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Critical carbon inputs to maintain soil organic carbon stocks under long-term finger-millet (*Eleusine coracana* [L.] Gaertn.) cropping on Alfisols in semiarid tropical India

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Abstract

Enrichment of soil organic carbon (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 while also improving crop productivity and sustainability. In a long-term fertility experiment carried out over 27 y under semiarid climatic condition, we evaluated the impact of crop-residue C inputs through rainfed fingermillet (*Eleusine coracana* [L.] Gaertn.) cropping, fertilization, and manuring on crop yield sustainability and SOC sequestration in a Alfisol soil profile up to a depth of 1 m and also derived the critical value of C inputs for maintenance of SOC. Five treatments, viz., control, farmyard manure (FYM) 10 Mg ha^{-1}, recommended dose of NPK (50 : 50 : 25 kg N, P_2O_5, K_2O ha^{-1}), FYM 10 Mg ha^{-1} + 50% recommended dose of NPK, and FYM 10 Mg ha^{-1} + 100% recommended dose of NPK imposed in a randomized block design replicated four times. Application of FYM alone or together with mineral fertilizer resulted in a higher C input and consequently built up a higher C stock. After 27 y, higher profile SOC stock (85.7 Mg ha^{-1}), C build up (35.0%), and C sequestration (15.4 Mg C ha^{-1}) was observed with the application of 10 Mg FYM ha^{-1} along with recommended dose of mineral fertilizer and these were positively correlated with cumulative C input and well reflected in sustainable yield index (SYI). For sustenance of SOC level (zero change due to cropping) a minimum quantity of 1.13 Mg C is required to be added per hectare per annum as inputs. While the control lost C, the application of mineral fertilizer served to maintain the priori C stock. Thus, the application of FYM increased the C stock, an effect which was even enhanced by additional amendment of mineral fertilizer. We conclude that organic amendments contribute to C sequestration counteracting climate change and at the same time improve soil fertility in the semiarid regions of India resulting in higher and more stable yields.

Key words: carbon inputs / carbon sequestration / sustainable yield index / fingermillet / semiarid tropics

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1 Introduction

To counter the adverse effects of climate change and global warming is an urgent need especially in view of the targets set by India for the reduction of CO_2 emissions of its gross domestic product by 20%–25% by 2020, below 2005 levels. In the light of this, the endeavor to enrich soil organic C (SOC) stocks by sequestering atmospheric carbon is crucial and so too is the need to understand soil health and crop productivity under different management strategies. Optimum levels of SOC can be managed through the adoption of appropriate crop rotation (*Wright* and *Hons*, 2005), fertility management, using inorganic fertilizers and organic amendments (*Schuman* et al., 2002; *Mandal* et al., 2007; *Majumder* et al., 2008), and tillage methods (*Lal*, 2009). Soils in rain-deficit environments of the tropical, subtropical regions are inherently low in SOC, and agronomic yield is related to soil quality. Therefore, reversing the declining trend of SOC stock is essential to enhancing agronomic productivity through balanced application of plant nutrients. Crop cultivation adversely affects the distribution and stability of soil aggregates and reduces SOC stock in soils (*Kong* et al., 2005). The magnitude of reduction in SOC due to cropping, however, varies depending upon the climatic conditions and intensity of cropping (*Lal*, 2004, 2010). The rate of decomposition/mineralization of SOC stock is generally higher in the tropics than in temperate regions (*Jenkinson* and *Ayanaba*, 1977). Nonetheless, crop species also play an important role in maintaining SOC stock through differences in quality and quantity of the residues returned which determine the mean residence time (MRT) of SOC (*Mandal* et al., 2007). Once the pathways of C sequestration in soils are identified, suitable agricultural strategies may be developed that have the potential to improve SOC stocks and thus attenuate CO_2 loading

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into the atmosphere and curb global warming (*Lal*, 2009). Most of the research so far on C sequestration in agricultural soils is confined to temperate regions while little information is available from tropical and subtropical countries including India (*Velayutham* et al., 2000; *Lal*, 2004, 2010). In India, C sequestration was up to now only studied under irrigation. There has been no study on semiarid rainfed conditions, moreover most of the crop-management impact studies on soil carbon sequestration are limited to only surface (0.15 m) or root zone (*Paustian* et al., 1997).

Rainfed croplands cover 1.132 billion ha and meet ≈ 60% of the food and nutritional needs of the world's population (*Biradar* et al., 2009). Rainfed agro-ecosystems occupy a considerable place in India's agriculture, covering 80 million ha, in arid, semiarid, and subhumid climatic zones; constituting nearly 57% of the net cultivated area. Alfisols which occur mainly in S India, and represent ≈ 30% of the rainfed regions (*Virmani* et al., 1991), support only a single rainy-season cropping (*kharif*) with productivity levels of 0.7 to 0.8 t ha^{-1} under semiarid conditions. In India, soils under rainfed agriculture are categorized by low SOC and N concentrations in most agro-ecoregions. The data on SOC concentrations determined in 21 locations in 1.05 m deep profile across rainfed regions of India, covering eight production systems, showed that these soils are low in concentration (< 5 g kg^{-1}) and stocks (20 to 97 Mg ha^{-1}) (*Srinivasarao* et al., 2009). Maintaining soil and crop productivity in the long term under continuous monocropping is the major challenge in rainfed regions of S India. Low crop yields, low or no biomass residue, coupled with long fallow periods which extend up to 7 months in the year, result in adverse environments that do not sustain SOC levels. However, the magnitude of decline or enhancement of SOC due to continuous cultivation depends on the balance between the loss of C by oxidative forces during tillage, the quantity and quality of crop residues that are returned, and the organic amendments added to the soils. Therefore, crop- and soil-management practices have to be tailored to ensure long-term crop/cropping systems. The use of plant nutrients, organic amendments, and the inclusion and cultivation of legumes support SOC and its sustainability. Organic crop residues are used for many purposes in India, and therefore not always available for agriculture due to competing alternate uses. Fingermillet (*Eleusine coracana* [L.] Gaertn.) is the most important small millet in the tropics (12% of global millet area) and cultivated in more than 25 countries in Africa and Asia, predominantly as a staple food grain. Fingermillet has high yield potential (>10 Mg ha^{-1} under optimum-irrigated condition). In India, it is cultivated on 1.8 m ha, with average yields of 1.3 Mg ha^{-1} (*FAO*, 2009). Major fingermillet growing area is confined to S India.

In the present study, in the semiarid, tropical conditions of S India, a fingermillet production system was observed; the effect of 27 y of chemical fertilization and the use of FYM on SOC sequestration in Alfisols were investigated; and the relationship between C sequestration and sustainable yield index were evaluated in long-term manurial trials and also requirement of critical C inputs for zero change in C levels were calculated.

2 Materials and methods

2.1 Site description

A long-term field experiment with fingermillet monocropping on an Alfisol located at the Agricultural Research Station, University of Agricultural Sciences, GKVK campus, Bengaluru, Karnataka, India (77°11′ E, 12°46′ N, 810 m MSL) was initiated in the rainy season of 1978. This field experiment was conducted under the aegis of the All India Coordinated Research Project on Dryland Agriculture (AICRPDA). During the period of the experiment (1978–2004), the mean maximum and minimum annual air temperature was 27.8°C and 19.3°C, respectively, and the mean annual precipitation during the 27 y was 768 mm (SD = 230; CV = 24.8%), of which 62% of the rainfall (SD = 169; CV = 31.9%) was during the rainy season (June–September). Annual rainfall as well as crop-season rainfall during 27 y experimental period is depicted in Fig. 1. Length of growing period is 120–150 d.

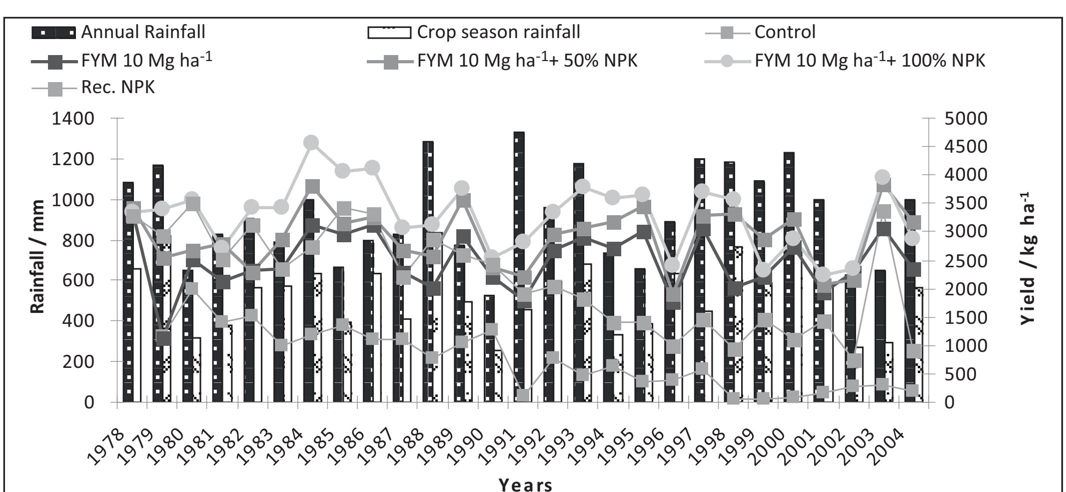

Figure 1: Mean annual and seasonal rainfall in relation to grain yields of fingermillet across the treatments during 27 y (1978–2004).

According to Köppen's classification experimental location falls under "tropical savanna climate".

The experimental soil was sandy loam in texture. At the beginning of the experiment, soil was acidic in reaction (pH 5.1 ± 0.2) with a low profile organic C ([4.6 ± 0.2] g [kg soil]$^{-1}$), medium available N ([302 ± 10.1] kg ha^{-1}), P ([19 ± 0.9] kg ha^{-1}), and K ([179 ± 10.2] kg ha^{-1}) contents, with a sand, silt, and clay content of (68.0 ± 1.9)%, (4.0 ± 0.2)%, and (28.0 ± 1.1)%, respectively, inorganic C (0.5 ± 0.03) g (kg soil)$^{-1}$, and cation-exchange capacity (4.8 ± 0.3) cmol (P^+) kg^{-1}. Soil is classified as fine, kaolinitic, isohyperthermic, Typic Kandiustalf.

2.2 Treatments and crop management

Fingermillet (variety: PR 202) was grown every year in the rainy season (June–October) during the 27 y period (1978–2004). Tillage consisted of plowing to an average depth of 0.15–0.20 m soon after rainfall in June, followed by blade harrowing. The experiment was laid out in a randomized block design with the following treatments:

(1) T_1 = control (no N-P-K fertilizers or organic amendments)

(2) T_2 = FYM 10 Mg ha^{-1}

(3) T_3 = FYM 10 Mg ha^{-1} + 50% NPK

(4) T_4 = FYM 10 Mg ha^{-1} + 100% NPK

(5) T_5 = recommended dose of NPK (50:50:25 kg N, P_2O_5, K_2O ha^{-1})

Each treatment was replicated four times. Farmyard manure which was decomposed well was spread manually and uniformly on the surface of the specified plots (13 m × 7 m) on a wet-weight basis and mixed thoroughly with the soil using a power tiller. Based on the analysis of every third year, FYM had 390 g moisture kg^{-1}. The C content and C : N ratio of the applied FYM was 332 g kg^{-1} and 58, respectively. Nitrogen, P, and K were applied as urea, di-NH_4-phosphate, and muriate of potash (KCl), respectively. The fertilizer was broadcast and mixed with soil before sowing. Manual weeding was done as an intercultural operation. Row-to-row 30 cm spacing was maintained. Fingermillet was harvested manually just above the ground in the first week of October using sickles and the biomass that was above the ground was removed from the field. Grain and stover yields of the fingermillet crop were recorded every year.

2.3 Soil sampling and analysis

From each of the 27-y-old experimental plots in each replication, three representative field-moist soil samples were collected with a tube auger at 0.2 m increments down to a depth of 1 m during February 2005. They were pooled together to make a composite sample for each depth and replication. Additionally, three samples were taken from all five depths using a core sampler (∅ 0.05 m, length 0.08 m) to measure the bulk density of the soil, following the method described by *Blake* and *Hartge* (1986).

The other soil properties viz., pH (1 : 2 soil-to-water extractant), $CaCO_3$ (titrimetrically by digesting with dilute HCl), and CEC (through Na^+ ion replacement) were done as per standard procedures (*Jackson*, 1973). Soil texture was determined by Bouyoucos hydrometer method (*Bouyoucos*, 1927). Soil samples were also analyzed for available N by alkaline permanganate method (*Subbiah* and *Asija*, 1956), P extracted by NH_4 fluoride (*Bray* and *Kurtz*, 1945), K by neutral 1 N NH_4 acetate method (*Hanway* and *Heidel*, 1952). All determinations were performed three times, and the results expressed are on the basis of the oven-dry weight of soil.

2.4 Total organic C

The soil samples were air-dried, powdered, and passed through a 2.0 mm sieve followed by 0.2 mm sieve, while the organic materials (FYM, leaf, stubbles, and roots) were oven-dried and finely ground in a mechanical grinder following the method described by *Nelson* and *Sommers* (1982). They were analyzed for C by a LECO CHN analyzer. Soil samples were also analyzed for inorganic C titrimetrically, by digesting them with dilute HCl, following the method of *Bundy* and *Bremner* (1972). The SOC concentrations of the soil samples were obtained from Eq. 1:

$$\textit{SOC concentration} = \textit{Total C} - \textit{Inorganic C} \quad (1)$$

2.5 Total organic C stock

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 = LECO C-HCl C) by the bulk density (Mg m^{-3}) and depth (m), and by 10.

2.6 Carbon inputs through plant and manure

Based on biomass yield of fingermillet, annual C inputs to the soil through stubbles, roots, and rhizodeposition were computed. Fingermillet stubbles constituted (4.8 ± 0.22)%, (5.1 ± 0.23)%, (5.2 ± 0.24)%, (5.5 ± 0.25)%, and (5.0 ± 0.23)% of the stover yield of fingermillet in the plots under control, FYM 10 Mg ha^{-1}, FYM 10 Mg ha^{-1} + 50% NPK, FYM 10 Mg ha^{-1} + 100% NPK, and recommended NPK, respectively. The root biomass was calculated using the root-to-shoot biomass ratios recorded from the experiment. Root biomass was measured immediately after harvesting the crop, following the core-sampling procedure as described by *Franzluebbers* et al. (1999). It was estimated that the root biomass represented (28.6 ± 1.5)%, (26.5 ± 1.4)%, (25.6 ± 1.3)%, (24.7 ± 1.3)%, and (27.1 ± 1.4)% of the stover biomass in the plots in the treatments listed above, respectively. Rhizodeposition of C from root turnover and exudates was assumed to be 1.4 times of the root C of fingermillet (*Shamoot* et al., 1968). Stubbles and roots contain 419 and 394 g kg^{-1} C, respectively. During the growth of the crop, weeds were either removed or killed with herbicides and so 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, as well as C inputs through organic amendments put into the soil, have been presented in Tab. 1.

2.7 Calculations for C budgeting

Carbon budgeting has been calculated using Eqs. 2 to 5.

$$C\ build\text{-}up\ /\ \% = \frac{C_{fert+org} \text{ or } C_{fert} - C_{cont}}{C_{cont}} \cdot 100, \quad (2)$$

where $C_{fert+org}$ represents profile SOC stock in fertilizer NPK + FYM treatments and C_{fert} and C_{cont} are the profile SOC stocks in fertilizer NPK and control treatments, respectively;

$$C\ build\text{-}up\ rate\ /\ \text{Mg C ha}^{-1}\text{y}^{-1} = \frac{C_{fert+org} \text{ or } C_{fert} - C_{cont}}{\text{Years of experimentation}} \cdot 100, \quad (3)$$

$$C\ stabilization\ /\ \% = \frac{C_{fert+org} - C_{fert}}{C_{FYM}} \cdot 100, \quad (4)$$

where C_{FYM} represent input of C applied through FYM;

$$C\ sequestered\ /\ \text{Mg C ha}^{-1} = SOC_f - SOC_i, \quad (5)$$

where SOC_f and SOC_i indicate the SOC stocks in 2005 (current) and that at the initiation of the long-term experiment (in 1978). Positive and negative values indicate SOC gains and losses, respectively.

2.8 Sustainable yield index (SYI)

The total fingermillet crop productivity was calculated through a sustainable yield index using yield data of 27 y. This was done to offset annual variations in the yield, and to highlight the performance of the treatments, during the entire experimental period. The sustainable yield index is defined as

$$SYI = \frac{Y - \sigma}{Y_{\max}},$$

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).

2.9 Statistical analysis

Statistical analysis was performed using the Windows-based SPSS program (Version 11.0, SPSS, Chicago, IL; *SPSS*; 2001). The SPSS procedure was used to analyze variance and to determine the statistical significance of treatment effects. The Duncan multiple-range test was used to compare treatment means. Simple correlation coefficients and regression equations were also developed to evaluate the relationships among the response variables (sustainable yield index [SYI], C inputs, profile SOC, C build-up, and C sequestration) using the same statistical package. The 95% probability level is regarded as significant, statistically.

3 Results

3.1 Carbon-input levels, yield, and sustainability

As estimates of component-wise (stubble, root, and rhizodeposition) as well as external input through FYM annual cumulative C inputs into soil under different treatments during the 27 y of continuous cropping are given in Tab. 1. The highest mean annual C inputs through crop residues and FYM were added in FYM 10 Mg ha^{-1} + 100% NPK, followed by FYM 10 Mg ha^{-1} + 50% NPK, FYM 10 Mg ha^{-1}, and the lowest was in control. Fertilization through balanced NPK or FYM or their combined use produced higher biomass and subsequently higher C input in terms of crop residue (0.79–1.08 Mg C ha^{-1} y^{-1}) compared to control.

Grain yield of fingermillet increased significantly over control ($p < 0.05$) with different fertilizer and manurial treatments. Mean grain yield of fingermillet (Fig. 1) during 27 y of cropping, showed that during the initial 2–3 y, there was not much differences in yield between chemical fertilization and integrated use of chemical fertilizer and organic manure, but in subsequent years consistently higher yields were obtained with the use of organic manure in combination with chemical fertilizer. Higher mean grain yields (3281 kg ha^{-1}) over 27 cropping seasons were obtained through integrated use of recommended dose of fertilizer along with 10 Mg FYM ha^{-1}

Table 1: Mean (1978–2004) annual C input to soil from rainfed fingermillet under different fertilizer and manurial treatments (± standard deviation from mean, n = 4). SYI, sustainable yield index; RD, rhizodeposition; 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.

Treatment	SYI	**Mean annual C input** / Mg ha^{-1}						**Cumulative C input in 27 y** / Mg ha^{-1}		
		stubble	root	RD	total crop-residue C input	C input through FYM	total annual C input	through crop residue	through FYM	total
Control	0.04 ± 0.00^{D}	0.02 ± 0.00	0.13 ± 0.01	0.18 ± 0.01	0.34 ± 0.02^{E}	–	0.34 ± 0.02^{E}	9.2 ± 0.5^{E}	–	9.2 ± 0.5^{E}
FYM 10 Mg ha^{-1}	0.58 ± 0.03^{B}	0.07 ± 0.00	0.35 ± 0.02	0.48 ± 0.03	0.90 ± 0.05^{C}	2.03 ± 0.11	2.92 ± 0.16^{C}	24.3 ± 1.3^{C}	54.7 ± 3.0	79.0 ± 4.4^{C}
FYM 10 Mg ha^{-1} + 50% NPK	0.62 ± 0.03^{A}	0.08 ± 0.00	0.38 ± 0.02	0.53 ± 0.03	1.00 ± 0.06^{B}	2.03 ± 0.12	3.02 ± 0.17^{B}	27.0 ± 1.5^{B}	54.7 ± 3.2	81.7 ± 4.5^{B}
FYM 10 Mg ha^{-1} + 100% NPK	0.59 ± 0.03^{B}	0.10 ± 0.01	0.41 ± 0.02	0.57 ± 0.03	1.08 ± 0.06^{A}	2.03 ± 0.11	3.10 ± 0.17^{A}	29.1 ± 1.6^{A}	54.7 ± 2.8	83.8 ± 4.7^{A}
Rec. NPK	0.36 ± 0.02^{C}	0.06 ± 0.00	0.30 ± 0.02	0.42 ± 0.02	0.79 ± 0.04^{D}	–	0.79 ± 0.04^{D}	21.3 ± 1.2^{D}	-	21.3 ± 1.2^{D}

followed by 2916 kg ha^{-1} with FYM 10 Mg ha^{-1} + 50% NPK. Even with the application of 10 Mg FYM sustained the crop yield, and significantly higher grain yield was obtained compared to sole application of chemical fertilizer or unfertilized control. Under arid and semiarid conditions, farm yields are usually influenced by seasonal rainfall. In the present study, seed yield of fingermillet showed significant positive correlation with the seasonal rainfall (r = 0.81, $p < 0.05$). Significantly higher sustainable yield index (SYI) was found with the application of organic amendments either alone or in combination with chemical fertilizers compared to control or sole application of chemical fertilizer. Highest SYI was found in 10 Mg FYM ha^{-1} + 50% NPK followed by 10 Mg FYM ha^{-1} + 100% NPK, FYM 10 Mg ha^{-1}, and recommended NPK (Tab. 1).

3.2 Change in bulk density and SOC concentration

The depth-wise bulk density (BD) of the experimental soil before the initiation of the long-term experiment, and the treatment-wise change in bulk density at the end of the experiment, is presented in Tab. 2. With FYM, the soil bulk density was lower than with mineral fertilization and unfertilized control. The lowest BD was observed in surface layer (0–0.2 m) of FYM-treated plots (1.46 Mg m^{-3}), and the highest was in control (1.49 Mg m^{-3}). The trend in all the treatments showed an increase in BD with depth.

The SOC concentration of the soil profile showed significant differences ($p < 0.05$) among treatments and depths (Tab. 3). In the surface layer (0–0.2 m), FYM 10 Mg ha^{-1} + 100% NPK showed the highest SOC concentration (7.1 g kg^{-1}) followed by FYM 10 Mg ha^{-1} + 50% NPK (6.7 g kg^{-1}). Even there was an improvement in SOC level with the balanced fertilization of NPK in recommended dose (5.9 g kg^{-1}). Cultivation of crop without any fertilization or manuring over the years caused a significant decrease in the SOC concentration. This decrease was more prominent in the surface (0–0.2 m) and subsurface (0.2–0.4) layer. Recommended dose of NPK just maintained the SOC concentration of the profile. In contrast, there was a significant improvement in SOC concentration with the application of FYM even at lower depths. The mean SOC concentration in the profile increased from 4.2 g kg^{-1} in control to 5.7 g kg^{-1} in FYM 10 Mg ha^{-1} + 100% NPK.

3.3 Profile SOC stock, C build-up, stabilization, and sequestration

Profile SOC stock was highest in the FYM 10 Mg ha^{-1} +100% NPK (85.7 Mg C ha^{-1}) followed by FYM 10 Mg ha^{-1} + 50% NPK (81.6 Mg C ha^{-1}) > FYM 10 Mg ha^{-1} (79.1 Mg C ha^{-1}) > NPK (70.5 Mg C ha^{-1}) and control (63.5 Mg C ha^{-1}) treatments. Higher percentage of C build-up was observed with FYM 10 Mg ha^{-1} + 100% NPK treatment (41.2%) followed by FYM 10 Mg ha^{-1} + 50% NPK treatment (36.2%) which

Table 2: Change in bulk density (Mg m^{-3}) in the experimental plot after 27 y cropping, fertilization, and manuring (± standard deviation from mean, n = 4). Different capital letters within columns and different small letters within rows are significantly different at p = 0.05 according to Duncan multiple-range test (DMRT) for separation of means.

	Depth / m				
	0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1.0
Initial bulk density (at 1978)	1.49 ± 0.01	1.50 ± 0.01	1.52 ± 0.01	1.53 ± 0.01	1.55 ± 0.01
Control	1.49 ± 0.01^{Ae}	1.51 ± 0.01^{Ad}	1.52 ± 0.01^{Ac}	1.53 ± 0.01^{Ab}	1.55 ± 0.01^{Aa}
FYM 10 Mg ha^{-1}	1.46 ± 0.01^{Ce}	1.49 ± 0.01^{Bd}	1.51 ± 0.02^{Bc}	1.53 ± 0.02^{Ab}	1.55 ± 0.01^{Aa}
FYM 10 Mg ha^{-1} + 50% NPK	1.46 ± 0.01^{Ce}	1.48 ± 0.01^{Cd}	1.51 ± 0.02^{Bc}	1.53 ± 0.02^{Ab}	1.55 ± 0.01^{Aa}
FYM 10 Mg ha^{-1} + 100% NPK	1.46 ± 0.01^{Ce}	1.48 ± 0.01^{Cd}	1.50 ± 0.02^{Cc}	1.53 ± 0.02^{Ab}	1.55 ± 0.01^{Aa}
Rec. NPK	1.48 ± 0.01^{Bd}	1.51 ± 0.01^{Ac}	1.51 ± 0.02^{Bc}	1.53 ± 0.02^{Ab}	1.55 ± 0.01^{Aa}

Table 3: Changes in SOC (g kg^{-1}) concentration in soil after 27 y of cropping with soil amendments (± standard deviation from mean, n = 4). Different capital letters within columns and different small letters within rows are significantly different at p = 0.05 according to Duncan multiple-range test (DMRT) for separation of means.

	Depth / m					**Mean**
	0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1.0	
Initial SOC	5.2 ± 0.28	4.9 ± 0.26	4.5 ± 0.24	4.7 ± 0.25	3.9 ± 0.21	4.6 ± 0.25
Control	4.0 ± 0.21^{Ec}	4.2 ± 0.22^{Cb}	4.3 ± 0.23^{Cb}	4.6 ± 0.24^{Ba}	3.8 ± 0.20^{Bc}	4.2 ± 0.22^{D}
FYM 10 Mg ha^{-1}	6.2 ± 0.33^{Ca}	6.1 ± 0.32^{Aa}	5.4 ± 0.29^{Bb}	4.8 ± 0.25^{Ac}	3.8 ± 0.20^{Bd}	5.3 ± 0.28^{B}
FYM 10 Mg ha^{-1} + 50% NPK	6.7 ± 0.36^{Ba}	6.3 ± 0.33^{Ab}	5.3 ± 0.28^{Bc}	4.9 ± 0.26^{Ad}	4.0 ± 0.21^{Be}	5.4 ± 0.29^{B}
FYM 10 Mg ha^{-1} + 100% NPK	7.1 ± 0.38^{Aa}	6.5 ± 0.34^{Ab}	5.7 ± 0.30^{Ac}	5.1 ± 0.27^{Ad}	4.2 ± 0.22^{Ae}	5.7 ± 0.30^{A}
Rec. NPK	5.3 ± 0.28^{Da}	5.0 ± 0.27^{Bb}	4.5 ± 0.24^{Cc}	4.6 ± 0.24^{Bc}	3.9 ± 0.21^{Bd}	4.7 ± 0.25^{C}
Mean	5.9 ± 0.31^{a}	5.6 ± 0.30^{b}	5.0 ± 0.27^{c}	4.8 ± 0.25^{c}	3.9 ± 0.21^{d}	

Table 4: Profile organic C (OC), C build-up, C build-up rate, C stabilization, and C sequestered in the soil profile as affected by 27 y of cropping and fertilization under arid conditions (± standard deviation from mean, $n = 4$). Different letters within columns are significantly different at $p = 0.05$ according to Duncan multiple-range test (DMRT) for separation of means.

Treatment	Profile OC / Mg ha^{-1}	C build-up / %	C build-up rate / Mg C ha^{-1} y^{-1}	C Sequestrated / Mg C ha^{-1}
Control	63.5 ± 3.3^{E}	–	–	–6.8 ± 0.38^{E}
FYM 10 Mg ha^{-1}	79.1 ± 4.1^{C}	24.6 ± 1.4^{C}	0.58 ± 0.03^{C}	8.8 ± 0.49^{C}
FYM 10 Mg ha^{-1} + 50% NPK	81.6 ± 4.2^{B}	28.5 ± 1.6^{B}	0.67 ± 0.04^{B}	11.3 ± 0.63^{B}
FYM 10 Mg ha^{-1} + 100% NPK	85.7 ± 4.5^{A}	35.0 ± 2.0^{A}	0.82 ± 0.05^{A}	15.4 ± 0.86^{A}
Rec. NPK	70.5 ± 3.7^{D}	11.0 ± 0.6^{D}	0.26 ± 0.01^{D}	0.2 ± 0.01^{D}

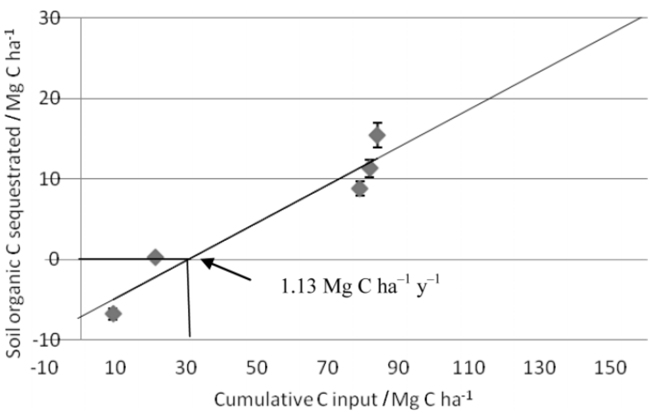

Figure 2: Critical C-input value and its influence on C sequestration in fingermillet-based system under semiarid conditions (error bars represents the standard error of mean for sequestrated C).

reflected in the profile SOC of respective treatments. Carbon build-up rate also followed similar trend as C build-up. According to our calculation, 27.7% C was stabilized from external input in the form of FYM. In all the treatments except the control, there was a sequestration of organic C ranging from 0.2 to 15.4 Mg ha^{-1}. Higher C sequestration was observed with the application of FYM alone or along with 100% and 50% recommended NPK. Cultivation of crop as such without using any organic and/or inorganic fertilizer inputs (control) caused a net depletion of 6.8 Mg C ha^{-1}, whereas recommended dose of NPK maintained the initial SOC stock.

4 Discussion

4.1 Build-up of SOC and C inputs

Higher biomass and C input in 50% or 100% NPK through fertilizer combined with FYM could be due to increased availability of deficient nutrients such as N, K, Ca, Mg, S, Zn, and B with organic manure (*Srinivasarao* and *Vittal*, 2007). Annual C inputs in terms of crop residue and external C application through FYM significantly affect C build-up and SOC stock of the profile. With application of FYM in a significant quantity (10 Mg ha^{-1}) with recommended dose of NPK or with half of the recommended dose during 27 y of cropping, significant build-up of SOC was observed over control. Build-up of C was highest in FYM 10 Mg ha^{-1} + 100% NPK (35.0%) followed by FYM 10 Mg ha^{-1} + 50% NPK > FYM 10 Mg ha^{-1} and NPK treatments. Though application of FYM decreased the bulk density of the soil particularly at surface and subsurface layer due to higher SOC and increased root biomass (*Halvorson* et al., 1999), it improves the SOC concentration significantly and ultimately increased SOC stock of the profile. The SOC content in the surface layer showed a negative correlation with BD ($r = 0.91$; $p < 0.05$) (*Du* et al., 2009).

There were positive relationships observed between the C stock of the profile and cumulative crop residue, external (FYM), and total C inputs. Similarly, C build-up also correlated with cumulative crop residue, external (FYM), and total C inputs. The higher C retention in manure-amended plots in comparison to control or mineral fertilization was probably because the manure was already partly decomposed and contains a lower proportion of chemically recalcitrant organic compounds (*Paustian* et al., 1992). A positive relationship between the crop-residue C, external C, and the total C inputs with the total SOC in the profile, indicated that the C input positively influences C stock in the soil, as well as C build-up percentage.

4.2 Sustainable yield index (SYI), C inputs, and C sequestrated

Sustainable yield index (SYI) of the crop was correlated with the improved SOC status of the soil. There was a certain relationship between SYI and annual crop-residue C inputs, total cumulative C input, C build-up, profile SOC, and C sequestered. Thus, the maintenance of SOC through regular organic or inorganic inputs determines the sustainability of rainfed production systems. The improvement in SOC is related to enhanced water-holding capacity of the soil profile (*Du* et al., 2009) which mitigates intermittent droughts, a common feature in dryland agriculture.

4.3 Carbon sequestration

The cultivation of the fingermillet crop over 27 y in Alfisol under semiarid conditions without using any organic- and/or inorganic-fertilizer input (control) caused a net depletion of total SOC, with a mean C release of –6.8 Mg C ha^{-1}. However, with addition of organic manures, either alone, or in combination with inorganic fertilizers, significant build-up of C was observed. The highest amount of C sequestered was in the 10 Mg FYM ha^{-1} + 100% NPK treatment (23.1 Mg C ha^{-1}) followed by 10 Mg FYM ha^{-1} + 50% NPK (19.9 Mg C ha^{-1}) and FYM 10 Mg ha^{-1} (15.0 Mg C ha^{-1}). Even with the application of recommended dose of fertilizer over 27 y, a net 1.0 Mg ha^{-1} C was sequestered. The C-sequestration potential (CSP), defined as the rate of increase in the SOC content over the initial soil at the 0–0.2 m soil depth, ranged from –0.18 Mg C ha^{-1} y^{-1} (unfertilized control) to 0.572 Mg C ha^{-1} y^{-1} (50% RDF + 4 Mg groundnut shells ha^{-1}) (*Bhattacharyya* et al., 2009).

4.4 Critical C inputs

The positive linear relationship between the changes in SOC and the total cumulative C inputs to the soils (external organic amendments *plus* crop residue) over the years (Fig. 2) indicates that even after 27 y of continuously adding C, ranging from 0.34 to 3.10 Mg C ha^{-1} y^{-1}, the soils of the present experiment were still unsaturated. Therefore, these soils have a better capacity and potential to sequester more C. As proposed by *Six* et al. (2002), this capacity and/or storage rate cannot continue indefinitely. Each soil with a different C loading might lead to the attainment of a new steady state of SOC over time. Assessment of SOC stock for these treatments at periodic, perhaps at decadal intervals, might provide insights in to C management in soils. The slope of the linear function (Fig. 2) represents the rate of conversion of inputs to SOC. This is ≈ 24% of each additional C input in this fingermillet-based production system. We wanted to compare our values with those of others if any, who have worked in the semiarid conditions of the world, but failed to do so since such information in literature is rare. However, our values were comparable to those reported by *Rasmussen* and *Collins* (1991) (14.0%–21.0%) from the cooler, temperate region of the USA and Canada, but higher than those obtained by *Kong* et al. (2005) (7.6%) under Mediterranean climate, and from the humid Indo-Gangetic plains of India under irrigated rice–wheat system (*Majumder* et al., 2008) (14%), rice–wheat–jute system (*Majumder* et al., 2007) (5%) and *Mandal* et al. (2007) (6.4%) in subtropical India. Critical C input was calculated from the linear function considering the zero change of SOC stock from the antecedent level. It reveals that, to maintain SOC levels (zero change), the critical amount of C input to the soil is 1.13 Mg C ha^{-1} y^{-1} for Alfisol under a fingermillet-based cropping system. This is much lower than the reports obtained from *Kong* et al. (2005) (3.1 Mg ha^{-1} y^{-1}) in Davis, California, USA in a Mediterranean-type climate, by *Majumder* et al. (2007) (4.59 Mg ha^{-1} y^{-1}) for a rice–wheat–jute system, *Majumder* et al. (2008) (3.56 Mg ha^{-1} y^{-1}) for irrigated rice–wheat systems of the Indo-gangetic plains, and by *Mandal* et al. (2007) (2.92 Mg ha^{-1} y^{-1}) under rice-based system in subtropical India. The lower input of C needed to maintain a constant level in this study may be due to lower initial SOC levels (4.6 g [kg soil]$^{-1}$ of mean profile SOC) (*Srinivasarao* et al., 2006). Another reason could be lower mean maximum temperature (27.8°C) of the studied location compared to studies carried out by other scientists. *Ogle* et al. (2005) reported higher sensitivity of management impacts in the tropical moist climate compared to any other climate. In the studies referred to above, the initial SOC values were almost three to six times higher (> 6–15 g [kg soil]$^{-1}$). The average SOC concentrations in the Indian Himalayan region ranged from 24.3 g kg^{-1} in cultivated soils to 34.5 g kg^{-1} in native or undisturbed soils (*Lal*, 2004).

5 Conclusions

The data presented support the conclusion that a regular input of biomass-C along with chemical fertilizers is essential to improve soil quality in the semiarid tropics of India and minimized the depletion of SOC stock under continuous cropping. Higher SYI were obtained with the integrated use of chemical fertilizer and FYM in a fingermillet-based production system. To maintain SOC at equilibrium (with no change), it was estimated that a critical C input of 1.13 Mg C ha^{-1} y^{-1} was needed. Among all the treatments tested, application of 10 Mg FYM ha^{-1} alone or in combination of recommended dose of NPK or half of the recommended dose of NPK not only sequesters higher C but also sustains crop productivity compared to unfertilized control or with sole application of chemical fertilizer. Hence, balanced use of NPK fertilizer along with FYM or other crop residues, which will take care of critical-C-input (1.13 Mg C ha^{-1} y^{-1}) addition quantitatively, will be a better option to stop SOC depletion and maintain and sustain crop production.

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