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Carbon Budgeting of a Long-term Rice-rice Cropping Sequence in the *Typic ustipsamments* of Kerala, India

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

A judicious management practice to improve the soil's organic carbon level and soil fertility is essential for agricultural and environmental sustainability. The present study was undertaken to assess the long-term effect of various management practices on soil carbon dynamics and agricultural sustainability by computation of indices like carbon pool index (CPI), carbon lability index (CLI), carbon management index (CMI), critical carbon input and carbon budgeting. CMI has been used as a more sensitive indicator to evaluate capacity of a management practice to promote soil quality. Sensitivity index was used to determine the degree of changes in each carbon fraction due to management practices. The study was carried out in a permanent manurial trial plot started in 1964 under a long term rice-rice cropping sequence in Kerala. Based on the results obtained, integrated application of NPK fertilizers along with FYM showed significantly higher carbon indices, increased soil carbon fractions, and carbon sequestration compared to other management

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practices. The study revealed that applying organics coupled with inorganic fertilizers will manage the SOC level and result in enhanced soil fertility, productivity, and agricultural sustainability.

Keywords: Long-term fertilization; soil organic carbon; carbon management index; carbon sequestration; carbon budgeting.

1. INTRODUCTION

Soil organic carbon (SOC) is an important soil fertility index because of its relationship to crop productivity. Declining SOC level often leads to decreased crop productivity [Lal, 2006]. Hence, maintaining the SOC level is essential for agricultural sustainability. The concept of sustainable agricultural production emphasizes the importance of SOC management for food security and environmental protection. A small change in the SOC pool may greatly influence the atmospheric C pool thus affecting the global C cycle. Hence it is important to maintain, preserve, and store SOC while addressing problems of climate change and food security.

Carbon content in soil depends on the size of the total C pool and the rate of C turnover. The C turnover in the soil is expressed in terms of the lability of C, carbon lability index (CLI), carbon pool index (CPI), and carbon management index (CMI). The loss of C from a soil with a small C pool size is of greater consequence than the loss of a same quantity of C loss from a soil with a large C pool size and CPI is calculated to account for this. Loss of labile C is of greater concern than the loss of non-labile C and to account for this, CLI is calculated. C management in a system is better understood by CMI. The CMI has been used as an index to determine the capacity of land use to enhance soil quality [Blair, G. J., et al. 1995] The loss of C from a unit area of a lesser C pool is of much more significance than the loss of C from an area with a larger C pool [Sruthi, S.N. and Ramasamy, E.V. 2018]. The sensitivity index was used to determine the degree of changes in each carbon fraction due to management practices.

It is difficult to detect SOC changes in the short term due to its slow rate of formation. Long-term field experiments are useful to study the effects of various cropping systems, soil, crop residues, climate, and management practices on the quantitative changes in SOC, and help to determine agricultural sustainability [Hemalatha, S., et al. 2013]. SOC dynamics in long-term experiments in rice-based cropping systems must be studied to determine the optimum nutrient management practices for sustaining soil quality and yield. Hence the present study was undertaken at the Onattukara Regional Agricultural Research Station, Kayamkulam, Kerala where a permanent manurial trial has been going on from 1964 and has completed 60 years of crop cycles of the rice- rice cropping sequence.

2. MATERIALS AND METHODS

2.1 Study Site and Experimental Details

A 60-year ongoing Permanent Manurial Trial (PMT), on rice at Onattukara Regional Agricultural Research Station, Kayamkulam, Kerala was selected for the study. The soils of the region are sandy loam, deep, well-drained, strongly acidic, and have low cation exchange capacity with shallow water table and single grain structure.

The experiment was laid out in the Randomized Block Design (RBD) with 8 treatments each replicated thrice with rice variety Jaya. The N, P, and K are supplied in the form of Ammonium sulphate (A.S), Rajphos and Muriate of Potash (MOP) respectively. The eight treatments were T_1-80 kg N ha^{-1} as FYM, T_2 -80 kg N ha^{-1} as Ammonium Sulphate (A.S), T_3 - 80 kg N ha^{-1} as A.S + 40 kg P_2O_5 ha^{-1} as Rajphos, T_4 -80 kg N ha^{-1} as A.S + 40 kg K_2O ha^{-1} as MOP, T_5 - 40 kg P_2O_5 ha^{-1} as Rajphos + 40 kg K_2O ha^{-1} as MOP, T_6 - 80 kg N ha^{-1} as A.S + 40 kg P_2O_5 ha^{-1} as Rajphos + 40 kg K_2O ha^{-1} as MOP, T_7- 80 kg N ha^{-1} (20 kg as FYM and 60 kg as A.S.) + 40 kg P_2O_5 ha^{-1} as Rajphos + 40 kg K_2O ha^{-1} as MOP, T_8-Absolute control. The change in treatments or variety may affect the long term effects of fertilization on soil properties and hence the same set of treatments and the same variety was followed from the beginning of the permanent manurial trial (1964) onwards to assess the long term effects.

2.2 Soil Sampling and Analysis

Soil samples were collected for various analyses for two seasons. The collected soil samples were brought to the laboratory, air dried, ground, passed through 2mm sieve and stored in polythene bags. These were further subjected to various analyses. Soil organic carbon was determined using the Walkley and Black method [Walkley, A. and Black, I. A. 1934], microbial biomass carbon was determined using the Chloroform fumigation and extraction method [Jenkinson, D. S. and Powlson, D. S. 1976], and total organic carbon was determined by the Dry combustion method using TOC analyzer [Tiessen, H. and Moir, J.O. 1993]. Soil microbial biomass acts as a key to understand the turnover of soil organic matter. It accounts for a small proportion of the soil organic C, which is more sensitive to the changes in soil quality and productivity than the TOC. Carbon fractions were determined by the Modified Walkley and Black Wet oxidation method using 6, 9, and 12 M H_2SO_4 for estimating very labile, labile, less labile, and nonlabile C fractions [Chan, K.Y., Bowman, A., and Oates, A. 2001].

2.3 Computation of Various Indices

Carbon Managemnt Index (CMI) was calculated from carbon pool index (CPI) and carbon lability index (CLI) [Blair, G. J., Lefroy, R. D., and Lisle, L. 1995]. The Sensitivity Index (SI) was computed to compare the magnitude of changes in different C pools relative to a stable reference (control) soil [Leite, L.F., Iwata, B.F., Araujo, A.S. 2014]. C budgeting was done by calculating C build-up per cent, C build-up rate and C sequestrated [Srinivasarao, C.H., et al. 2012].

$$\text{CMI} = \text{CPI} \times \text{CLI} \times 100$$

$$\text{SI} = \frac{(\text{C fraction in soil of a given treatment} - \text{C fraction in control soil}) \times 100}{(\text{C fraction in control soil})}$$

2.3.1 Carbon budgeting

$$\text{C build up \%} = ((C_{\text{fert}} - C_{\text{cont}}) \times 100) / C_{\text{cont}}$$

$$\text{C build up rate (Mg C ha}^{-1}\text{ y}^{-1}) = \frac{(C_{\text{fert}} - C_{\text{cont}})}{\text{Years of experimentation}}$$

$$\text{C sequestered (Mg C ha}^{-1}) = \text{SOC}_{\text{final}} - \text{SOC}_{\text{initial}}$$

Here C_{fert} indicates SOC stock in respective treatments and C_{cont} indicates SOC stock in control plot. SOC_{final} indicates the present SOC stock and $SOC_{initial}$ indicates the SOC stock at the start of the experiment. For the present study, SOC before 15 years was taken as the $SOC_{initial}$.

3. RESULTS AND DISCUSSION

3.1 Soil Organic Carbon (SOC)

Soil organic carbon (SOC) was significantly influenced by treatments. During the Kharif and Rabi seasons, treatment receiving FYM+ Ammonium Sulphate + Rajphos + M.O.P (T_7) recorded the highest value (0.67% and 0.71%). T_8 recorded the lowest value (0.31% and 0.33%) during the Kharif and Rabi seasons (Table 1). The increase in SOC in FYM + NPK treated plots can be ascribed to an increase in total N and soil organic matter contents compared to the sole application of fertilizers [Chakraborty, A., et al. 2011].

3.2 Total Organic Carbon (TOC)

TOC was significantly influenced by various treatments (Table 3). During both these seasons, treatment receiving FYM + Ammonium Sulphate + Rajphos + M.O.P (T_7) recorded the highest value (1.33% and 1.37%). T_8 (control) recorded the lowest value among all the treatments in both Kharif and Rabi seasons with TOC content of 0.87% and 0.88 % respectively. The increase in TOC may also be due to an increase in carbon input through organic amendments under integrated nutrient management [Venkatesh, M.S., et al. 2013]. At the end of *Rabi* season, a slight improvement in TOC was observed for all treatments.

3.3 Computed Indices

3.3.1 CPI, CLI and CMI

The maximum carbon pool index (1.56) was obtained in treatment receiving FYM+A.S+ Rajphos+MOP (T_7) and the lowest (1.25) in control plot (T_8) (Table 4). In cotton also the highest CPI was recorded under integrated nutrient management [Reddy, D.D., et al. 2017].

Maximum carbon lability index (1.34) was obtained in treatment receiving FYM+ A.S+Rajphos+MOP (T_7) and the lowest (1.06) in treatment receiving sole application FYM (T_1) (Table 4). Integrated nutrient management system recorded the highest CLI under rice-wheat-jute agroecosystem [Majumder, B., et al. 2007]. CPI and CLI values of control plot was obtained as 1 since, the total C content and lability of C in control plot was taken as reference for computing these indices.

Table 1. Effect of treatments on SOC %

Treatments	SOC (%)	
	Kharif	Rabi
T_1- 80 kg N ha^{-1} as FYM	0.65	0.67
T_2-Ammonium Sulphate(A.S)(80 kg N ha^{-1})	0.51	0.53
T_3- A.S (80 kg N ha^{-1})+Rajphos (40 kg P_2O_5 ha^{-1})	0.56	0.57
T_4-A.S(80 kg Nha^{-1})+MOP (40 kg K_2O ha^{-1})	0.58	0.60
T_5-Rajphos(40 kg P_2O_5 ha^{-1})+MOP (40 kg K_2O ha^{-1})	0.55	0.58
T_6-A.S. (80 kg N ha^{-1}) +Rajphos (40 kg P_2O_5 ha^{-1})+MOP (40 kg K_2O ha^{-1})	0.61	0.63
T_7- FYM (20kg N ha^{-1}+A.S (60 kg Nha^{-1})+Rajphos (40 kg P_2O_5 ha^{-1})+ MOP (40 kg K_2 O ha^{-1})	0.67	0.71
T_8-Control	0.31	0.33
CD (0.05)-(Treatments)	0.043	0.040
SE(m) (Treatments)	0.016	0.014

Table 2. SOC % before 15 years (2009)

Treatments	SOC %
T_1	0.56
T_2	0.44
T_3	0.48
T_4	0.51
T_5	0.47
T_6	0.53
T_7	0.60
T_8	0.28

Table 3. Effect of treatments on TOC, %

Treatments	TOC (%)	
	KHARIF	RABI
T_1- 80 kg N ha^{-1} as FYM	1.26	1.30
T_2-Ammonium Sulphate(A.S)(80 kg N ha^{-1})	0.97	1.10
T_3- A.S (80 kg N ha^{-1})+Rajphos (40 kg P_2O_5 ha^{-1})	1.13	1.15
T_4-A.S(80 kg Nha^{-1})+MOP (40 kg K_2O ha^{-1})	1.16	1.22
T_5-Rajphos(40 kg P_2O_5 ha^{-1})+MOP (40 kg K_2O ha^{-1})	1.11	1.15
T_6-A.S. (80 kg N ha^{-1}) +Rajphos (40 kg P_2O_5 ha^{-1})+MOP (40 kg K_2O ha^{-1})	1.22	1.25
T_7- FYM (20kg N ha^{-1}+A.S (60 kg Nha^{-1})+Rajphos (40 kg P_2O_5 ha^{-1})+MOP (40 kg K_2O ha^{-1})	1.33	1.37
T_8-Control	0.87	0.88
CD (0.05)-(TREATMENTS)	0.125	0.120
SE(M) (TREATMENTS)	0.044	0.043

In the present study, the highest CMI value of 209.04 was obtained in treatment receiving FYM+A.S+Rajphos+MOP (T_7) and the lowest (142.5) in treatment receiving sole application of ammonium sulphate (T_2) (Table 4). CMI in control plot (T_8) was 100 since CPI and CLI of control plot was 1.

The higher CMI in plot receiving combined application of organics and inorganics was mainly due to addition of fertilizers that increased biomass and in turn improves soil organic matter status and other nutrients through these sources. The incorporation of organics with inorganic fertilizers resulted in greater stability and promoted the quality of soil. Land use with higher CMI value seems to have better C rehabilitation. Increase in CMI through addition of organic manure like compost and addition of mineral N were already reported [Nogueirol, R.C., et al. 2014]. Higher the CMI value, more will be the carbon rehabilitation in soil and lower the CMI value indicates that the C is being degraded [Sainepo, B.M., et al. 2018]. C rehabilitation was the highest in treatment receiving FYM+ Ammonium Sulphate +Rajphos+M.O.P(T_7) and the lowest in control (T_8). Since both labile and non labile C fractions are taken into account for the calculation of CMI, a more definite picture of soil can be drawn.

3.3.2 Sensitivity index

Sensitivity index (SI) is used to compare the magnitude of changes in different C pools relative to a control soil under different management practices (Das *et al.,* 2016). The Table 5 and Fig. 1 revealed that active C pool (30.43% to 89.13%), SOC (90% to 133.33%) and soil microbial biomass carbon (50.01% to 250.03%)were more sensitive while TOC (25.28% to 56.32%) and passive carbon pool (14.7% to 44.18%) were less sensitive. Labile C pools have greater sensitivity [Das, D., et al. 2016]. The sensitivity index reflects the degree of change in each SOC fraction due to different management practices.

3.3.3 Carbon budgeting

The highest SOC stock (15.64 Mg C ha^{-1}) was recorded in treatment receiving FYM+A.S+Rajphos+MOP (T_7) followed by treatment receiving sole application of FYM (T_1) (15.3Mg C ha^{-1}) and the lowest in control plot (T_8) (11.92 Mg C ha^{-1}) (Table 6). Though the application of FYM decreased soil bulk density, it significantly increased soil organic carbon and root biomass thus ultimately increased SOC stock. Higher per cent of C build up (31.21%) was recorded in treatment receiving FYM+A.S+Rajphos+MOP (T_7) followed by sole application of FYM (T_1) (28.35%). Similar trend was followed in C build up rate with T_7 recorded the highest value (0.37Mg C ha^{-1}y^{-1}) followed by T_1 (0.34Mg C ha^{-1}y^{-1}) (Table 6). Under finger millet cropping system also a higher C build up per cent and C buildup rate were recorded in FYM+NPK treated plot [Srinivasarao, C.H., et al. 2012]. Annual carbon input in the terms of FYM application significantly affected soil carbon build up and SOC stock in profile.Addition of organic manures either alone or in combination with NPK fertilizers resulted in significant build up of C in soil profile.

Carbon sequestration was found the highest (2.57Mg C ha^{-1}) in treatment receiving FYM+A.S+Rajphos+MOP (T_7) followed by T_1 (2.32 Mg C ha^{-1}) and the lowest (1.9 Mg C ha^{-1}) in control plot (Table 6). One of the main strategies for green house gas mitigation identified by IPCC is the sequestration of C in soils. Improving C content of terrestrial carbon pool through residue incorporation, application of organics, conservation agriculture and reducing erosion have been documented. An increase in SOC over a period of 15 years under integrated nutrient management may be due to the increased microbial activity and root biomass on application of FYM [Katkar, R.N., et al. 2012].

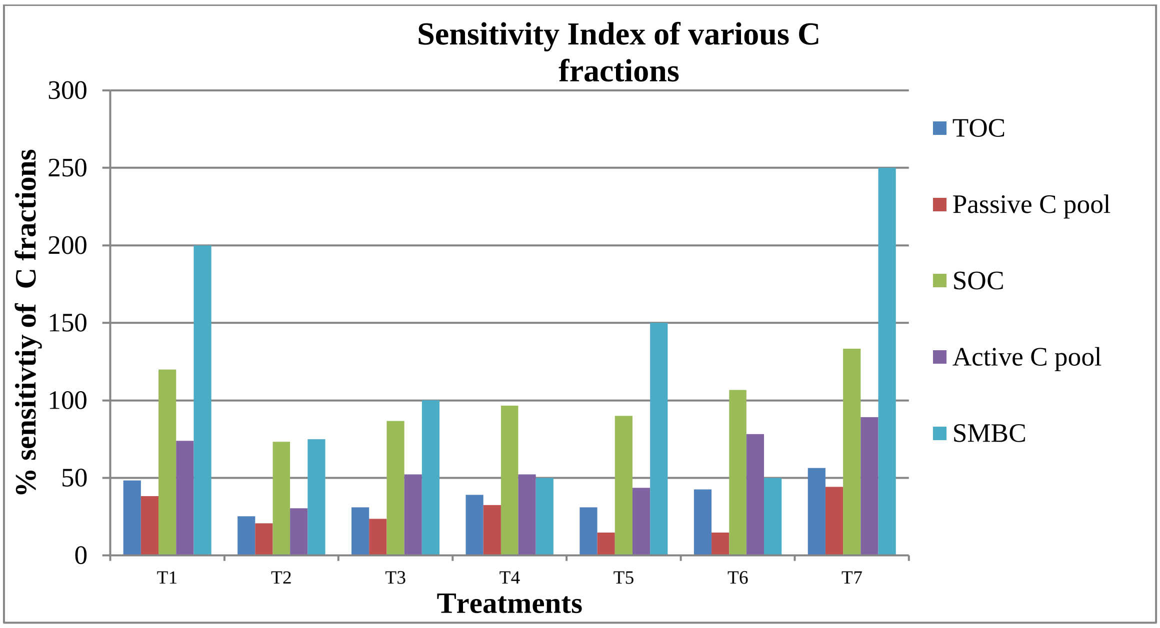

Fig. 1. Sensitivity index of various C fractions under different treatments

Table 4. Carbon pool index, carbon lability index and carbon management index under different treatments

Treatments	Carbon pool index	Carbon lability index	Carbon management index
T_1- 80 kg N ha^{-1} as FYM	1.48	1.14	168.72
T_2-Ammonium Sulphate(A.S)(80 kg N ha^{-1})	1.25	1.06	132.5
T_3- A.S (80 kg N ha^{-1})+Rajphos (40 kg P_2O_5 ha^{-1})	1.31	1.15	150.65
T_4-A.S(80 kg N ha^{-1})+MOP (40 kg K_2O ha^{-1})	1.39	1.09	151.51
T_5-Rajphos(40 kg P_2O_5 ha^{-1})+MOP (40 kg K_2O ha^{-1})	1.31	1.29	168.99
T_6-A.S (80 kg N ha^{-1}) +Rajphos (40 kg P_2O_5 ha^{-1})+MOP (40 kg K_2O ha^{-1})	1.42	1.18	167.56
T_7- FYM (20kg N ha^{-1}+A.S (60 kg N ha^{-1}) +Rajphos (40 kg P_2O_5 ha^{-1})+MOP (40 kg K_2O ha^{-1})	1.56	1.34	209.04
T_8-Control	1	1	100

Table 5. Sensitivity indices of different carbon fractions under different treatments, %

Treatments	TOC	SOC	Active C pool	Passive C pool	Soil microbial biomass carbon
T_1- 80 kg N ha^{-1} as FYM	48.27	120	73.91	38.23	200.02
T_2-A.S(80 kg N ha^{-1})	25.28	73.33	30.43	20.59	75.01
T_3- A.S (80 kg N ha^{-1})+Rajphos (40 kg P_2O_5 ha^{-1})	31.03	86.67	52.17	23.53	100.01
T_4-A.S(80 kg N ha^{-1})+MOP (40 kg K_2O ha^{-1})	39.08	96.67	52.17	32.35	50.01
T_5-Rajphos(40 kg P_2O_5 ha^{-1})+MOP (40 kg K_2O ha^{-1})	31.03	90	43.48	14.7	150.02
T_6-A.S (80 kg N ha^{-1}) +Rajphos (40 kg P_2O_5 ha^{-1})+MOP (40 kg K_2O ha^{-1})	42.53	106.67	78.26	14.7	50.01
T_7- FYM (20kg N ha^{-1}+A.S (60 kg N ha^{-1})+Rajphos (40 kg P_2O_5 ha^{-1})+ MOP (40 kg K_2O ha^{-1})	56.32	133.33	89.13	44.18	250.03

Table 6. SOC stock, C build up %, C build up rate, C sequestered under different treatments

Treatments	SOC stock (Mg C ha^{-1})	C build up %	C build up rate (Mg C $ha^{-1}y^{-1}$)	C sequestered (Mg C ha^{-1})
T_1- 80 kg N ha^{-1} as FYM	15.3	28.35	0.34	2.32
T_2-Ammonium Sulphate(A.S)(80 kg N ha^{-1})	14.46	21.31	0.25	1.94
T_3- A.S (80 kg N ha^{-1})+Rajphos (40 kg P_2O_5 ha^{-1})	14.95	25.42	0.30	2.22
T_4-A.S(80 kg N ha^{-1})+MOP (40 kg K_2O ha^{-1})	15.01	25.92	0.31	2.16
T_5-Rajphos(40 kg P_2O_5 ha^{-1})+MOP (40 kg K_2O ha^{-1})	14.87	24.75	0.29	2.02
T_6-A.S (80 kg N ha^{-1}) +Rajphos (40 kg P_2O_5 ha^{-1})+MOP (40 kg K_2O ha^{-1})	14.90	25.00	0.29	2.27
T_7- FYM (20kg N ha^{-1}+A.S (60 kg N ha^{-1})+Rajphos (40 kg P_2O_5 ha^{-1})+ MOP (40 kg K_2O ha^{-1})	15.64	31.21	0.37	2.57
T_8-Control	11.92	-	-	1.90

At sites initially low in organic matter status, continuous cropping increased the SOC levels even in soils not treated with organic manures [Yadav, R.L., et al. 2000]. The application of fertilizers significantly enhanced soil C sequestration, by enhancing biomass production and improving C: N ratios of residues retained in the field. Thus combining organic manures with inorganic fertilizers seems most promising for C sequestration in agricultural soils.

4. CONCLUSION

The study revealed that the integrated use of FYM and NPK fertilizers increased soil fertility and pools of SOC. Significant and positive correlations of active C pool with yield indicates that these pools are more important for nutrient turn-over and their availability to plants than TOC. CMI revealed that integrated nutrient management could be followed for enhancing crop productivity, nutrient availability and soil C pools for long term. Long term balanced fertilizer application along with FYM resulted in an increased SOC and C sequestration compared to unfertilized plot. The study also provided an insight on the effect of various management practices on soil carbon fractions. The increase in SOC through increased crop residues by adding inorganic fertilizers alone may not be sufficient to meet the depleted SOC. Therefore, we must revert to the age-old practice of the addition of organic manures also along with inorganic fertilizers to maintain soil fertility and to sustain agricultural productivity.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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