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Soil Carbon Dynamics, Sequestration and Productivity of Predominant Cropping Systems under Long Term (9 years) Inorganic and Organic Fertilization in Semi-Arid Deccan Plateau, India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Soil organic carbon (SOC) sequestration in agricultural soils is one of major agricultural strategies to mitigate the greenhouse gas (GHG) emissions as it is a potential sink for atmosphere carbon. Cropping systems and management practices adopted will affect the SOC sequestration. Dynamics of SOC is very important for understanding the pathways of C stabilization into different SOC pools. An attempt was made to assess the importance of different cropping systems on C sequestration and its stabilization in a 9 year old experiment at PJTSAU, Hyderabad, India. In comparison to initial TOC, cropping system perennial super napier fodder showed greater C build up (46.5%) followed by maize intercropped with pigeonpea followed by sunhemp (23.1%). In fact, all the cropping systems there were net increases in TOC. There was only 6.86% of C applied through various sources was stabilized as SOC. A minimal input of 1.24 Mg C ha^{-1} yr^{-1} is needed to maintain SOC level. Cropping system perennial super napier fodder showed a higher carbon

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management index (145.9), sustainable yield index (64.1), BC ratio (16.99) and least amount is required to sequester the kg of carbon to soil (Rs. 59).

Keywords: Cropping systems; SOC pool; TOC; C sequestration; critical carbon input; cost of carbon sequestration; sustainable yield index; carbon management index.

1. INTRODUCTION

Globally farming contributes to around 10-12% of the green house gaseous emissions [1]. It was around 18% in Indian context, which was placed at third position after energy and industry sector [2]. The global soil C pool of 2500 pg is constituted by 60% of organic pools (1550 pg) and 40% of inorganic pools (950 pg) and organic pool in soil is about 3.1 times the atmosphere pool and 4.5 times the live biotic pool [3]. Inherent low organic carbon coupled with no adoption of sustainable agricultural practices further depletes the soil carbon, with more emission of C into atmosphere and inturn the deterioration of soil quality [4]. Sequestering carbon is the key strategy to mitigate the climate change and to improve the soil quality. Total oxidizable carbon (TOC) is the most important constituent in the soil to increase the crop yields [5], to sustain the farming in economic terms and to improve the soil health in terms of physical, chemical and biological properties. Less amount of TOC in soils leads to many soils related problems.

In semiarid tropics because of higher soil temperature, and faster rate of decomposition inherently soils are low in organic carbon and their pools compared with temperate regions (slower mineralization) as a result it’s difficult to reach the equilibrium levels of SOC. To achieve equilibrium levels huge quantities of organic inputs, have to be supplied to soil. But little or no use of organics, injudicious use of inorganic fertilizers, mono cropping and lack of crop diversification have further multiplied the soil related problems by degrading the soil oxidizable carbon (SOC). Crop productivity is greatly affected by the SOC. Very poor quality of soil limits the crop production, there by decreases the food and fodder availability. Sustaining and improving the SOC pools in long run in these regions there by improving soil quality and alleviate the ill effects of above problems by developing and adapting the best nutrient management and cropping system practices is need of hour strategy. There is wide scope to increase soil organic carbon in soil by adapting sustainable management practices in upcoming years in semi-arid regions of India. Cropping system pattern and nutrient management plays a vital role in influencing the carbon sequestration in the soils [6, 7,8]. Crop rotation with diversified crops, has the potential to alter the SOC storage capacity by increasing the soil crop association both temporally, spatially and also affects the decomposition rate of organic matter. Organic manure application and crop residue incorporation are also the vital factors to increase the soil SOC and its pools.

Carbon inputs like roots, organic manures, root exudates etc. under different cropping systems and nutrient management practices influence the TOC content and their pools [9]. Quality and persistence of SOC can be can be known by the lability fraction of total organic carbon (TOC). Carbon management index (CMI), measures the relative potential of different cropping systems (management practices), strategies to influence TOC, its pools and C sequestration. Greater value of CMI represents that given cropping system is sustainable and improved in terms of TOC in comparison with low CMI, which indicates that system is demising.

The changes SOC and its pools, especially passive fractions of TOC are long term processes [10]. Very scarce information is available on effect of cropping systems on dynamics of soil carbon, which was key player in sequestration of soil carbon in the semi-arid region or Deccan Plateau of India. To assess the impact of different cropping systems and nutrient management on SOC and their pools. the present investigation was taken up in a long term (9 years old) experiment. An attempt to know the cost of carbon sequestration was also made.

2. MATERIALS AND METHODS

2.1 Site Description and Climate

The study site is a long-term fixed plot under All India Coordinated Research Project on Integrated Farming Systems that was initiated in the year 2010 at the research farm of the

Professor Jayashankar Telangana State Agricultural University, Hyderabad, Telangana, India. Study area geospatial location is $17^{o}19'0''$N, $78^{o}24'39''$E and climate of the region is semi-arid eco region of Deccan plateau and it receives the mean annual precipitation of 745 mm, its mean annual maximum and minimum temperatures were 34.7 and 17.5^{o}C respectively and characterized by hot summer and cold winters. The soil of the study site belongs to order Inceptisol (*Typic Ustochrept*).

2.2 Treatment Details and Crop Management

Treatments comprises of 6 predominant cropping systems of the region i.e. rice followed by groundnut (T1); pigeonpea intercropped with maize followed by bajra (T2); maize intercropped with pigeonpea followed by sunhemp (T3); cotton intercropped with green gram followed by fodder sorghum (T4); maize followed by groundnut followed by sunhemp (T5); perennial super napier fodder (T6) and it is non replicated with plot size of 1000 m^2 (50m × 20m). Well decomposed FYM was uniformly applied one month before sowing of rainy season crop at rate of 1 kg per m^2 in every cropping system once in every year. Recommended N, P, K were applied through the inorganic fertilizers in each of treatments. Amount of NPK fertilizers required were different for different crops. Recommended doses of nutrients per ha area for rice, groundnut, maize, pigeonpea, bajra, sunhemp, cotton, green gram, fodder sorghum, super napier were 120-60-40, 20-40-50, 200-60-50, 20-50-0, 100-40-30, 20-30-0, 150-60-60, 20-40-0, 100-40-30, 300-50-30 kg NPK respectively. Inorganic fertilizers were supplied through urea, single super phosphate, muriate of potash form respectively. For cultivating the crops *viz*, spacing, irrigation, fertilizer application, weed management, other crop production and crop protection measures were followed according to package of practices of the region. Crop stubbles left over in the field after harvest of the crop were buried into the field before sowing of next crop.

2.3 Soil Sampling

Composite soil samples from 0 to 0.15 depth were collected after the harvest of winter crops in the year 2019 (after completion of 9 years of experimentation) with the aid of soil auger. The collected soil samples were shade dried and passed through 0.5mm sieve for analysis of fractions of SOC and TOC. Soil bulk density at all the depths was determined by method as described by Blake and Hartge [11].

2.4 Analysis

TOC in the soil samples was estimated by improved chromic acid digestion method as described by Haenes [12]. TC in the organics was analyzed by using CHNS analyser. Various fractions of SOC were determined through a modified Walkley and Black method as described by Chan et al. [13] using 5, 10 and 20 ml of concentrated H_2SO_4 which was corresponded to 12.0 N, 18.0 N and 24.0 N of H_2SO_4 respectively.

Very labile carbon (C_{VL} or fraction I): organic C oxidised using the 12.0 N H_2SO_4.

Labile carbon (C_L or fraction II): difference in organic C oxidised under 18.0 N and 12.0 N H_2SO_4.

Less labile carbon (C_{LL} or fraction III): difference in organic C oxidised under 24.0 N and 18.0 N H_2SO_4.

Non labile carbon (C_{NL} or fraction IV): difference in TOC and organic C oxidised under 24.0 N.

C stock in soil = C content × Bulk density (BD) × Depth

Where, C content is expressed in g kg^{-1}, BD in Mg m^{-3}, depth in m and C stock in Mg ha^{-1}.

C sequestration (Mg C ha^{-1} soil) = Current C stock – initial C stock

$$\text{Rice grain equivalent yield (RGEY)} = \frac{\text{Non rice crop yield (Mg/ha)} \times \text{Price of non rice crop (INR/kg)}}{\text{Price of rice grain (INR/kg)}}$$

RGEY was worked out for both grain and straw/fodder of each crop.

The Carbon Management Index (CMI) was calculated using the mathematical procedure given by Blair et al. [14]. Where an initial soil is considered as reference sample.

$$\text{Lability Index (LI)} = \frac{\text{Lability of C in sample soil}}{\text{Lability of C in referance soil}}$$

$$\text{Carbon Pool Index (CPI)} = \frac{\text{Sample total C}}{\text{Reference total C}}$$

Carbon Management Index (CMI) = CPI × LI × 100

2.5 Sustainable Yield Index (SYI)

Treatment average 9 years RGEY was taken for both rainy, winter and summer crops. SYI of individual treatment was computed using the below equation:

SYI = (A-Y) / Ymax

Where, A= Mean yield of a particular treatment
Y = Standard deviation of a particular treatment
Y max = Maximum yield obtained of a particular treatment over the years

2.6 Carbon Sequestration Economics

The investment on crop production will be the cost of carbon sequestration. As we consider yield as complement of carbon sequestration. The cost of cultivation of different crops per hectare in the treatment were calculated separately duly accounting the prices of various inputs like land preparation, seed material, fertilizers, intercultural operations, pesticides, pesticide application, fertilizer application, harvesting, threshing etc. Yields of various crops were transformed into rice grain equivalent yield (as given in the equation). The cost of cultivation and returns on investments were calculated based on current market prices of inputs and rice grain equivalent yield (minimum support price offered by Government of India is 17.5/1 kg rice). Net returns were calculated as difference between gross returns and total investment of inputs.

2.7 Cumulative Carbon Input through Plant and Organic Sources

Cumulative annual C inputs to the soil through FYM, roots, stubbles and rhizo-deposition were computed. 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 as described by Franzluebbers et al. [15]. It was estimated that the root biomass represented 14.1, 30.9, 12.2, 19.2, 26.1, 16.4, 9.0, 8.3, 12.9, 5.9 % of harvestable above-ground biomass (both economical part and non-economical part was taken into consideration) in rice, groundnut, pigeonpea, maize, bajra, sunhemp, cotton, green gram, fodder sorghum, napier crops, respectively. Root rhizodeposition was estimated to be 65% of C in roots as given by Kuzyakov and Schneckenberger, [16] Bolinder et al. [17]. Stubble biomass of crops were 2.5% of aboveground biomass (considered both economical part and non-economical parts). Per cent C content in the roots of crops were 41.2, 40.9, 36.38, 48.1, 44.8, 40.9, 32.14, 35.33, 46.40, 44.8% in rice, groundnut, pigeonpea, maize, bajra, sunhemp, cotton, greengram, fodder sorghum, napier respectively. Stubble percent C content was 31.8, 48.2, 46.4, 46.0, 45.5, 41.17, 42.96, 48.0, 45.1 in rice, pigeonpea, maize, bajra, sunhemp, cotton, green gram, fodder sorghum, napier respectively. Mean C concentrations of FYM was 26.4%.

3. RESULTS AND DISCUSSION

3.1 Soil Bulk Density

Long term adoption of different cropping systems in conjugation with organic and inorganic fertilizers affected the bulk density negatively. Continuous cropping systems for a period of 9 years along with integrated organic and inorganic fertilizers caused a reduction in bulk density as compared to the initial bulk density. The effect of perennial super napier fodder was superior over the other cropping systems, the reduction in bulk density over the initial values followed the order perennial super napier fodder (1.57 Mg m^3) > rice followed by groundnut (1.58 Mg m^3) = cotton intercropped with green gram followed by fodder sorghum (1.58 Mg m^3) > pigeonpea intercropped with maize followed by bajra (1.59 Mg m^3) = maize intercropped with pigeonpea followed by sunhemp (1.59 Mg m^3) = maize followed by groundnut followed by sunhemp (1.59 Mg m^3) (Table 1). The reduction in bulk density after 9 years of continuous cropping systems is due to the higher soil organic carbon due to more addition of root and plant biomass [18,19] and bulk density decreased as rates of organic matter addition increased. Irrespective of cropping system bulk density increased with an increase in soil depth. This may be attributed to the soil compaction and low soil organic carbon in the lower soil depths [20,21].

3.2 Total Organic Carbon, Dynamics of Organic Carbon of Different Degree of Oxidisability and Critical Carbon Input

Continuous cultivation of different cropping systems for 9 years with combined application of chemical fertilizers and organic fertilizers demonstrated strong influence on the soil organic carbon fractions and total organic carbon content in the surface (0-15 cm) irrespective of treatment. On the whole, all the cropping systems under integrated organic and inorganic fertilizer application increased the soil total carbon and might be because of increased biomass of crop (root exudates and biomass) with complementary effect of inorganic and organic fertilizers, as compared to initial total carbon. Intensive cultivation of different cropping systems increased the TOC in the sequence perennial super napier fodder (17.4 Mg C ha^{-1}) > maize intercropped with pigeonpea followed by sunhemp (14.62 Mg C ha^{-1}) > pigeonpea intercropped with maize followed by bajra (14.57 Mg C ha^{-1}) > maize followed by groundnut followed by sunhemp (14.12 Mg C ha^{-1}) > rice followed by groundnut (13.83 Mg C ha^{-1}) > cotton intercropped with greengram followed by fodder sorghum (13.63 Mg C ha^{-1}). TOC sequestered over the initial TOC was 46.5% with perennial super napier fodder, 23.1% (maize intercropped with pigeonpea followed by sunhemp), 22.6% under pigeonpea intercropped with maize followed by bajra, 18.8% (maize followed by groundnut followed by sunhemp), 16.4% (rice followed by groundnut), 14.7% (cotton intercropped with green gram followed by fodder sorghum). Increase in TOC over the initial TOC and rate of carbon sequestration followed the same sequence as above discussed (Table 1). Bhattacharyya et al. [22] reported that there was a decrease in organic carbon content in the soils in the cropping systems because of presence of high temperature in the subtropical region and carbon additions to soil through organics and manures application etc. increased the carbon content in the soil. Srinivasarao et al. [23], Hutchinson et al. [24] and Krishna et al. [25] also reported that intensive cropping in combination with application of chemical fertilizers and organic manures helps in buildup of organic carbon in soil.

After 9 years of continues cropping there was distinguish difference in organic carbon fractions in different treatments because of variable crop rotations and crop nutrient management practices. Similar finding was reported by Venkatesh *et al.* (2012) in different pulse and cereal intensive cropping systems. The amount of TOC fractions extracted under gradient of (12N, 18N and 24N of H_2SO_4) of oxidizing conditions varied among the treatments. Perennial super napier fodder cropping system had higher very-labile (Table 1), labile (Table 1), less labile (Table 1) and non-labile organic carbon (Table 1) because of higher carbon input (year around root bimass) and also because of elimination of summer fallow (as reported by Nath *et al.* [26]), whereas it was least for cotton intercropped with green gram followed by fodder sorghum intensive cropping system. Similar findings were reported by Majumder *et al.* [27], Samal *et al.* [28], Naik et al. [29] and Ghosh et al. [30] because of higher microbial activity arising from organics and low translocation of organics from crop and applied organic fertilizers. Active pool fraction (C_{VL} + C_L) constitutes about 78.0% and passive pool fraction (C_{LL} + C_{NL}) constitute about 22.0% of the TOC. Chan *et al.* [13], also reported more active pool fraction than the passive pool fraction in the semiarid region. Passive pool of organic carbon is more stable from of organic carbon and least sensitive to crop and soil management practices [31].

A significant positive relationship between the changes in total organic carbon and the cumulative carbon applied as input to the soil over the 8 years (Y=0.0686x – 0.4906; R^2= 0.9511, p<0.05) was observed (Fig. 1). Similar relationship was also observed by Kong *et al.* [32] and Mandal *et al.* [33].

The Fig. 1 indicated a strong linear relationship between the total C applied and C sequestrated in soil even after the 8 years of C addition through FYM and root biomass, the soil still had capacity to store C and had potential for further sequestration. The slope of the curve represented the rate of conversion of input C to SOC, which is about 6.86% of each additional Mg C input per hectare under the different cropping systems. The results also revealed that in order to maintain the existing SOC level (zero change) for long term sustenance of the production system, a critical amount of 1.24 Mg C ha^{-1} yr^{-1} has to be incorporated into the soil.

3.3 Carbon Management Index (CMI)

CMI is an important indicator of sensitivity of soil organic carbon to management practices, it is also used to compare, describe and evaluate the soil quality. This index compares the efficiency of different crop management practices to assess the long-term effectiveness of soil productivity, soil nutrient supply and soil carbon stocks. The CMI value of more than 100 denotes that crop management practices followed for different cropping systems in the present study are

Table 1. Changes in bulk density (Mg m^{-3}), TOC and fracation of organic carbon (Mg C ha^{-1}) under various cropping systems

Treatments	Bulk density	Total organic carbon	Very Labile	Labile	Less Labile	Non Labile
Initial	1.61	11.88	5.69	3.18	1.84	1.17
rice followed by groundnut (T1)	1.58	13.83	6.61	3.70	2.15	1.37
pigeonpea intercropped with maize followed by bajra (T2)	1.59	14.57	6.96	3.89	2.26	1.46
maize intercropped with pigeonpea followed by sunhemp (T3)	1.59	14.62	6.97	3.92	2.28	1.45
cotton intercropped with green gram followed by fodder sorghum (T4)	1.58	13.63	6.52	3.64	2.11	1.36
maize followed by groundnut followed by sunhemp (T5)	1.59	14.12	6.75	3.79	2.19	1.39
perennial super napier fodder (T6)	1.57	17.4	8.31	4.67	2.70	1.72

Table 2. Crop productivity, BC ratio, Rs per kg C sequestration, CMI, SYI

Treatments	RGEY	COC	Returns	BC ratio	Rs/ kg C	CPI	L	LI	CMI	SYI
T1	88032.4	679520	1540567	2.27	348	1.16	9.09	0.99	115.7	60.5
T2	87877.59	789280	1537858	1.95	293	1.23	8.98	0.98	120.4	43.4
T3	80032.31	556720	1400566	2.52	203	1.23	9.08	0.99	122.2	59.2
T4	122091.4	730160	2136599	2.93	417	1.15	9.02	0.99	113.1	39.0
T5	86946.77	810560	1521569	1.88	362	1.19	9.16	1.00	119.0	52.6
T6	318653.1	328240	5576430	16.99	59	1.46	9.12	1.00	145.9	64.1
System					**231**					

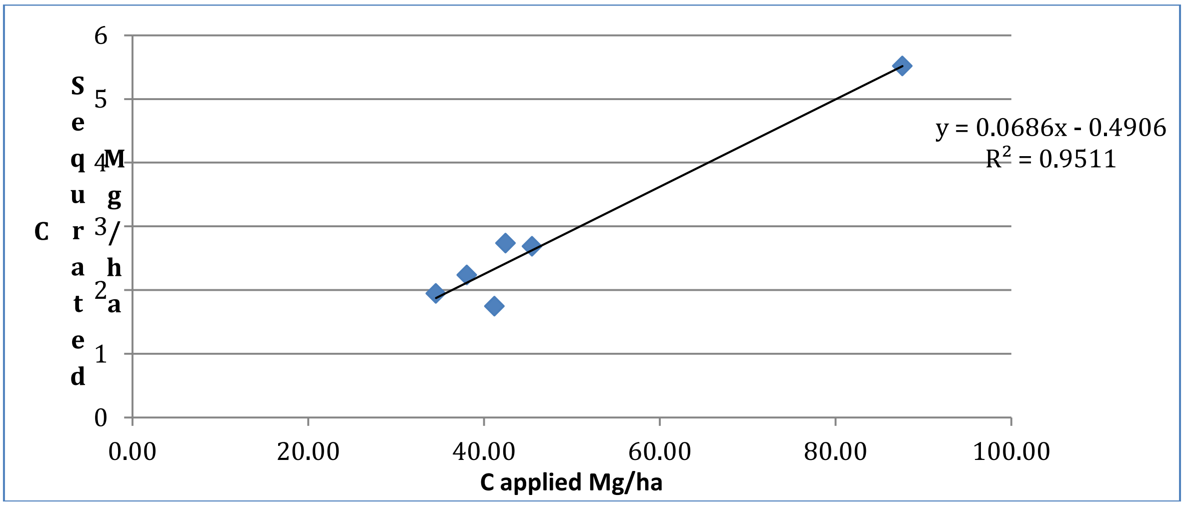

Fig. 1. Relationship between cumulative C input and C sequestration and critical value for zero change in total organic carbon (TOC) stock

sustainable in respect to the soil organic carbon stocks [34]. Crop management practices followed for T6 was superior to that of other intensive cropping systems in increasing soil health and carbon sequestration. The crop management practices followed in the T6 was better by 45.9% for improving the status of soil carbon stocks taking 100 as bench mark. The values of CMI (Table 2) followed the order T6 (145.95) > T3 (122.2%) > T2 (120.4%) > T5 (119.0%) > T1 (115.7%) > T4 (113.1). The highest CMI in T6 is may be attributed to higher addition of organic carbon through manures, rhizodeposition and *in situ* incorporation of crop waste into the soil. T6 treatment has higher stable soil organic carbon than that of other treatments, is considered as the sustainable crop management practice for maintaining the soil organic carbon stocks and had higher rehabilitation.

3.4 Economics of C Sequestration, B:C Ratio and SYI

Carbon sequestration cost in soil is function of crop management practices, cropping intensity and cropping system (Krishna *et al*. 2018). Among various treatments under present study T6 treated soils showed least carbon sequestration cost (Rs. 59 kg^{-1} C) followed by T3 (Rs.203 kg^{-1} C), T2 (Rs.293 kg^{-1} C), T1 (Rs.318 kg^{-1} C) highest was observed in T5 (Rs.417 kg^{-1} C) (Table 2).

T6 treatment has got more profits over the other treatments in the study, as calculated by the benefit: cost ratio. B:C ratio followed the following tread T6 (16.99) > T4 (2.93) > T3 (2.52) > T1 (2.27) > T2 (1.95) > T5 (1.88). Results have demonstrated that T6 treatment brought more returns to farmers and also maintained the soil sustainability. This was also supported by higher SYI in T6 treatment (64.1%) followed by T1 (60.5%) least was observed in T4 (39.0%).

4. CONCLUSIONS

Soil organic carbon was increased under different cropping systems under the hot semi-arid climate with integrated nutrient management. Even though there was an increase in soc in all cropping system a high proportion of (93.14%) of applied carbon was lost to environment leaving behind a minimal amount (6.86%) to stabilize into soil. In order to counter the loss and maintain the SOC under given semi-arid climatic conditions 1.24 Mg C ha^{-1} y^{-1} need to incorporate into soil. Among the different cropping systems, fodder cropping system outperformed in respect of total organic carbon, pools of SOC, BC ratio, Rs kg^{-1} C sequestration, CMI and SYI. Thus, inclusion of fodder cropping system not only helped to sustain the crop yields but also health of soils under hot semi-arid climatic conditions.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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