SOC stocks (Kong et al., 2005). The magnitude of reduction in SOC stocks, however, varies depending on climate and cropping systems (Lal, 2004). In accord with the Vant Hoff rule, the rate of decomposition of SOM is higher in the tropics than in temperate regions (Jenkinson and Ayanaba, 1977). However, the choice of crop species plays an important role in maintaining the SOC stock. The quality and quantity of the residues returned to the soil also impact the stocks and the turnover or the mean residence time (MRT) in the soil (Mandal et al., 2007). Within a particular cropping sequence, the duration and timing of "fallowing" also affect the SOC stock (Halvorson et al., 2002). Yet, soil and site-specific data are required concerning the effects of intensive cultivation with different cropping systems and the associated management practices on the SOC concentration and stock. Once the pathways of C sequestration in soils are identified, suitable agricultural strategies may be used to enhance SOC stocks, reduce net CO_2 loading into the atmosphere and curb the rate and magnitude of global warming (Lal, 2009). However, a large proportion of the research done on SOC sequestration in agricultural ecosystems is for cold and temperate regions. Research information on tropical and subtropical regions is rather scanty (Velayutham et al., 2000; Lal, 2004). A few studies in the Indian subcontinent (Majumder et al., 2007; Mandal et al., 2007) have been conducted under irrigated conditions. Thus, research data are needed for rainfed agriculture in semiarid conditions, where drought stress, high temperatures, and low biomass productivity are common features. Furthermore, most of the crop management impact studies on SOC sequestration are limited to surface (0.15 m) layers (Paustian et al., 1997), and data are needed for the entire soil profile (Lorenz and Lal, 2005).

Rice-based cropping systems are the backbone of India's food security, covering a total area of 38 million hectares (Mha) (FAI, 2010). Low-yielding traditional varieties, low soil fertility, and soils depleted of SOC stocks are among major constraints to increasing and stabilizing the productivity of rainfed rice. Thus, integrated nutrient management (INM) practices are needed to sustain soil fertility through an integration of different available nutrient sources and application methods which maximize crop yield per unit input (De Datta et al., 1990). In this context, integrating FYM and green manures with mineral fertilizers offer a large potential as a feasible and economic complement to mineral fertilizers for improving soil quality. Besides fixing atmospheric N and benefitting the succeeding crop, lentils are also adapted to local climatic and soil fertility conditions. Because of its adaptation to intercropping and relay cropping, lentil occupies a unique place in cropping systems in northern, eastern, and central India. It is seeded into a standing paddy crop just before the harvest. Its incorporation into the rice-based cropping system improves SOC by increasing crop residue inputs, recycling, and integrating use of organics along with mineral fertilizers, and sustaining productivity of upland rice-based systems.

Rainfed crops are grown on 1.132 billion ha worldwide and meet about 60% of the food and nutritional needs of the global population (Biradar et al., 2009). The United States, Russia, China, India, Australia, Canada, and Argentina account for more than 50% of the rainfed cropland areas in the world (Biradar et al., 2009). In India, rainfed cropping is practiced on 80 Mha in arid, semiarid and subhumid climatic zones, constituting ~60% of the net cultivated area. These regions in India are characterized by erratic rainfall, degraded soils, poor infrastructure, and tropical or subtropical environments where air temperature rises frequently above 40 to 45°C in summer. Inceptisols (around 130 Mha in India) are the predominant soils of these regions (NAAS, 2010). Soils under rainfed agriculture in India are categorized by low SOC and N concentrations in most agro-ecoregions. Data from 21 locations across rainfed regions of India covering eight production systems showed that these soils (to 1-m depth)are low in SOC concentration (<5 g kg^{-1}) and stocks (20–97 Mg ha^{-1}) (Srinivasarao et al., 2009). Low crop yields, low or no biomass return to the soil, coupled with long fallow periods, lead to a severe SOC depletion. The magnitude of change in SOC due to continuous cultivation depends on the balance between the loss of C by oxidation and erosion, the quantity and quality of crop residues returned, and additional biomass C added to the soils. Therefore, crop and soil management practices must be designed to ensure sustainability of long-term cropping systems. Sustainable yield index reflects the stability of yield with different management practices withstanding variations of rainfall and other climatic conditions. A balanced application of plant nutrients, organic amendments, and inclusion of legumes can enhance and sustain SOC concentration and stock (Majumder et al., 2007; Mandal et al., 2008; Verma et al., 2010; Srinivasarao et al., 2011).

Therefore, the present study was conducted in the subhumid tropical conditions of northern India to assess the effects of 21 yr of cropping, mineral fertilization, and the use of organics on SOC sequestration in Inceptisols, establish the relationship between SOC sequestration and SYI, and determine requirement of critical C-inputs for zero change in SOC levels.

MATERIALS AND METHODS

Site Description

A long-term field experiment involving a rice–lentil crop sequence on an alluvial soil was established in 1986 at the Banaras Hindu University farm (BHU), Varanasi, Uttar Pradesh, India (82°51’ E, 25°11’ N, at 480 m mean sea level). The site is characterized by hot, dry, subhumid, tropical climate (Velayutham et al., 1999). The mean maximum and minimum annual air temperatures for the study period (1986–2007) were34.4 and 26.6°C, the mean annual precipitation 1080 mm (909 mm dependable), and the mean annual potential evapotranspiration (PET) 1525 mm. The data on annual and seasonal rainfall during the 21 yr of the experimental period are depicted in Fig. 1. The length of the growing season is 150 to 180 d.

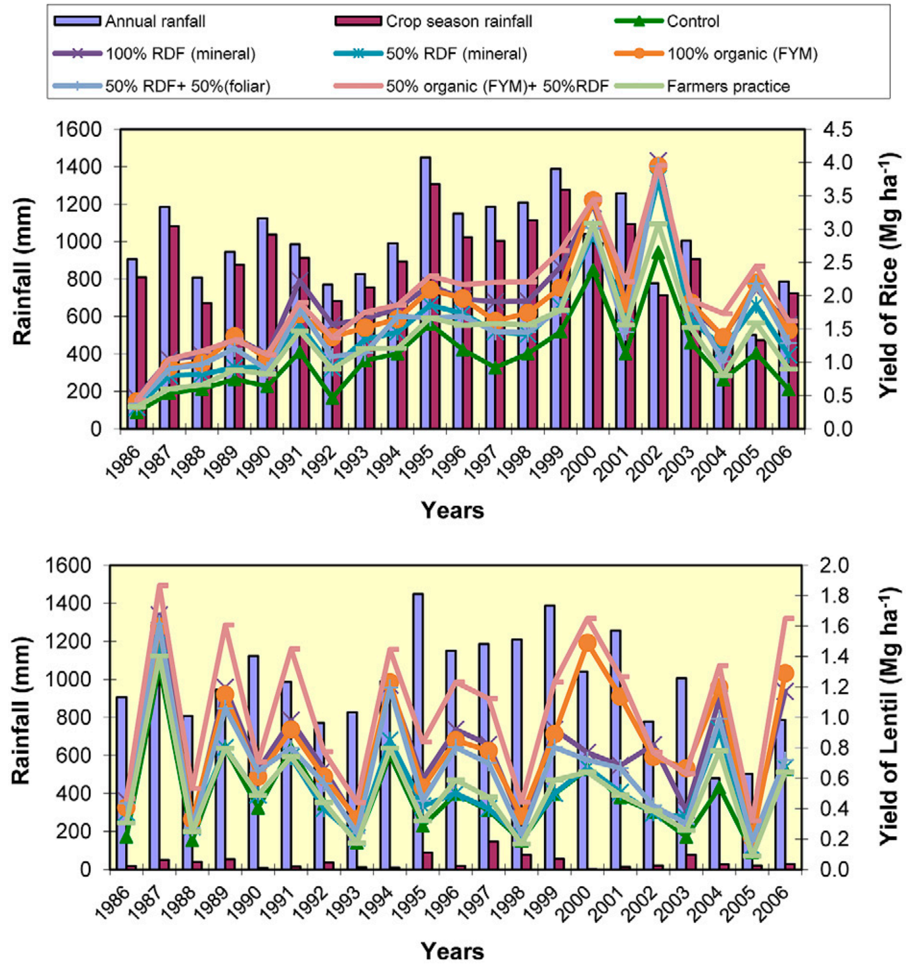

Fig. 1. Mean annual and seasonal rainfall in relation to grain yields of (a) rice and (b) lentil across the treatments during 21 yr (1986–2007).

Soil of the experimental site is a deep loamy alluvium with an extremely low profile (1-m depth) SOC concentration (1.4 g kg^{-1} soil). Available N, P, K, pH, textural composition, and CEC were analyzed for 0 to 0.15-m depth. The soil is neutral in reaction (pH 6.7), has low available N (160 kg ha^{-1}) and K (119 kg ha^{-1}), and medium available P (21.2 kg ha^{-1}). It is a sandy clay loam with a textural composition consisting of 582 g kg^{-1} of sand, 140 g kg^{-1} of silt and 278 g $kg^{-1}$of clay and has an effective CEC of 9.0 cmol kg^{-1} and 7.0 g kg^{-1} of inorganic C. The soil is classified as fine-silty, mixed, hyperthermic Udic Ustochrepts.

Treatments and Crop Management

The rice (variety NDR 118)–lentil (variety HUL-11) crop sequence was followed every year for the 21 yr period (1986–2007). Upland rice was grown in the rainy season (June–September) followed by lentil in the postrainy (October–December) season. The experiment was laid out in a Randomized Block Design with the following treatments:

1. T_1 = Control (no N–P–K fertilizers or organics)
2. T_2 = 100% RDF (mineral)
3. T_3 = 50% RDF (mineral)
4. T_4 = 100% organic as sole FYM
5. T_5 = 50% RDF+50% RDF(foliar)
6. T_6 = 50% organic (FYM) + 50%RDF, and
7. T_7 = Farmer’s practice (20 kg N ha^{-1} only)

Each treatment was implemented in triplicate. The FYM was incorporated into the soil with a wooden plow during June to July every year depending on the rainfall. The gross and net plot size was 12.0 × 11.1 m and 10.0 × 9.9 m, respectively. Plant density of rice and lentil was 400,000 ha^{-1} (Spacing 25 × 10 cm). Planting times for rice and lentil were the second week of June and the first week of October, respectively. Average annual addition of FYM (N concentration of 5.6 ± 0.3 g kg^{-1}) was 10.7 ± 0.46 Mg ha^{-1}. The FYM used contained 2.0 ± 0.1, 5.0 ± 0.2, 1.6 ± 0.2, 3.2 ± 0.1, 3.0 ± 0.1 g kg^{-1} P, K, S, Ca, Mg and 20 ± 0.8, 10 ± 0.5 mg kg^{-1} Zn and B, respectively, and had a C/N ratio of 59:1.The RDF (60–50–30 kg N, P_2O_5, and K_2O ha^{-1}) was followed in appropriate treatments in rice as per the state recommendations for that region. Nutrient solutions were sprayed on leaf canopy of rice during its physiological active stage as a foliar application. Lentil, the second crop in the sequence, was grown on residual fertility. The added FYM was better decomposed because of the rainfall during the rainy season. Manual weeding was done when needed. Grain and stover yields of rice and lentil were recorded at maturity, and moisture contents of grains and stover were determined. Grain yield was expressed at 14% moisture level.

Soil Sampling and Analysis

Three representative field-moist soil samples were obtained from each plot with a tube auger at 0.2 m increments to 1-m depth during April 2007, and were composited for each depth and replication. Soil properties (i.e., pH, $CaCO_3$, and CEC) were analyzed per standard procedures (Jackson, 1973). Soil texture was determined by Bouyoucos hydrometer (Bouyoucos, 1927). Soil samples were also analyzed for available N (Subbiah and Asija, 1956), P (Olsen and Sommers, 1982), and K (Hanway and Heidel, 1952) concentrations. Three additional samples were obtained from all five depths using a core sampler (0.05 m in diameter, 0.08 m in length) for soil bulk density (BD) determination (Blake and Hartge, 1986). All determinations were performed in triplicate, and the results expressed on the oven-dry basis.

Estimation of Carbon in Soil and Organic Materials

Soil samples were air dried, gently ground, and sieved through a 2.0-mm sieve. A subsample was finely ground and sieved through 0.2-mm sieve. The organic materials (FYM, leaf, stubbles, nodules, and roots) were oven dried and finely ground in a mechanical grinder, and soil and organic materials were analyzed for C by a LECO CHN analyzer (Nelson and Sommers, 1996). Soil samples were also analyzed for inorganic C titrimetrically, by digesting them with dilute HCl (Bundy and Bremner, 1972). The SOC concentration of the soil samples was obtained from the following calculation (Eq. [1])

SOC concentration = Total C – Inorganic C [1]

The total SOC stock of the profile expressed as Mg ha^{-1} for each of the five depths (0–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, and 0.8–1.0 m) was computed by multiplying the SOC concentration (g kg^{-1}) (obtained by SOC = LECOC-HCl C) by the bulk density (Mg m^{-3}) and depth (m), and by 10.

Carbon Inputs through Plant and Organic Materials

Annual C inputs to the soil through leaf fall, stubbles, roots, nodules, and rhizodeposition were computed based on the biomass yield of rice and lentil. Harvestable crop residues were removed. The remaining stubbles constituted 6.4, 6.8, 6.5, 6.7, 6.6, 6.9 and 6.4% of the total harvestable biomass yield of rice, and 6.2, 7.1, 6.4, 6.9, 6.7, 7.4 and 6.3% of lentil in the control, 100% RDF (mineral), 50% RDF (mineral), 100% organic (FYM), 50% RDF+50% (foliar), 50% organic (FYM)+50% RDF, and farmer's practice, respectively. The root biomass was calculated using the root/shoot biomass ratios recorded from the experiment. Root biomass was measured immediately after harvesting the crop, following the core-sampling procedure (Franzluebbers et al., 1999). The root biomass represented 39.2, 43.1, 40.2, 43.8, 41.5, 44.1 and 41.0% of the total harvestable biomass yield of rice and 25.7, 28.2, 27.3, 28.8, 27.6, 29.9 and 25.9% total harvestable biomass yield of lentil for the treatments listed above, respectively. Leaf fall constituted 6.2, 7.1, 6.4, 6.9, 6.7, 7.4, and 6.3% total harvestable biomass yield of lentil, and nodules constituted 15% of the root biomass for different treatments, respectively. Leaf-fall from rice crop was not considered in the calculation of crop residue C inputs because it was negligible. Ratio of root C/rhizodeposition C from root turnover and exudates was assumed to be 1:0.81 for rice and 1:1.33 for lentil (Shamoot et al., 1968). Rice stubbles and roots contain 332 and 345 g C kg^{-1}, respectively. Lentil leaf, stubbles, and roots contain 354, 348, and 342 g kg^{-1} C, respectively. Because weeds were removed during the intercultivation operation, C inputs from roots and rhizodeposition by the weeds were not considered. Using all the measurements described above, a treatment-wise estimate of plant-derived C inputs, and those through organics applied are presented in Table 1.

Calculations for Carbon Budgeting

Carbon budgeting was computed by using the following equations:

$$\text{C restoration } (\%) = \frac{C_{fert+org} \text{ or } C_{fert} - C_{cont}}{C_{cont}} \times 100 \qquad [2]$$

where $C_{fert+org}$ represents C in Fertilizer+FYM treatments and C_{fert} and C_{cont} are the C in fertilizer and control treatments, respectively.

$$\text{C build-up rate} (\text{Mg C ha}^{-1}) = \frac{C_{fert+org} \text{ or } C_{fert} - C_{cont}}{\text{Years of experimentation}} \qquad [3]$$

$$\text{C stabilization } (\%) = \frac{C_{fert+org} - C_{fert}}{C_{org}} \times 100 \qquad [4]$$

where C_{org} represents C applied through organic material (i.e., FYM)

$$\text{C sequestered } \left(\text{Mg C ha}^{-1}\text{soil}\right) = SOC_{current} - SOC_{init} \qquad [5]$$

where $SOC_{current}$ and SOC_{init} indicate the SOC stocks in 2007 (current) and that at the initiation of the long-term experiment (in 1986). Positive and negative values indicate gains and losses in SOC stocks, respectively.

Sustainable Yield Index

Total crop productivity of rice and lentil was calculated through a SYI using yield-data of 21 yr. This was done to adjust any annual variations in the yield due to differences in rainfall, and to highlight the relative productivity of the treatments for the entire experimental period. The SYI is defined according to Eq. [6]:

$$SYI = \frac{Y - \sigma}{Y_{max}} \qquad [6]$$

where Y is the estimated average yield of a practice across the years, σ is its estimated standard deviation, and Y_{max} is the observed maximum yield in the experiment during the years of cultivation (Singh et al., 1990).

Statistical Analysis

Statistical analyses of the data were done using the Windows based Statistical Package for the Social Sciences (SPSS, 2001) program (Version 11.0, SPSS, Chicago, IL to analyze variance and to determine the statistical significance of the treatment effects. The Duncan Multiple Range Test was used to compare treatment means. Regression models were developed from yields of each crop with individual treatment and month by rainfall during the season. Since rice was grown from June to October and lentil from October to December, an assessment of effect of the fertilizer treatments was done with a treatment-wise regression model of grain yield as a function of monthly rainfall (Eq. [7]) for rice,

$$Y = \pm\,\alpha \pm \beta1\,(\text{RF June}) \pm \beta2\,(\text{RF July}) \pm \beta3\,(\text{RF Aug}) \pm \beta4\,(\text{RF Sept}) \pm \beta5\,(\text{RF Oct}) \qquad [7]$$

and for lentil (Eq. [8]).

$$Y = \pm\,\alpha \pm \beta1\,(\text{RF Sept}) \pm \beta2\,(\text{RF Oct}) \pm \beta3\,(\text{RF Nov}) \pm \beta4\,(\text{RF Dec}) \qquad [8]$$

where, Y is dependant variable (Yield, Mg ha^{-1}) and independent variable is rainfall (RF) in mm.

Because lentil is grown mostly on residual soil moisture, rainfall received during September was also taken into consideration.

In Eq. [7] and [8], α is the intercept and β's are regression coefficients of monthly rainfall over years. The models of treatments could be assessed for significance based on: (i) coefficient of determination (R^2) and (ii) standard error.

Simple correlation coefficients and regression equations were also computed to evaluate the relationships among the response variables (SYI, C inputs, profile SOC, C build up and C sequestration) using the same statistical package at 95% probability level.

RESULTS AND DISCUSSION

Carbon Input Levels, Yield, and Sustainability

Estimates of cumulative C inputs into soil under different treatments during 21 yr of continuous cropping through crop residues (leaf, stubble, root, nodule, and rhizo-deposition) and manures are given in Table 1. Inputs of C ranged from 1.1 Mg C ha^{-1}yr^{-1} in the control to 2.4 Mg C ha^{-1}yr^{-1} in the 50% organic (FYM)+50% RDF treatment. Integrated use of FYM along with fertilizer produced higher biomass and subsequently higher C input, as crop residues (2.4 Mg C ha^{-1} yr^{-1}) compared with the 100% RDF treatment (2.0 Mg C ha^{-1} yr^{-1}).Overall, treatments involving FYM received an additional 1.77 to 3.55 Mg C ha^{-1} yr^{-1}.

Grain yield of rice and lentil differed among fertilizer and manure treatments. Yield trends over 21 yr of cropping (Fig. 1a,1b) indicated similar initial yields (2–3 yr) among mineral fertilization and INM with organic manure, but significant differences occurred during the later periods. Pooled data of 21 yr suggest a higher grain yield (Mg ha^{-1} of rice and lentil, respectively) through the application of 50% organic (FYM)+50% RDF (1.95,1.04) followed by 100% RDF (mineral) (1.85,0.77) and was on par with 100% organic (FYM) (1.75,0.82), and the least yield was measured in control (1.08,0.48) (Table 1). Under rainfed conditions, crop yields are usually influenced by seasonal rainfall, particularly the amount received at the critical stages of the crop growth.

Table 1. Mean (1986–2007) grain yield and annual C input to soil from rainfed rice–lentil under different fertilizer and manure treatments.

Treatment	Mean grain yield, Mg ha^{-1}		SYI†		Annual C input, Mg ha^{-1}								Mean annual crop residue C inputs	Mean annual C inputs through FYM	Total C input in 21 yr
					Rice			Lentil							
	Rice	Lentil	Rice	Lentil	Stubbles	Root	RD	Leaf fall	Stubbles	Roots	Nodules	RD			
														–Mg ha^{-1}–	
Control	1.08^{F}‡	0.48^{D}	17.1^{D}	14.2^{F}	0.06^{F}	0.36^{F}	0.29^{E}	0.06^{F}	0.04^{E}	0.03^{C}	0.15^{D}	0.02^{D}	1.13^{E}	–	23.8^{G}
100% RDF (mineral)	1.85^{B}	0.77^{B}	25.2^{B}	24.1^{C}	0.10^{B}	0.66^{B}	0.53^{B}	0.10^{B}	0.06^{C}	0.04^{B}	0.24^{B}	0.04^{B}	2.00^{B}	–	42.0^{C}
50% RDF (mineral)	1.51^{D}	0.54^{D}	21.2^{C}	16.3^{E}	0.08^{D}	0.51^{D}	0.41^{C}	0.08^{D}	0.04^{E}	0.03^{C}	0.17^{D}	0.03^{C}	1.50^{C}	–	31.4^{E}
100% organic (FYM)	1.75^{C}	0.82^{B}	26.3^{B}	26.1^{B}	0.09^{C}	0.63^{C}	0.51^{B}	0.09^{C}	0.07^{B}	0.04^{B}	0.26^{B}	0.04^{B}	2.00^{B}	3.55	116.6^{A}
50% RDF+50% (foliar)	1.57^{D}	0.66^{C}	22.1^{C}	19.2^{D}	0.08^{D}	0.53^{D}	0.43^{C}	0.08^{D}	0.05^{D}	0.04^{B}	0.21^{C}	0.03^{C}	1.65^{C}	–	34.7^{D}
50% organic (FYM)+50% RDF	1.95^{A}	1.04^{A}	29.1^{A}	30.1^{A}	0.11^{A}	0.70^{A}	0.57^{A}	0.11^{A}	0.09^{A}	0.06^{A}	0.34^{A}	0.05^{A}	2.37^{A}	1.77	87.0^{B}
Farmer's practice	1.37^{E}	0.51^{D}	20.3^{C}	15.2^{F}	0.07^{E}	0.47^{E}	0.38^{D}	0.07^{E}	0.04^{E}	0.03^{C}	0.16^{D}	0.02^{D}	1.38^{D}	–	29.1^{F}

† SYI, sustainable yield index; RD, rhizodeposition; RDF, recommended dose of fertilizer; FYM, farmyard manure.

‡ Different letters within columns are significantly different at $P = 0.05$ according to Duncan Multiple Range Test (DMRT) for separation of means.

Table 2. Regression models of rice grain yield through monthly rainfall over years.

Treatment	Regression model	R^2†	Φ
Control	Y‡ = 0.62+0.002(RF_{June})+0.001(RF_{Jul})+0.001(RF_{Aug})+0.001(RF_{Sept})–0.005(RF_{Oct})	0.21	0.59
100% RDF§ (mineral)	Y = 1.52+0.002(RF_{June})+0.001(RF_{Jul})+0.001(RF_{Aug})+0.001(RF_{Sept})–0.005 (RF_{Oct})	0.14	0.79
50% RDF (mineral)	Y = 1.21+0.003(RF_{June})+0.001(RF_{Jul})+0.002(RF_{Aug})+0.001(RF_{Sept})–0.006(RF_{Oct})	0.17	0.72
100% organic (FYM)	Y = 1.41+0.003(RF_{June})+0.002(RF_{Jul})+0.002(RF_{Aug})+0.001(RF_{Sept})–0.006(RF_{Oct})	0.17	0.73
50% RDF+50% (foliar)	Y = 1.44+0.003(RF_{June})+0.002(RF_{Jul})+0.002(RF_{Aug})+0.001(RF_{Sept})–0.004(RF_{Oct})	0.13	0.74
50% organic (FYM)+50% RDF	Y = 1.49+0.003(RF_{June})+0.001(RF_{Jul})+0.001(RF_{Aug})+0.002(RF_{Sept})–0.003(RF_{Oct})	0.14	0.76
Farmer's practice	Y = 0.73+0.003(RF_{June})+0.001(RF_{Jul})+0.001(RF_{Aug})+0.002(RF_{Sept})–0.003(RF_{Oct})	0.16	0.65

† R^2: Coefficient of determination Φ: Standard error (Mg ha^{-1}).

‡ Y is dependant variable (Yield, Mg ha^{-1}) and independent variable is rainfall (RF) in mm.

§ RDF, recommended dose of fertilizer; FYM, farmyard manure.

Significantly higher SYI was observed with the application of FYM either alone or in combination with mineral fertilizers compared to control or sole application of mineral fertilizer. The highest SYI (% for rice and lentil, respectively) was observed in 50% organic (FYM)+50% RDF (29.1,30.1) followed by 100% organic (FYM) (26.3,26.1), and the lowest was in control (17.1, 14.1)(Table 1). This trend is mainly due to the resilience of soil system to intermittent droughts with high moisture retention capacity in FYM-treated compared with those receiving mineral fertilizers and also due to a slow N-releasing capacity of FYM (Srinivasarao et al., 2011). It also underlines the importance of organics in enhancing soil resilience under weather aberrations during the cropping period, a common feature of rainfed agriculture (Ghosh et al., 2003, 2006). Ghosh et al. (2006) reported that total system productivity was 130% higher in a groundnut (*Arachis hypogaea* L.)-based (rainy season groundnut followed by other postrainy season crops namely, groundnut, chickpea [*Cicer arietinum* L.], wheat [*Triticum aestivum* L.], mustard [*Brassica* spp.], sunflower [*Helianthus annuus* L.]) than in a fallow-based (rainy season fallow followed by other postrainy season crops) system and was in the order: groundnut–groundnut > groundnut–chickpea > groundnut–wheat > groundnut–mustard > groundnut–sunflower, though SYI was the highest in the groundnut–groundnut system in Vertisols (Typic Haplustert). The gross C input was relatively higher in the groundnut-based system but the C loss rate was greater. The amount of crop residues needed per ha per year to compensate the loss of SOC was estimated to be 4.3 Mg in the fallow-based and 7.6 Mg in the groundnut-based cropping system. Though the total system productivity was greater in groundnut–groundnut and groundnut–chickpea systems, yet SOC concentration declined. The groundnut–wheat system contributed more C, particularly root biomass C, than other systems, improved the restoration of SOC and maintained total system productivity.

Effect of Rainfall during the Growing Season on Grain Yield of Rice and Lentil

Rainfall received during each month was positively correlated with the grain yield except for the month of October ($R^2 = 0.14–0.21$; $n = 21$) (Table 2). Similarly, rainfall received in other months of the growing season positively influenced grain yield of lentil except for the month of November ($R^2 = 0.49–0.63$; $n = 21$) (Table 3). Residual soil moisture due to rainfall received in September significantly ($P < 0.01$) influenced lentil yield. In contrast, there was a highly significant but negative relationship between lentil yield and the amount of rainfall received in November. Higher rainfall during the pod formation and grain-filling stages seriously damaged lentil crop, and reduced its grain yield.

Change in Bulk Density

With organic amendments BD was lower than with mineral fertilization and the unfertilized control (Table 4). The lowest BD was observed in 0- to 0.2-m depth under 100% organic (FYM) (1.46 Mg m^{-3}) and the highest was in the control (1.52 Mg m^{-3}). Soil BD decreased with the application of FYM, likely due to higher SOC and increased

Table 3. Regression models of lentil seed yield through monthly rainfall over years.

Treatment	Regression model	R^2†	Φ
Control	Y‡ = 0.28+0.001**(RF_{Sept})+0.002(RF_{Oct}) –0.015**(RF_{Nov})+0.007(RF_{Dec})	0.63	0.20
100% RDF§ (mineral)	Y = 0.53+0.001**(RF_{Sept})+0.002(RF_{Oct}) – 0.016**(RF_{Nov})+0.012(RF_{Dec})	0.49	0.30
50% RDF (mineral)	Y = 0.31+0.001**(RF_{Sept})+0.003(RF_{Oct})–0.019**(RF_{Nov})+0.007(RF_{Dec})	0.54	0.21
100% organic (FYM)	Y = 0.56+0.002**(RF_{Sept})+0.003(RF_{Oct})–0.020**(RF_{Nov})+0.008(RF_{Dec})	0.56	0.30
50% RDF+50% (foliar)	Y = 0.40+0.002**(RF_{Sept})+0.003(RF_{Oct})–0.016**(RF_{Nov})+0.009(RF_{Dec})	0.57	0.25
50% organic (FYM)+50% RDF	Y = 0.69+0.002**(RF_{Sept})+0.001(RF_{Oct})–0.022**(RF_{Nov})+0.015(RF_{Dec})	0.59	0.33
Farmer's practice	Y = 0.31+0.001**(RF_{Sept})+0.002(RF_{Oct})–0.016**(RF_{Nov})+0.007(RF_{Dec})	0.58	0.21

* Significance at $P < 0.05$ level.

** Significance at $P < 0.01$ level.

† R^2: Coefficient of determination Φ: Standard error (Mg ha^{-1}).

‡ Y is dependant variable (Yield, Mg ha^{-1}) and independent variable is rainfall (RF) in mm.

§ RDF, recommended dose of fertilizer; FYM, farmyard manure.

Table 4. Change in bulk density (Mg m^{-3}) in the experimental plot after 21 yr cropping, fertilization and manuring(± standard deviation from mean).

Soil depth	Initial (1986)	At the end of experiment (in 2007)						
		Control	100% RDF† (mineral)	50% RDF (mineral)	100% organic (FYM)	50% RDF+ 50%(foliar)	50% organic (FYM)+ 50%RDF	Farmers practice
cm								
0–20	1.49 ± 0.08	1.52 ± 0.09^{Aa}‡	1.51 ± 0.09^{Ba}	1.51 ± 0.09^{Ba}	1.46 ± 0.07^{Dd}	1.50 ± 0.08^{Cb}	1.47 ± 0.07^{Cd}	1.50 ± 0.08^{Cb}
20–40	1.49 ± 0.08	1.50 ± 0.08^{Ac}	1.50 ± 0.08^{Ab}	1.49 ± 0.08^{Bb}	1.47 ± 0.08^{Dc}	1.49 ± 0.08^{Bc}	1.48 ± 0.09^{Cc}	1.49 ± 0.08^{Bc}
40–60	1.47 ± 0.07	1.47 ± 0.07^{Be}	1.48 ± 0.07^{Ad}	1.48 ± 0.07^{Ac}	1.46 ± 0.07^{Cd}	1.47 ± 0.07^{Bd}	1.47 ± 0.07^{Bd}	1.47 ± 0.07^{Bd}
60–80	1.49 ± 0.08	1.49 ± 0.08^{Ad}	1.49 ± 0.08^{Ac}	1.49 ± 0.08^{Ab}	1.49 ± 0.08^{Ab}	1.49 ± 0.08^{Ac}	1.49 ± 0.07^{Ab}	1.49 ± 0.08^{Ac}
80–100	1.51 ± 0.09	1.51 ± 0.09^{Ab}	1.51 ± 0.10^{Aa}	1.51 ± 0.10^{Aa}	1.51 ± 0.10^{Aa}	1.51 ± 0.09^{Aa}	1.51 ± 0.10^{Aa}	1.51 ± 0.09^{Aa}

† RDF, recommended dose of fertilizer; FYM, farmyard manure.

‡ Different capital letters within rows and different small letters within columns are significantly different at $P = 0.05$ according to Duncan Multiple Range Test (DMRT) for separation of means.

root biomass (Halvorson et al., 1999), which resulted in better soil aggregation and thus aeration.

Depth Distribution of Organic Carbon

The SOC concentration of the soil profile was low in all systems, but differed significantly ($P < 0.05$) among treatments and depths (Table 5). Cultivation of the crop without any fertilizer or manuring over the years significantly decreased the SOC concentration, and the decrease was most prominent in the 0- to 0.2-m and 0.2- to 0.4-m depths. In contrast, there was a significant increase in SOC concentration with the application of FYM even in the subsoil layers. In the 0- to 0.2-m depth, the SOC concentration was the highest (3.4 g kg^{-1}) in the100% organic (FYM) followed by that in the50% organic (FYM)+50% RDF (3.1 g kg^{-1}) treatment. There was also an increase in the mean profile SOC concentration in the balanced fertilizer (NPK) use with the RDF (1.4 g kg^{-1}) or 50% of RDF (1.3 g kg^{-1}) compared with the control (1.2 g kg^{-1}). The mean SOC concentration in the profile increased from 1.2 g kg^{-1} in the control to 1.9 g kg^{-1} in 100% organic (FYM). In general, use of FYM and compost enhances the SOC concentration more than application of the same amount of nutrients through mineral fertilizers (Gregorich et al., 2001).There was a negative correlation between SOC concentration and the BD in the surface 0.2 m layer (Fig. 2), similar to the relationship reported by Du et al. (2009).

Profile Soil Organic Carbon Stock, Carbon Restoration, Stabilization, and Sequestration

The SOC stock (Mg C ha^{-1} to 1-m depth) in 2007 differed significantly ($P < 0.05$) among treatments (Table 6), and was in the order 100% organic (FYM) (27.5) > 50% organic (FYM)+50% RDF (24.0) > 100% RDF (mineral) (20.5) > 50% RDF+50% (foliar) (19.2) = 50% RDF (mineral) (19.0) = farmer's practice (18.7) > control (17.8 Mg C ha^{-1}). In comparison with the control, % increase in SOC stock was in the order 100% organic (FYM) treatment (55.0) > 50% organic (FYM)+50% RDF (35.2) > 100% RDF (mineral) (15.3).This trend was reflected in the profile SOC stock of the respective treatments. The mean rate of change in SOC stock followed a trend similar to that of SOC stock (Table 6). The SOC stock declined in all but two treatments (100% FYM, 50% FYM + 50% RDF). The mean rate of SOC sequestration in two treatments which enhanced SOC stock over 21 yr was 0.32 Mg ha^{-1} yr^{-1} for 100% FYM and 0.15 Mg ha^{-1} yr^{-1} for 50% FYM + 50% RDF. The results of the present study show that 13.4% C applied as FYM was stabilized in SOC stock. Majumder et al. (2008) reported 67.9% of C stabilization from FYM applied in a rice–wheat system in the lower Indo-Gangetic plains. In comparison with the present data, the higher value of C stabilization from FYM reported by Majumder et al. (2008) might be due to the higher annual rainfall (approximately 1400 mm) in the lower Gangetic alluvium, where soils are comparatively fertile with high initial

Table 5. Changes in soil organic carbon (SOC) (g kg^{-1}) concentration in soil after 21 yr of cropping with soil amendments (± standard deviation from mean).

Soil depth	Initial (1986)	At the end of experiment (in 2007)							
		Control	100% RDF† (mineral)	50% RDF (mineral)	100% organic (FYM)	50% RDF+ 50%(foliar)	50% organic (FYM)+ 50%RDF	Farmers practice	Mean
cm									
0–20	2.6 ± 0.16	2.1 ± 0.13^{Fa}‡	2.7 ± 0.17^{Ca}	2.3 ± 0.15^{Ea}	3.4 ± 0.21^{Aa}	2.4 ± 0.16^{Da}	3.1 ± 0.19^{Ba}	2.3 ± 0.14^{Ea}	2.6 ± 0.16^{a}
20–40	1.2 ± 0.07	1.0 ± 0.06^{Eb}	1.2 ± 0.07^{Cb}	1.1 ± 0.07^{Db}	1.6 ± 0.10^{Ab}	1.2 ± 0.07^{Cb}	1.5 ± 0.09^{Bb}	1.1 ± 0.06^{Db}	1.3 ± 0.07^{b}
40–60	1.0 ± 0.06	1.0 ± 0.06^{Db}	1.1 ± 0.07^{Cc}	1.1 ± 0.07^{Cb}	1.4 ± 0.09^{Ad}	1.0 ± 0.07^{Dc}	1.3 ± 0.08^{Bc}	1.0 ± 0.06^{Dc}	1.1 ± 0.07^{c}
60–80	1.1 ± 0.07	0.9 ± 0.05^{Dc}	0.9 ± 0.07^{Dd}	1.0 ± 0.07^{Cc}	1.5 ± 0.09^{Ac}	0.9 ± 0.07^{Dd}	1.2 ± 0.08^{Bd}	0.9 ± 0.05^{Dd}	1.0 ± 0.07^{d}
80–100	1.1 ± 0.07	0.9 ± 0.05^{Cc}	0.9 ± 0.08^{Cd}	0.9 ± 0.07^{Cd}	1.4 ± 0.09^{Ad}	0.9 ± 0.07^{Cd}	1.0 ± 0.07^{Be}	0.9 ± 0.05^{Cd}	1.0 ± 0.07^{d}
Mean	1.4 ± 0.09	1.2 ± 0.07^{E}	1.4 ± 0.09^{C}	1.3 ± 0.09^{D}	1.9 ± 0.11^{A}	1.3 ± 0.09^{D}	1.6 ± 0.10^{B}	1.2 ± 0.07^{E}	

† RDF, recommended dose of fertilizer; FYM, farmyard manure.

‡ Different capital letters within rows and different small letters within columns are significantly different at $P = 0.05$ according to Duncan Multiple Range Test (DMRT) for separation of means.

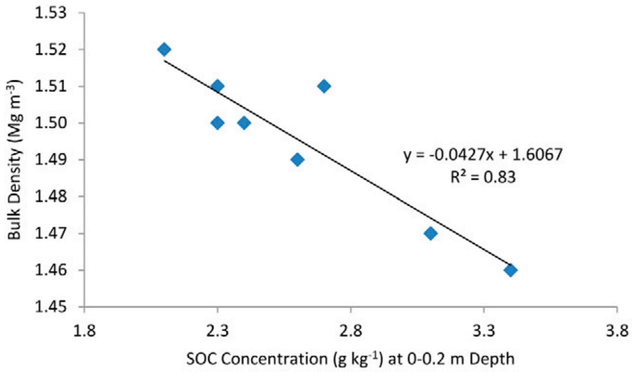

Fig. 2. Influence of soil organic carbon (SOC) concentration on bulk density of soils after 21 yr cropping, fertilization, and manuring in Inceptisols of Indo-Gangetic Plain.

SOC (8.8 g kg^{-1}) concentration. In all non-FYM treatments, the SOC stock declined at a rate ranging from 0.4 Mg ha^{-1} (in 100% RDF) to 3.1 Mg ha^{-1} (in control). Higher SOC sequestration was observed with the application of FYM equivalent to 60 kg N ha^{-1} (6.6 Mg C ha^{-1}) followed by 50% organic (FYM)+50% RDF (3.1 Mg C ha^{-1}). However, application of mineral fertilizer at the RDF was not adequate to curtail depletion of the SOC stock. Crop cultivation without use of organic and/or mineral fertilizer amendments (control) depleted the SOC stock by 3.1 Mg C ha^{-1}. In contrast, the magnitude of SOC depletion was comparatively lower in the 50% RDF and 50% RDF+50% (foliar) treatments. Regardless of the cropping system, maintaining SOM above the critical level is necessary to sustaining agronomic productivity and reducing risks of soil degradation. Thus, there was a positive relationship between SOC stock in the root zone and the grain yield of rice (159 kg ha^{-1} yr^{-1} Mg^{-1} of SOC) and lentil (184 kg ha^{-1} yr^{-1} Mg^{-1} of SOC).Similarly, there was a positive relationship between SOC stock to 1-m depth and the grain yield of rice (74 kg ha^{-1} yr^{-1} Mg^{-1} of SOC) and lentil (91 kg ha^{-1} yr^{-1} Mg^{-1} of SOC).The attendant improvement in soil quality with increasing in SOC stock has a strong positive impact on agronomic productivity and world food security. An increase in the SOC stock within the root zone by 1 Mg C ha^{-1} yr^{-1} can enhance food production in developing countries by 30 to 50 Mg yr^{-1} including 24 to 40 Mg yr^{-1} of cereal and legumes, and 6 to 10 Mg yr^{-1} of roots and tubers (Lal et al., 2007).The prevailing low levels of SOC concentrations are attributed to soil-mining practices: little or no crop residues returned to the soil, excessive tillage, imbalance in fertilizer use and severe soil degradation (Lal et al., 2007).

Higher biomass and C input through application of 60 kg N ha^{-1}, FYM, and conjunctive use of organic and mineral fertilizers may be due to increased availability of deficient nutrients such as N, P, K, Ca, Mg, S, Zn, and B with organic manure (Srinivasarao and Vittal, 2007). Annual application of biomass C through crop residues and FYM significantly enhanced SOC stock. A linear relationship (y = 6.340x+10.04, $R^2 = 0.58$, $P < 0.01$) was observed between SOC and the annual inputs of C as crop residues in different treatments, indicating the latter's influence on SOC stock (Fig. 3). Though application of FYM decreased soil BD (Fig. 2) because of increase in the SOC concentration and root biomass (Halvorson et al., 1999), yet it significantly increased the SOC stock in the profile. The SOC stock of the profile was positively correlated with the input of crop residues ($R^2 = 0.58^*$; $P < 0.05$), and external (organic materials) ($R^2 = 0.94^{***}$; $P < 0.001$) and total C inputs ($R^2 = 0.99^{***}$; $P < 0.001$) (Fig. 4). The higher C retention and stock in the FYM-amended plots was probably because of the partial decomposition of the labile fraction (Paustian et al., 1992).A significant relationship between the crop residue C, external C, and the total C input with the total SOC stock in the profile, indicated that the C input positively influences SOC stock (Fig. 4). A significant improvement in SOC, after 10 yr of the incorporation of a cover crop [horsegram, *Macrotyloma uniflorum* (Lam.) Verdc.] biomass grown with off-season rainfall in a rainfed Alfisol under semiarid tropical conditions was reported by Venkateswarlu et al. (2007). However, the availability of adequate quantities of organic amendments under such conditions is a major constraint because of a lower biomass production, the competing use of dung as a fuel, and use of crop residues for animal feed and other uses.

Relationship among Carbon Inputs and Sequestrated Carbon with Yield Sustainability

The SYI of the crop was in accord with an increase in the SOC stock. Thus, a significant relationship was observed

Table 6. Profile soil organic carbon (SOC), C restoration, C restoration rate, and C sequestered in soil profile as affected by 21 yr of cropping and fertilization under subhumid tropical conditions (± standard deviation from mean).

Treatment	SOC stock		Δ SOC Stock in 21 yr		SOC sequestration in 21 yr	Mean of C sequestration rate
	1986	2007	Total percent	Mean rate		
	Mg ha^{-1}		%	kg C ha^{-1}yr^{-1}	Mg ha^{-1}	kg ha^{-1}yr^{-1}
Control	20.9 ± 1.6	17.8 ± 1.2^{E}†	–	–	–3.1 ± 0.28^{F}	–150 ± 10^{F}
100% RDF‡ (mineral)		20.5 ± 1.5^{C}	15.3 ± 1.1^{C}	129 ± 0.011^{C}	–0.4 ± 0.04^{C}	–20 ± 2^{C}
50% RDF (mineral)		19.0 ± 1.3^{D}	6.8 ± 0.6^{D}	57 ± 0.005^{D}	–1.9 ± 0.17^{D}	–90 ± 7^{D}
100% organic (FYM)		27.5 ± 1.9^{A}	55.0 ± 3.9^{A}	462 ± 0.039^{A}	6.6 ± 0.59^{A}	320 ± 20^{A}
50% RDF+50% (foliar)		19.2 ± 1.3^{D}	8.1 ± 0.6^{D}	67 ± 0.006^{D}	–1.7 ± 0.16^{D}	–80 ± 9^{D}
50% organic (FYM)+50% RDF		24.0 ± 1.7^{B}	35.2 ± 2.5^{B}	245 ± 0.024^{B}	3.1 ± 0.27^{B}	150 ± 10^{B}
Farmer's practice		18.7 ± 1.3^{D}	5.2 ± 0.4^{E}	43 ± 0.005^{E}	–2.2 ± 0.20^{E}	–110 ± 9^{E}

† Different letters within columns are significantly different at $P = 0.05$ according to Duncan Multiple Range Test (DMRT) for separation of means.
‡ RDF, recommended dose of fertilizer; FYM, farmyard manure.

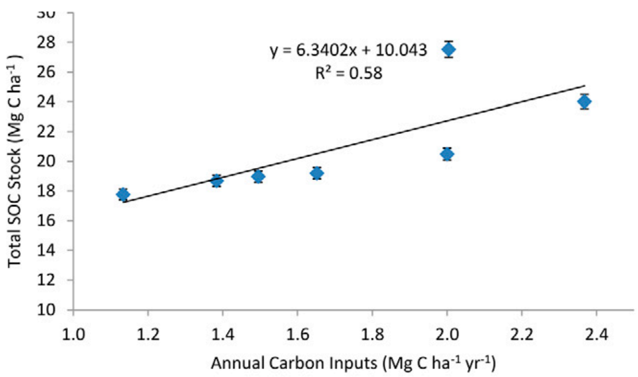

Fig. 3. Crop residue C inputs influence soil organic carbon (SOC; error bars represents the standard error of mean, *P* < 0.05).

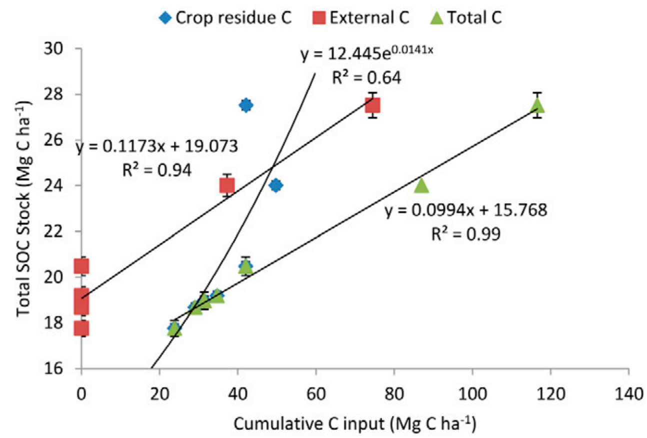

Fig. 4. Influence of cumulative C input through (a) crop residue, (b) external C (organics) and (c) total C on total soil organic C stock(error bars represents the standard error of mean, *P* < 0.05).

between SYI and annual crop residue C input (R^2 = 0.97–0.99*, P < 0.01), total cumulative C input (R^2 = 0.63–0.68*, P < 0.05), C restored (R^2 = 0.65–0.69*, P < 0.05), profile SOC stock (R^2 = 0.65–0.69*, P < 0.05), and total SOC sequestrated (R^2 = 0.65–0.69*, P < 0.05) (Table 7). These data indicate that maintenance of SOC concentration through regular organic or mineral inputs determines the sustainability of rainfed production systems. The improvement in SOC stock is also related to an enhanced water holding capacity of the soil profile (Du et al., 2009) which mitigates intermittent droughts, a major constraint in dryland agriculture.

Carbon Sequestration and Derivation of Critical Carbon Inputs

The cultivation of rice–lentil sequence over 21 yr in Inceptisols under subhumid tropical conditions without using any organic amendment and/or mineral fertilizers (control) caused a net depletion of the SOC stock, with a cumulative mean depletion of 3.1 Mg C ha^{-1}. However, addition of FYM, either alone or in combination with mineral fertilizers, significantly increased the SOC stock. In a similar study, the carbon sequestration potential (CSP), defined as the rate of increase in the SOC stock over the antecedent stock (1986) in the 0- to 0.2-m depth, ranged from –0.178 Mg C $ha^{-1}yr^{-1}$ (unfertilized control) to 0.572 Mg C $ha^{-1}yr^{-1}$ (50% RDF+ 4 Mg groundnut shells ha^{-1}) (Bhattacharyya et al., 2009). Globally, rates of C sequestration by different types of management range from 0.11 to 3.04 Mg C ha^{-1} yr^{-1}, with a mean of 0.54 Mg C $ha^{-1}yr^{-1}$, and are highly influenced by biome type and climate (Conant et al., 2001). In our study, the positive linear relationship between the changes in SOC stock and the total cumulative C inputs to the soils (external organics plus crop residue) over the years (Y = 0.099X – 5.131; R^2 = 0.99***, P < 0.001) (Fig. 5) was highly significant and indicates that even after 21 yr of C input, ranging from 1.13 to 5.55 Mg C $ha^{-1}yr^{-1}$, the unsaturated C sink capacity is not filled. Therefore, these soils have a high C sink capacity. However, sink capacity and/or storage rate cannot continue indefinitely (Six et al., 2002). Each soil with a different C loading may reach a new steady state of SOC stock over time. Assessment of SOC stock for these treatments at periodic, perhaps decadal, intervals may provide insights into the strategies of C management in these soils. Lal et al. (2007) estimated that the rate of SOC sequestration in the United States, ranging from 100 to 1000 kg ha^{-1} yr^{-1}, depends on climate, soil type, and site-specific management. The global potential of SOC sequestration and restoration of degraded/desertified soils is estimated at 0.6 to 1.2 Pg C yr^{-1} for about 50 yr with a cumulative sink capacity of 30 to 60 Pg (Lal, 2003; Lal et al., 2007), comprising 0.4 to 0.8 Pg C yr^{-1} through adoption of recommended management practices (RMP) on cropland (1350 Mha), and 0.01 to 0.03 Pg C yr^{-1} on irrigated soils (275 Mha), and 0.01 to 0.3 Pg C yr^{-1} through improvements of rangelands and grasslands (3700 Mha).The slope of the linear function (Fig. 5) represents the net loss of SOC without the addition of C inputs, which is about ~0.1 Mg in this rice–lentil system. These values are lower than those reported by Rasmussen and Collins (1991) (14.0–21.0%) from temperate regions of United States and Canada, and those from the humid Indo-Gangetic plains of India (14%) under irrigated rice–wheat system (Majumder et al., 2008), but higher than those reported by Kong et al. (2005) (7.6%) under the Mediterranean climate,

Table 7. Relationships of C input, C buildup, profile soil organic carbon (SOC) and C sequestration with sustainable yield index (SYI) in 21-yr-old long-term experiment.

Parameters		Regression equation	R^2
Annual crop residue C input (X)	SYI (Y)	Y_{rice} = 0.09X**+0.07	0.99
		Y_{lentil} = 0.14X**–0.03	0.97
Total cumulative C input (X)		Y_{rice} = 0.001X*+0.18	0.62
		Y_{lentil} = 0.001X*+0.13	0.68
C buildup % (X)		Y_{rice} = 0.002X*+0.20	0.65
		Y_{lentil} = 0.003X*+0.16	0.69
Profile SOC (X)		Y_{rice} = 0.01X*+0.04	0.65
		Y_{lentil} = 0.01X*–0.09	0.69
C sequestrated (X)		Y_{rice} = 0.01X* +0.22	0.65
		Y_{lentil} = 0.02X*+0.19	0.69

* Significance at P < 0.05 level.

** Significance at P < 0.01 level.

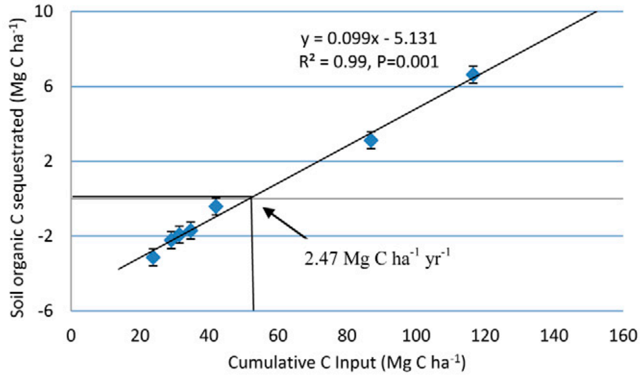

Fig. 5. The magnitude of critical C input and its influence on soil organic carbon (SOC) sequestration (error bars represents the standard error of mean for sequestrated C).

for a rice–wheat–jute (*Corchorus capsularis* L.) system of 5% to 6 to 4% in subtropical regions (Majumder et al., 2007; Mandal et al., 2007).The present study also shows that maintaining a constant level of SOC stock (zero change) requires C input of 2.47 Mg C ha^{-1}yr^{-1} for these Inceptisols under a rainfed rice-based system. This rate of C input is lower than those reported by Kong et al. (2005) (3.1 Mg ha^{-1} yr^{-1}) for Davis, CA, and 4.59 Mg ha^{-1} yr^{-1} by Majumder et al. (2007) for rice–wheat–jute system, 3.56 Mg ha^{-1} yr^{-1}(Majumder et al., 2008) for irrigated rice–wheat systems of the Indo-Gangetic Plains, and 2.92 Mg ha^{-1} yr^{-1} by Mandal et al. (2007) for rice-based system in subtropical India. To achieve a similar quantity of C (2.47 Mg ha^{-1} yr^{-1}) purely through cropping, 7.1 Mg of biomass is required to be produced every year vs. the average rice and lentil yield of 1.6 and 0.7 Mg ha^{-1}, respectively under these rainfed conditions. The lower input of C needed to maintain a constant level in this study may be due to lower initial SOC levels (1.4 g kg^{-1} soil) (Srinivasarao et al., 2006). In the studies referred to above, the initial SOC concentrations were approximately three to six times higher (>6–15 g kg^{-1} soil) than those in the present study.

CONCLUSIONS

Results of this 21 yr long experiment suggest that C input along with mineral fertilizers is essential to improving soil health in the subhumid tropics of India, and to curtail the depletion of SOC stocks under continuous cropping. Even the fertilizer rate applied, which was the recommended rate for the state, apparently was not sufficient to meet the crop nutrient requirements which could potentially limit the rice and lentil crop yields and in consequence, the input of C through the crop residues. Higher SYI of rice and lentil was obtained with the conjunctive use of FYM and mineral fertilizers. A critical biomass C input of 2.47 Mg C ha^{-1}yr^{-1}was needed to maintain SOC at equilibrium (with no change). Available research data on SOC under rice-based systems in the Indo-Gangetic Plains are confined to irrigated lowland paddy system. This report quantifies the critical level of C required to maintain SOC stock in upland rice-based systems involving a cereal–legume sequence in tropical subhumid degraded Inceptisols with low antecedent SOC stocks. In view of the decreasing availability of FYM, however, application of 10.7 Mg ha^{-1} of FYM (equivalent to 60 kg N) on dry weight basis is difficult. Thus, conjunctive use of FYM or other crop residues along with 50% recommended dose of fertilizers, is a viable option for curbing SOC depletion and sustaining crop production.

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