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Soil Carbon Stock and Carbon Pool Indices under Major Land Use Systems of Mayiladuthurai District, Cauvery Delta Zone, India

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ABSTRACT

Background: Soil organic carbon serves as potential indicator of the soil quality which is influenced by the changes in management practices. The conversion of natural ecosystem by anthropogenic activities resulted in decline of SOC. So, this study was conducted to assess the carbon indices and understand the dynamics to develop the management strategies for enhancing the C pool in the soil.

Methods: The present study was conducted in major land use systems of Mayiladuthurai district of Cauvery delta zone in Tamil Nadu. Soil samples were collected by stratified random sampling at two different depths and estimated for soil carbon indices.

Result: The SOC, C stock, bulk density, microbial biomass carbon, dehydrogenase, carbon management index of the study area varied with the mean value of 12.51 Mg ha^{-1}, 10.57 t ha^{-1}, 1.26 Mgm^{-3}, 302.52 µg kg^{-1}, 38.21µg TPF g^{-1} $day^{-1}$and 126.91% respectively. C stock were in the order of forestry > rice-pulses > rice-cotton > sugarcane > uncultivated among the different land uses of the study area. The difference in vegetation, litterfall, soil chemistry, microbial activity, substrate, root exudate, root biomass and root turnover influenced the variation in carbon pool under different land uses of the study area.

Key words: Carbon management index, Carbon stock, Microbial biomass, Soil organic carbon.

INTRODUCTION

Soil serves as the repository for soil organic carbon (SOC) in the terrestrial ecosystem which stores about 2500 gigatons of C (Ontl and Schulte, 2012). SOC plays a major role in global carbon cycle. The capacity and proportion of the soil to store SOC represents the key function of the soil. SOC content in soil is controlled by biotic factors (microbial, faunal and plant species abundance), environmental factors (micro-climate, temperature, moisture) and soil inherent properties (texture, clay content, CEC). Climate and soil forming factors affect the C storage in long-term whereas land use pattern and vegetation affect the C storage in short-term (Wiesmeier *et al.,* 2019).

The storage of SOC in soil results from interaction of ecological processes like decomposition, soil respiration and photosynthesis (Ontl and Schulte, 2012). Intensive agriculture paves the way for accelerated decomposition of soil organic carbon which results in loss of carbon into atmosphere and contributes to the greenhouse effect. Soil carbon stocks are sensitive to the land use changes and management practices during crop cultivation (Jackson *et al.,* 2017). Approximately 75% of SOC stock is lost from native lands of tropical ecosystem (Ghimire *et al.,* 2017).

SOC stocks are generally controlled by C inputs, including residues, secretion and exudates of plant, animal and microbial and C outputs, such as mineralization, soil erosion and losses (Sasmito *et al.,* 2020). Increasing the above ground biomass helps to sequester more carbon from atmosphere and further increases the carbon stocks. The protection of SOC stock will benefit the ecosystem through increase in fertility status, reduce erodibility, improved resilience and reduction in land use conversion (Bossio *et al.,* 2020). The different type of land use and management practices affect the volume of C stock and dynamics in top soil. The lower status of soil organic carbon is a hinderance

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to soil quality and in turn affects the crop yield potential (Nandhini *et al.,* 2021). Although, many researches are primely focused on the surface layer and the database on subsurface soil is minimal, which play a vital role in SOC storage, greater stability and longevity than surface soils (Gray and Bishop, 2016).

The objective of the present study was to compute the soil carbon pool indices and assess depth wise distribution of soil carbon stock under different cropping systems of Mayiladuthurai district of Cauvery Delta Zone of Tamil Nadu. The database generated by the computation of indices would expect to help in formulating strategies for better rehabilitation of carbon source in soil. A better understanding on spatial variability of soil carbon stocks helps to refine the agricultural practices and improve sustainability of the land use.

MATERIALS AND METHOD

Site description

Mayiladuthurai, a coastal district of Cauvery Delta region geographically covering an area of 1173.58 km^2 lies between 10°57′N to 11°26′N Latitude, 79°31′E to 79°55′E Longitude. Geologically it is formed by the alluvial deposit from both riverine and marine landform. The district is affluence with agricultural cultivation covering net area of 725.17 km^2. The major crops grown are paddy, green gram, black gram, sugarcane and cotton, which covers about 97% of the agricultural area sown. The forest land use covers about 1102 ha of the total geographical area of the district.

Sampling methodology and analysis

Soil samples were collected from five major land uses *viz*., rice-pulses, rice-cotton, sugarcane, forestry and uncultivated/ fallow during the year of 2022. About 75 composite samples were collected by means of stratified random sampling from two different depths (0-15 cm and 15-30 cm). The collected soil samples were air dried, processed and stored for chemical analyses whereas portion of fresh sample was refrigerated for microbial analysis.

Soil organic carbon was determined by oxidation of chromic acid produced by potassium dichromate and concentrated sulphuric acid. The excess chromic acid left unused was back titrated with 0.5N ferrous ammonium sulphate using diphenylamine (Walkley and Black, 1934). Microbial Biomass Carbon (C_{mic}) was measured by chloroform fumigation extraction (CFE) using 0.5M K_2SO_4 (Vance *et al.,* 1987). Dehydrogenase activity (DHA) was estimated by incubation with 3% 2,3,5-triphenyl tetrazolium chloride (TTC) followed by methanolic extract determined spectrophotometrically at 485nm (Casida *et al.,* 1964).

The static method of CO_2 respiration using alkali trap (standard alkali) was used to study the mineralization rate of carbon by incubating the samples for 32 days at 25°C. The CO_2 evolved was titrated against standard acid at periodic intervals. The cumulative amount of CO_2 evolved was taken as carbon mineralization (C_{min}). The CO_2 collected during 31st and 32nd day was taken as basal soil respiration (BSR).

$$\text{SOC stock} = \text{SOC (\%)} \times \text{B.D} \times \text{Depth} \times 100$$

$$\text{Carbon pool index (CPI)} = \frac{\text{TOC in sample soil}}{\text{TOC in reference soil}}$$

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

$$\text{Carbon management index (CMI)} = \text{CPI} \times \text{LI} \times 100$$

Soils in uncultivated/barren land use was taken as reference.

Mineralization Quotient (qM) is the ratio of CO_2-C released during 32 days of incubation to the total organic carbon present (C_{min} / TOC) and expressed as mg CO_2-C mg^{-1} TOC. Respiration Quotient or Metabolic Quotient (qCO_2) was estimated by the ratio of basal soil respiration to microbial biomass carbon (BSR / MBC) and expressed as mg CO_2-C mg^{-1} MBC. Microbial Quotient (q_{mic}) is the ratio of microbial biomass carbon to TOC and expressed in %.

Statistical analysis

The analysed soil parameters were summarized using descriptive statistics. The soil properties were calculated for the variables like median, mean, minimum, maximum, standard deviation, variance, coefficient of variation, skewness and kurtosis. Pearson correlation coefficient was developed for all paired combination of response variables. Duncan's multiple range test (DMRT) was used to compare the means and significance of the mean variations between different land uses and the statistical significance was determined at $P<0.05$. The statistical analyses were carried out using tools like Microsoft Office 2021, R Studio 4.2.2 and SPSS Statistics 20.0

RESULTS AND DISCUSSION

Soil bulk density serves as a significant indicator for changes in soil physical health. The soil bulk density varied significantly ($P<0.05$) among different land uses (Table 1). The BD was significantly higher in sugarcane based cropping system (1.30 Mg m^{-3}) compared with other agricultural land uses. The presence of the finer particles owing to puddling resulted in lesser bulk density of rice based cropping system. The bulk density in sub soil was comparatively higher than surface soil resulting from compaction of soil, less porosity, less organic matter and weight of the overlying surface layer. Similar phenomenon was noticed by Khan *et al.* (2017); Soleimani *et al.* (2019); Lepcha and Devi (2020).

The soil organic carbon (SOC) was significantly higher in forestry land use. The mean SOC was in the following order of Uncultivated < Sugarcane < Rice-cotton < Rice-pulses < Forest land use (Table 1). The higher SOC content in forest land-use might be due to continuous addition of litter, higher microbial activity and decomposition rate. The uncultivated land use had lowest SOC due to the lack of vegetation cover and comparatively lesser microbial activity. The vegetation type influences the content of organic carbon through the influence of substrate, root exudate, litterfall, microbial activity, soil chemistry, root biomass and root turnover (Sundarapandian *et al.,* 2015).

The SOC content was inversely related with depth. The lower root biomass, microbial activity and aeration in subsoil resulted in decrease of SOC with increasing depth. Similar trend was noticed by Francaviglia *et al.* (2017); Soleimani *et al.* (2019). SOC storage in soil depends upon the balance between C inputs and losses of C (Luo *et al.,* 2017). SOC was highly correlated with DHA (r^2 = 0.764**), CPI (r^2 = 0.731**) and carbon stock (r^2 = 0.973**).

The carbon stock varied significantly among different land uses. The C stock was highest in forest land use (12.15 t ha^{-1}) and lowest in uncultivated areas (9.34 t ha^{-1}). The C stock followed similar trend as SOC among different land uses (Fig 1). Among the agricultural land use C stock was comparatively higher in rice - pulses (11.15 t ha^{-1}). The C stock decreased with depth as the SOC content decreased with depth. As a result of puddling, the finer texture of rice growing soils aided to store more C stocks. Moreover, application of nutrient for crop cultivation induced the microbial community which favoured SOC accumulation in soil. The difference in land management practices resulted in variation of carbon stock among the different land uses. Similar variation was noticed by Gray and Bishop (2016); Wang *et al.* (2020); Liu *et al.* (2021).

There was a significant variation in microbial biomass carbon (MBC) content between different cropping systems of the study area (Table 2). MBC followed the sequence of uncultivated (277.2 µg kg^{-1}) < sugarcane (291.6 µg kg^{-1}) < rice - cotton (301.3 µg kg^{-1}) < rice-pulses (317.6 µg kg^{-1}) < forest land use (320 µg kg^{-1}). MBC was lower in subsoil in comparison with surface soil. The highest MBC in the forest might be due to production of continuous litter and deeper root systems allowing more microbial activities. The size of microbial biomass pool is affected by land use pattern and soil management practices. The discrepancy in MBC among agricultural systems could be due to different agricultural practices, resource availability and plant composition. The findings were in relation with Khan *et al.* (2017); Bolat (2019); Lepcha and Devi (2020). The MBC had a positive correlation relationship with SOC (r^2 = 0.175), LI (r^2 = 0.354*) and q_{mic} (r^2 = 0.695**) (Fig 2).

Soil dehydrogenase activity (DHA) serves as a good indicator of soil microbial activity and represents the oxidative activity of the microflora (Solanki *et al.,* 2020). The different cropping system had significant effect on DHA activity (Table 2). DHA was significantly higher in forestry (42.1 µg TPF g^{-1} day^{-1}) and lowest in uncultivated land use (34.9 µg TPF g^{-1} day^{-1}). Generally, soil enzyme activity is closely related to the organic matter content of the soil (Adak *et al.,* 2014). Higher DHA in agricultural land use indicates pronounced biological activity and stabilization of enzymes by complexation with humic substances. DHA is influenced directly or indirectly by soil management system and decreased with depth. Similar findings were reported by Datta *et al.* (2015); Brkljaca *et al.* (2019). The dehydrogenase activity was highly correlated with the CPI (r^2 = 0.727**), carbon stock (r^2 = 0.719**) and CMI (r^2 = 0.251).

Carbon pool index (CPI) was calculated by taking uncultivated land as reference. CPI varied significantly

Table 1: Bulk density (BD), Soil organic carbon (SOC) and C Stock under different depths of major cropping systems of Mayiladuthurai district.

Cropping system	BD (Mg m^{-3})		SOC (Mg ha^{-1})		C stock (t ha^{-1})	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Rice-cotton	1.26±0.01^{bc}	1.31±0.01^{ab}	12.42±0.21^{bc}	10.27±0.16^{c}	10.50±0.20^{bc}	9.00±0.15^{b}
Rice-pulses	1.25±0.01^{c}	1.29±0.01^{b}	13.37±0.28^{b}	11.17±0.18^{b}	11.15±0.23^{ab}	9.68±0.16^{b}
Sugarcane	1.30±0.01^{a}	1.33±0.02^{ab}	11.40±0.52^{cd}	9.22±0.51^{d}	9.93±0.50^{cd}	8.17±0.40^{c}
Forestry	1.26±0.01^{bc}	1.34±0.01^{a}	14.51±0.07^{a}	13.25±0.06^{d}	12.15±0.06^{a}	11.86±0.13^{a}
Uncultivated	1.28±0.02^{ab}	1.32±0.02^{ab}	10.88±0.60^{d}	8.44±0.38^{a}	9.34±0.53^{d}	8.12±0.35^{c}

The data represents mean±standard error. The means and mean variations between land uses was compared by Duncan's Multiple range test at statistical significance of (P<0.05). The values in the same column followed by same letter are not significantly different (P<0.05).

Table 2: Microbial biomass carbon (MBC), Dehydrogenase activity (DHA) and C mineralization under major cropping systems of Mayiladuthurai district.

Cropping system	Microbial biomass carbon (µg kg^{-1})		Dehydrogenase activity (µg TPF g^{-1} day^{-1})		Mineralization C (mg kg^{-1})
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	
Rice-cotton	301.30±3.54^{ab}	267.65±2.82^{b}	37.57±0.41^{b}	32.10±0.40^{c}	219.86±3.67^{ab}
Rice-pulses	317.63±3.73^{a}	278.62±2.68^{b}	40.63±0.59^{a}	34.48±0.63^{b}	233.03±4.76^{a}
Sugarcane	291.60±3.18^{bc}	252.00±7.35^{c}	35.92±0.93^{bc}	31.08±0.84^{c}	213.12±4.56^{ab}
Forestry	320.00±3.21^{a}	312.00±1.40^{a}	42.08±0.19^{a}	37.09±0.17a	223.20±1.00^{ab}
Uncultivated	277.20±3.56^{d}	231.60±2.40^{d}	34.92±0.66^{c}	30.42±1.11^{c}	204.96±9.54^{b}

between different cropping system (P<0.05). The CPI was lowest in sugarcane based cropping system (1.02) and was highest in forestry land use (1.33) (Table 3). The CPI also decreased along the depth. The lability index (LI) obtained from the ratio of labile carbon to non-labile carbon was highest in rice-pulses and was lowest forestry land use. As the proportion of labile carbon was more in cultivated land uses, the LI was significantly higher in agricultural systems. The LI decreased with increase in depth. Carbon management index (CMI) is considered as one of the most effective tools for quantitative estimation of soil quality index. The CMI derived from the lability concepts was designed to indicate the C dynamics of any ecosystem (Ghosh *et al.,* 2016). The CMI among the different cropping systems varied significantly (P<0.05). CMI was lowest in sugarcane cropping system (119.1%) and highest in forest areas (147.4%). CMI was in the sequence of forestry > rice-pulses > rice-cotton > sugarcane. Like all other indices, CMI also decreased with depth. Similar trend was recorded by Kalambukattu *et al.* (2013); Tiwari and Joshi (2022). The increased CMI in forestry and agricultural system might be attributed to regular addition of organic matter supplemented with increase inputs and lower loss of C.

The higher values of CMI and LI reflects the rehabilitation of C resources whereas the lower values indicate the soils undergoing degradation and depletion of C fractions. The CMI serves as an early indicator tool for soil quality changes affected due to land management practices (Venkatesh *et al.,* 2013; Moharana *et al.,* 2017).

The soil carbon mineralization rate was evaluated by soil respiration experiment, which is a widely used parameter for assessing the potential of microbial activity. The soil

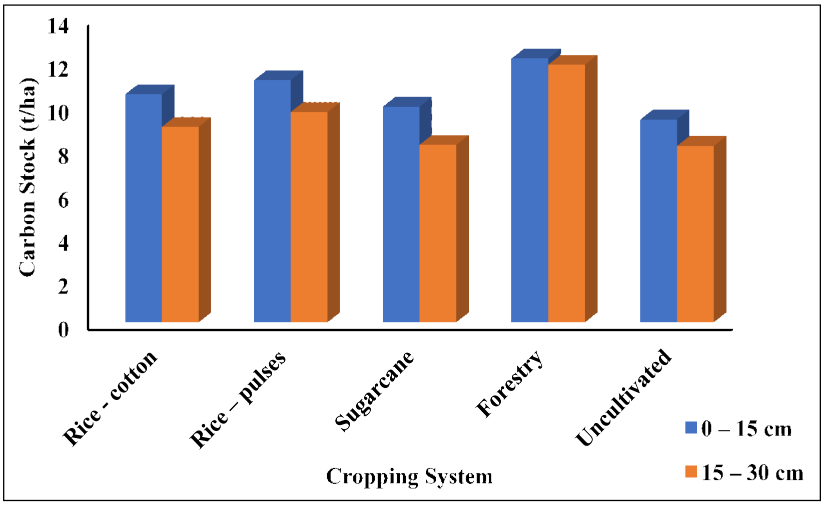

Fig 1: Carbon stock under major cropping systems of Mayiladuthurai district.

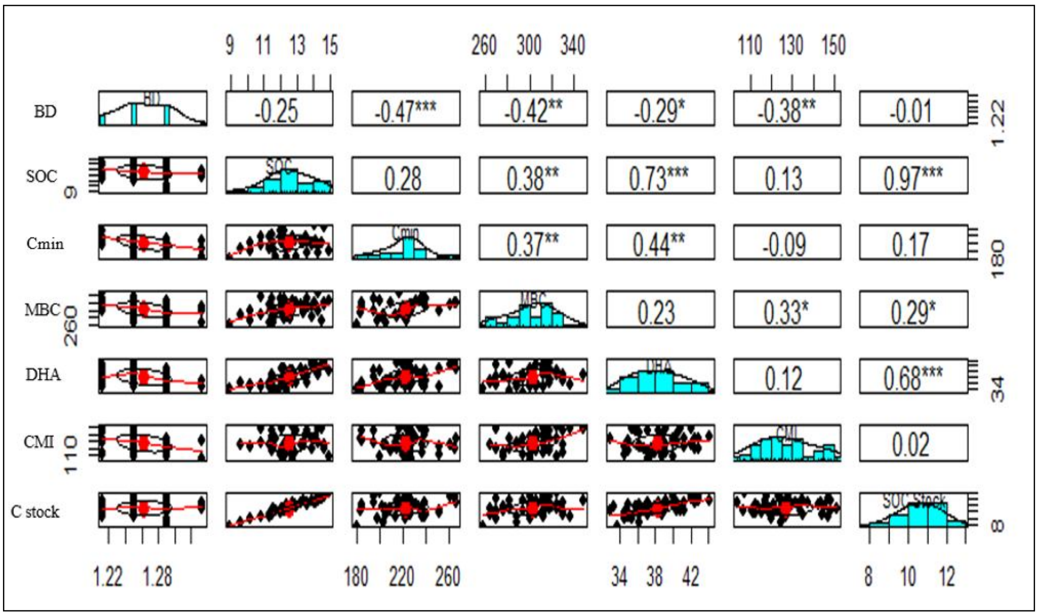

Fig 2: Correlation matrix between soil carbon indices under different cropping systems.

respiration was measured by CO_2 evolution using alkali trap. The cumulative amount of CO_2-C evolved from the incubated soil was highest in rice-pulse based cropping system (233.03 mg kg^{-1}) and was lowest in uncultivated landuse (204.96 mg kg^{-1}). The amount of CO_2 released by the mineralization process was rapid during initial days and evolution rate exhibited a decreasing trend with an increase in incubation period (Fig 3). This may be attributed to the decrease in soil microbial activity with time. The lower CO_2 evolution corresponds to the lower biomass and less microbial activity. Similar results were observed by Hamarashid *et al.* (2010).

The litter fall and addition of crop residue increase the SOC mineralization rate (Wang *et al.,* 2014; Bolat, 2019). The respiration activity is governed by factors like temperature, moisture, microbial load, pH, nutrient availability, O_2 supply, quality and quantity of crop residue incorporated. Dotaniya *et al.* (2017) noted the oxidation rate of the substrate depends on the physical and chemical conditions of the environment. The mineralization rate of carbon was highly correlated with MBC (r^2 = 0.336*), DHA (r^2 = 0.420**), CPI (r^2 = 0.290*) and qM (r^2 = 0.756**).

The mineralization quotient (qM) varied significantly with different land uses (Table 4). The qM was highest in forestry land use (32.6 mg CO_2-C mg^{-1} TOC) and followed in the sequence by rice-pulses (31.57) > rice-cotton (30.9) > sugarcane (30.63). The qM was lowest in uncultivated land use (29.03 mg CO_2-C mg^{-1} TOC). The respiratory quotient (qCO_2) is the ratio of basal respiration rate to the microbial biomass helps in indicating the maturity of the soil system. There was no significant variation in qCO_2 of soils under different cropping systems. The qCO_2 was lowest in uncultivated land use (15.53 mg CO_2-C mg^{-1} MBC) and comparatively higher in forest land use (17.78 mg CO_2-C mg^{-1} MBC). The qCO_2 helps to identify the efficiency of soil microbes in processing the litter and residues which assist in availability of C. Kaur *et al.* (2019) proclaimed that higher qCO_2 in different land uses resulted from prevalence of recalcitrant carbon.

The microbial quotient (q_{mic}) is the percent contribution of MBC to the total soil carbon (MBC/TOC). It usually ranges between 1-5% in soil (Masto et al., 2006). The q_{mic} reflects the availability of the substrate to the microflora (Suman *et al.,* 2006). The microbial quotient significantly differed between different land uses of the study area (Table 4.). The contribution of q_{mic} was higher in rice-pulse cropping system (4.32%) and lowest in uncultivated areas (3.93%). Kaur *et al.* (2019) reported the occurrence of higher q_{mic} might be due to existence of more carbon in labile nature and lesser q_{mic} implies the soil with nutritional stress. The q_{mic} is impacted by microbial growth which depends on the substrate and nutrient source. The q_{mic} in surface soil is regulated predominantly by the nature of cropping ecosystem (Sun *et al.,* 2020). The plants root and its

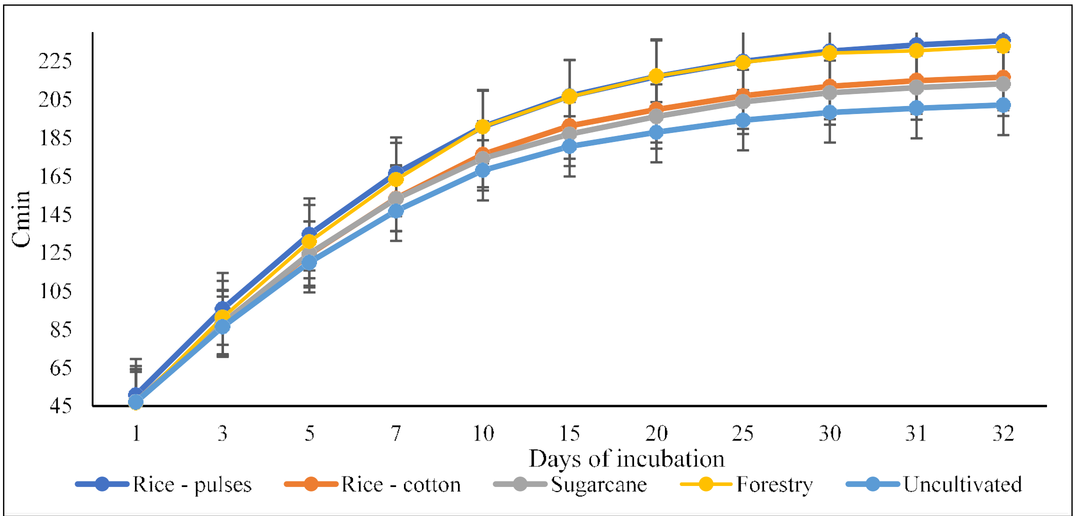

Fig 3: Cumulative C mineralization (CO_2-C) in 32 days of incubation under major cropping systems.

Table 3: Carbon pool indices (CPI), lability index (LI) and carbon management index (CMI) under different depths of major cropping systems of Mayiladuthurai district.

Cropping system	CPI		LI		CMI	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Rice - cotton	1.05±0.01[bc]	0.99±0.01[bc]	1.16±0.03[ab]	1.07±0.03[ab]	121.62±2.14[b]	105.44±2.58[b]
Rice-pulses	1.09±0.02[b]	1.02±0.01[b]	1.25±0.04[a]	1.19±0.03[a]	135.68±2.74[c]	121.21±2.81[c]
Sugarcane	1.02±0.02[c]	0.95±0.03[c]	1.18±0.08[ab]	1.11±0.09[ab]	119.10±2.04[c]	103.92±4.97[c]
Forestry	1.33±0.01[a]	1.31±0.01[a]	1.11±0.01[b]	1.03±0.01[b]	147.41±0.66[a]	134.70±1.76[a]

Uncultivated land use was taken as reference.

Table 4: Mineralization quotient (qM), respiratory quotient (qCO2) and microbial quotient (q_{mic}) under major cropping systems.

Cropping system	Mineralization quotient (qM) mg CO_2-C mg^{-1} TOC	Respiratory quotient (qCO_2) mg CO_2-C mg^{-1} MBC	Microbial quotient (q_{mic}) %
Rice-cotton	30.90±0.67^{ab}	16.53±0.85^{a}	4.23±0.06^{ab}
Rice-pulses	31.57±0.60^{ab}	17.68±0.67^{a}	4.32±0.10^{a}
Sugarcane	30.63±1.10^{ab}	15.74±1.74^{a}	4.20±0.11^{ab}
Forestry	32.60±0.15^{a}	17.78±0.08^{a}	3.94±0.02^{b}
Uncultivated	29.03±0.91^{b}	15.53±1.02^{a}	3.93±0.06^{b}

Table 5: Descriptive statistics of soil carbon indices under major cropping systems of the study area.

Parameter	Mean	Median	SD	Variance	CV	Skewness	Kurtosis
BD	1.26	1.25	0.03	0.001	2.66	0.131	-0.541
SOC	12.51	12.34	1.36	1.84	10.83	-0.343	0.020
MBC	302.52	306.00	20.61	424.79	6.81	-0.269	-0.372
DHA	38.21	38.13	2.82	7.96	7.38	0.154	-0.827
Cmin	221.98	223.20	19.93	397.06	8.98	-0.007	0.174
CMI	126.91	124.99	12.81	164.08	10.09	0.248	-0.873
Cstock	10.57	10.51	1.11	1.24	10.53	-0.291	-0.099

exudates are major source of substrate to microbial growth which vary with the cropping systems. The higher q_{mic} indicates the higher rate of conversion of microbial biomass which purveys better C stability in any system.

The descriptive statistical parameters like mean, median, standard deviation, variance, coefficient of variation, skewness and kurtosis were calculated. The mean of BD, SOC, MBC, DHA, CMI and C stock of the study area was 1.26 Mgm^{-3}, 12.51 Mg ha^{-1}, 302.52 µg kg^{-1}, 38.21µg TPF g^{-1} day^{-1}, 126.91% and 10.57 t ha^{-1} respectively (Table 5). The coefficient of variation was comparatively higher for the parameters like SOC, CMI and C stock indicating the difference in cropping system influencing the spatial variation with in the study area.

CONCLUSION

The study clearly suggests that changes in cropping system had a significant influence in the soil carbon stock and soil carbon pool indices. The SOC directly affect the physical, chemical and biological properties of the soil. C stock ranged from 9.34 to 12.15 t ha^{-1} and the SOC exhibited low to medium rating within the study area. The higher levels of mineralization, basal respiration, dehydrogenase activity and microbial quotient reflects the favourable microbial activity in decomposition of residues into the organic matter. The higher CMI indicates the soils were undergoing rehabilitation and restoration of resources in comparison with uncultivated land uses. The positive correlation between the carbon indices emulates that changes in managements practices will affect the dynamics of C. Therefore, to sustain the carbon resource in the cultivated regions management practices like residue incorporation, reduced tillage, cover crops, enrichment with organics, *etc*., has to be manifested.

Conflict of interest: None.

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