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Research Article

Unravelling the carbon pools and carbon stocks under different land uses of Conoor region in Western Ghats of India

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Abstract
Land uses are pivotal in global carbon cycles. The native forest lands possess a greater potential to sequester higher carbon, which can directly address soil quality and climate change problems. Unfortunately, the rapid conversion of forests to other land use over the past few decades has significantly declined the concentration of carbon in the soils. Therefore, in order to estimate the impact of land-use change (LUC) on soil carbon status, this present study was attempted under major ecosystems (Forest (FOR), cropland (CRP), tea plantation (TEA)) of Conoor. Results from findings revealed that total organic carbon (TOC) concentration and carbon pools were significantly ($p<0.05$) higher in FOR than in CRP and TEA. TOC (0-45 cm) recorded in FOR, CRP and TEA was 32.88, 11.87 and 18.84 g kg^{-1} and it decreased along the depth increment. Carbon stock (t ha^{-1}) in FOR, CRP and TEA (0-45cm) was 68.10, 26.04, 42.42. Microbial biomass carbon (MBC) was higher in FOR (283.08 mg kg^{-1}) followed by TEA (94.64 mg kg^{-1}) and CRP (76.22 mg kg^{-1}). The microbial biomass nitrogen (MBN) followed; FOR > TEA > CRP. These results clearly indicate that the LUC has inflicted a greater impact on soil carbon status and its extent was quantified using the land degradation index (LDI). The LDI (0-45 cm) recorded in CRP (-38.65) and TEA (-61.75) signals the need for immediate implementation of carbon management strategies in the CRP and TEA ecosystem to keep the soils of Conoor alive and prevent land degradation.

Keywords: Carbon pools, Carbon stocks, Carbon management index, Land-use change; Western ghats

INTRODUCTION

Soils play an important role in the global carbon cycle (Scharlemann *et al*., 2014) with its highest carbon reservoir (1,500 Pg) (Bhattacharyya, 2000; Jacobson, 2000) in the terrestrial ecosystem. The organic carbon (OC) present in the soils is considered as an ecosystem engineer (Lugato *et al*., 2014), due to its ability to restore sustainability and maintain soil quality (Chaplot *et al*., 2010; Srinivasarao, 2020a). It decides whether soils act as sinks or carbon sources in the global carbon cycle. If OC is stabilized, soils acts as a sink

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(Paustian *et al*., 2019) and this process shows a tremendous promise of reducing the carbon footprint.

OC in soils with its varying degrees of decomposition rate and stability (Wolters, 2000, Regnier *et al*., 2013) can be classified as a) an active pool; with a turnover period of few days, b) a slow pool; which has a turn over a period up to centuries, and they represent the physically stabilized form of carbon, c) passive pools are the most stabilized and they persist for over thousands of year (Trumbore, 1997).

Owing to minimal disturbances, the OC fostered in forest land is considered the most stable (Wei et al., 2013) and sequesters about 25% of global carbon emissions. Unfortunately, the increased LUC has led to deforestation of forest land, thereby altering the carbon pools with the depletion of carbon stock (Sahoo *et al*., 2019). Findings from various studies have also revealed the inverse relationship between the concentration of soil carbon and LUC (Golchin *et al*., 1995).

Connor a part of UNESCO's World heritage site has undergone a large-scale conversion of native forest land to cropland and tea plantation (Saravanan *et al*., 2021). The Conoor region in western ghats is highly vulnerable to landslides (Jaiswal *et al*., 2011; Chandrasekaran *et al*., 2013). An increase in agricultural land resulting from LUC of native forest land (Sanderman *et al*., 2017) has inflicted soil degradation of around 33% globally (Food and Agriculture Organization, 2019) and this, in turn, increased the atmospheric CO_2 (143.3 × 10^9 to 148.8 × 10^9 tn) (Sanderman *et al*., 2017; Lal *et al*., 2018; Ramesh *et al*., 2019) and welcomed the climate change (Marble *et al*., 2016; Vanhala *et al*., 2016; Cha-un *et al*., 2017). Therefore carbon which was a sink in forest soil has now become a source through the LUC and this warns the global community to curb it through the implementation of suitable strategies (Ross *et al*., 2016). At this juncture, the Connor undergoing large-scale LUC has no previous studies on carbon pools and stocks; hence, this study attempted to address the unexplored carbon stocks and carbon pools of the Conoor region to keep soils alive to achieve land degradation neutrality.

MATERIALS AND METHODS

Field description and investigation

Conoor is located in Nilgiris and lies between 11^{0}20' and 11^{0}25' North latitudes and 76^{0}44' and 77^{0}00' East longitudes, with topography ranging between 1500 to 2546 m above mean sea level. The Southwest monsoon brings maximum rainfall and its average annual rainfall ranges between 1400 – 2000 mm year^{-1}. Around 22% of the area in Conoor is under forest (Saravanan *et al*., 2021). The average annual temperature in summer ranges between 18°C to 28 °C and in winter it ranges between 0 to 16 °C. Investigations were carried out with local people to study different ecosystems of this region. It is clear that Connor had undergone a rampant LUC from forests to cultivation, plantation and other commercial activities. Farmers portrayed the prevalence of rainfed cultivation with large-scale tillage, pesticides and fertilizer application. Tea, carrot, potato, garlic, beans and cauliflower were amongst the commonly grown crops and plantations in Conoor.

Charnockite group of metamorphic rock was the most predominant bedrock overlain with laterite and forms an irregular horizon in the soil profile. Denudational Hill, Denudational Slope, Debris slope, and Plateau are common geomorphic features in Conoor.

Soil sampling and analysis

Soil sampling was carried out randomly from different ecosystems (FOR, TEA and CRP) of Conoor. Samples were collected from all ecosystems (30 samples from each ecosystem). During sampling, the soils were earthed out from five different quadrats and at different depth classes (0 - 15, 15 - 30 and 30 - 45 cm) in each location. Those sub-samples were pooled to get three bulk samples in a plot, were sieved to separate the debris and rock fragments and were packed to the laboratory for analysis. Triplicates of the sample were analyzed for TOC, BD, carbon stocks and carbon pools. TOC (Elementar) analyzer was used to perform TOC (Total organic carbon) estimation (Jackson, 1973) Carbon stock was estimated as per Sisti *et al*. (2004).

TOC – Total organic carbon (%), BD – Bulk Density (Mg m^{-3}), D – Depth (cm) (1)

Microbial biomass carbon

10 grams of moist soil were fumigated with ethanol-free chloroform for 24 hr at 25°C. The fumigated and non-fumigated samples were shaken for 1 hr and extracted with 30ml of 0.5 M K_2SO_4. The extracts were filtered, and the organic carbon in the extracts was determined by Walkley and Black method (Walkley and Black, 1934). The differences in filtrates between fumigated and unfumigated soil divided by the K_2SO_4 extract efficiency factor (KC = 0.41) were calculated as MBC. The carbon content in MBC was determined fumigation-extraction method (FEM) using 0.38 as the correction factor (Vance *et al*., 1987).

Microbial Biomass Nitrogen - Biomass N was determined by fumigation – incubation technique (FIN). Ammonium Nitrogen (N) was extracted with 2M KCL and an aliquot of 20 ml of this filtrate was distilled with freshly ignited MgO in Bremner's distillation apparatus and the distillate was collected in 2% boric acid containing mixed indicator and titrated against standard H_2SO_4 (Keeney and Bremner, 1964). The net N flush was converted into biomass N using a K_n factor of 0.57

(Jenkinson, 1988).

Land degradation index (LDI)

Land degradation of an ecosystem can be computed by comparing the degraded one with the best ecosystem (Barrow, 1991).

$$LDI = \left(\frac{D}{ND} \times 100\%\right) - 100 \quad (2)$$

D- Soil parameter values of samples

ND – Parameter values of reference soil

Statistical analyses

Analysis of variance (ANOVA) has been carried out with the sampling sites as replicates or as random effects and the various ecosystem as a treatment or fixed effects. Duncan's multiple range test (DMRT) was used to compare the means and significance of the mean variations between ecosystems. The statistical significance was determined at $P < 0.05$.

R program V 4.1.1 was used for other statistical analysis like, correlation using the native function *"cor"*, for creating network maps using the package "*qgraph*", and for computing the PCA (Principal Component Analysis). For visualization R packages like *ggplot, Complex Heatmap, Factoextra, FactoMineR, and dendextend* were used.

RESULTS

TOC concentration each ecosystems of Conoor varied significantly ($P < 0.05$). The highest TOC was recorded in FOR at 0-15 cm (40.91 g kg^{-1}) (Fig. 1). The average TOC (0-45 cm) of different ecosystems followed; FOR > TEA > CRP. The overall average TOC (0-45 cm) found in FOR (25.88 g kg^{-1}) was 64% and 43% higher than CRP and TEA, whereas it was 37% higher in TEA when compared with CRP. The concentration of TOC decreased with the depth increment. The decrease in TOC was maximum between 0-15 cm and 15-30cm depth for CRP and it was between 15-30cm and 30-45 cm depth for TEA and FOR.

BD across all the ecosystems in Conoor was denser with an increase in depth (Table.1). BD recorded at surface soils (0-15cm) of FOR (1.32 Mg m^{-3}) were significantly lower ($P<0.05$) when compared to TEA (1.43 Mg m^{-3}) and CRP (1.39 Mg m^{-3}). The overall BD (0-45cm) in different ecosystem followed TEA (1.52 Mg m^{-3}) > CRP (1.48 Mg m^{-3}) > FOR (1.39 Mg m^{-3}). The increase in density between 0-15 cm and 15-30 cm depth was found equal in CRP and FOR. The increase in density between 15-30cm and 30-45 cm depth was highest in CRP.

Carbon stock (t ha^{-1}) under different ecosystems of Conoor was calculated at different depths using BD and TOC. The overall stock (0-45cm) followed ; FOR (68.10 t ha^{-1}) > TEA (42.42 t ha^{-1}) > CRP (26.04 t ha^{-1}). The carbon stock recorded in FOR at various depths was significantly ($p<0.05$) higher than TEA and CRP. The lowest stock was recorded in CRP (22.70 t ha^{-1}) at 30 - 45 cm. FOR (0-45 cm) stock was 38% and 62% higher than TEA and CRP. Between 0-15 and 15 – 30 cm, the decrease in carbon stock was more rapid in CRP than in FOR and TEA, whereas between 15-30cm and 30-45 cm depth, the decrease was almost stable (3%) in CRP, but it was rapid in TEA (36%). However, all the ecosystems recorded a decline, with depth increment (Table 1).

MBC among each ecosystems of conoor varied significantly ($p < 0.05$) and it follows (0-45cm): FOR (283.08 mg kg^{-1}) > TEA (94.64 mg kg^{-1}) > CRP (76.22 mg kg^{-1}). MBC in FOR was significantly higher when compared to all the other ecosystems at various depths of the soil profile. FOR recorded 67% and 73% higher MBC than TEA and CRP. TEA on the other hand rec-

Table 1. Bulk density (BD) and Carbon stock under different ecosystems of Conoor region

Ecosystems	BD (Mg m^{-3})			C Stock (t ha^{-1})		
	0-15 cm	15 -30 cm	30 - 45 cm	0-15 cm	15 -30 cm	30 - 45 cm
Tea plantation	1.43[a]	1.54[a]	1.59[a]	54.38[b]	44.32[b]	28.56[b]
Crop land	1.39[b]	1.46[b]	1.59[a]	32.02[c]	23.40[c]	22.70[c]
Forest	1.32[c]	1.40[c]	1.45[b]	81.24[a]	66.62[a]	56.44[a]

Values in same column followed by different letters are significantly different ($p<0.05$).

Table 2. Distribution of various carbon pools under different ecosystems of Conoor region

Ecosystems	MBC (mg kg^{-1})			MBN (mg kg^{-1})		
	0-15 cm	15 -30 cm	30 - 45 cm	0-15 cm	15 -30 cm	30 - 45 cm
Tea plantation	121.62[b]	90.51[b]	71.79[b]	19.94[b]	13.39[b]	11.99[b]
Crop land	94.04[c]	74.35[c]	60.26[b]	16.79[c]	12.31[b]	7.98[c]
Forest	339.21[a]	281.09[a]	228.93[a]	32.39[a]	29.63[a]	24.49[a]

Values in same column followed by different letters are significantly different ($p<0.05$).

orded 19% higher MBC than the CRP. There was a significant decrease in MBC across the depth of soil profile. FOR recorded 17% decrease in MBC between 0-15 cm and 15-30 cm, 19% decrease between 15-30 cm and 30-45cm, whereas TEA and CRP recorded 26%, 21% decrease between 0-15 cm and 15-30 cm and 21% and 19% decrease between 15-30 cm and 30 -45cm (Table. 2).

MBN in the different ecosystems in conoor ranged between 32.39 mg kg^{-1} to 7.98 mg kg^{-1} with the highest being recorded at FOR at all depths. The overall average MBN in FOR was 28.83 mg kg^{-1}, which is 48% and 57% higher than TEA and CRP. The average MBN under different ecosystems of NHR ranged from 67.14 mg kg^{-1} to 9.51 mg kg^{-1}. The concentration of MBN was higher at 0-15 cm depth and decreased significantly across the depth of the soil profile. The soils under cultivation (CRP and TEA) recorded the lowest MBN in all depths when compared with FOR. CRP and FOR registered a maximum decline in MBN between 15-30 cm and 30-45cm, in the case of TEA it was higher between 0-15 cm and 15-30 cm depth (Table. 2).

BD was negatively correlated with TOC, carbon stocks and carbon pools, whereas TOC was positively correlated with carbon stocks and carbon pools. There exists a strong correlation between carbon pools (MBC and MBN) (Fig. 1)

Since carbon stock accounts for more soil properties (TOC and BD) than other parameters, it was chosen to evaluate the LDI of the different ecosystems. The FOR with the highest carbon stock has been chosen as a reference land use to compare other ecosystem. The results of LDI in TEA at different depth are -33.07 (0-15cm), -33.48 (15-30 cm), -49.40 (30-45cm) and in case of CRP it is -60.59 (0-15cm), -64.87 (15-30 cm), -59.78 (30-45cm). LDI in TEA was maximum at surface soils (0-15 cm and 15 -30 cm), whereas the LDI in CRP was maximum at sub-surface soil (30-45cm). CRP registered 83%, 94% and 21% higher degradation at 0 - 15 cm, 15 - 30 cm and 30 - 45cm when compared to

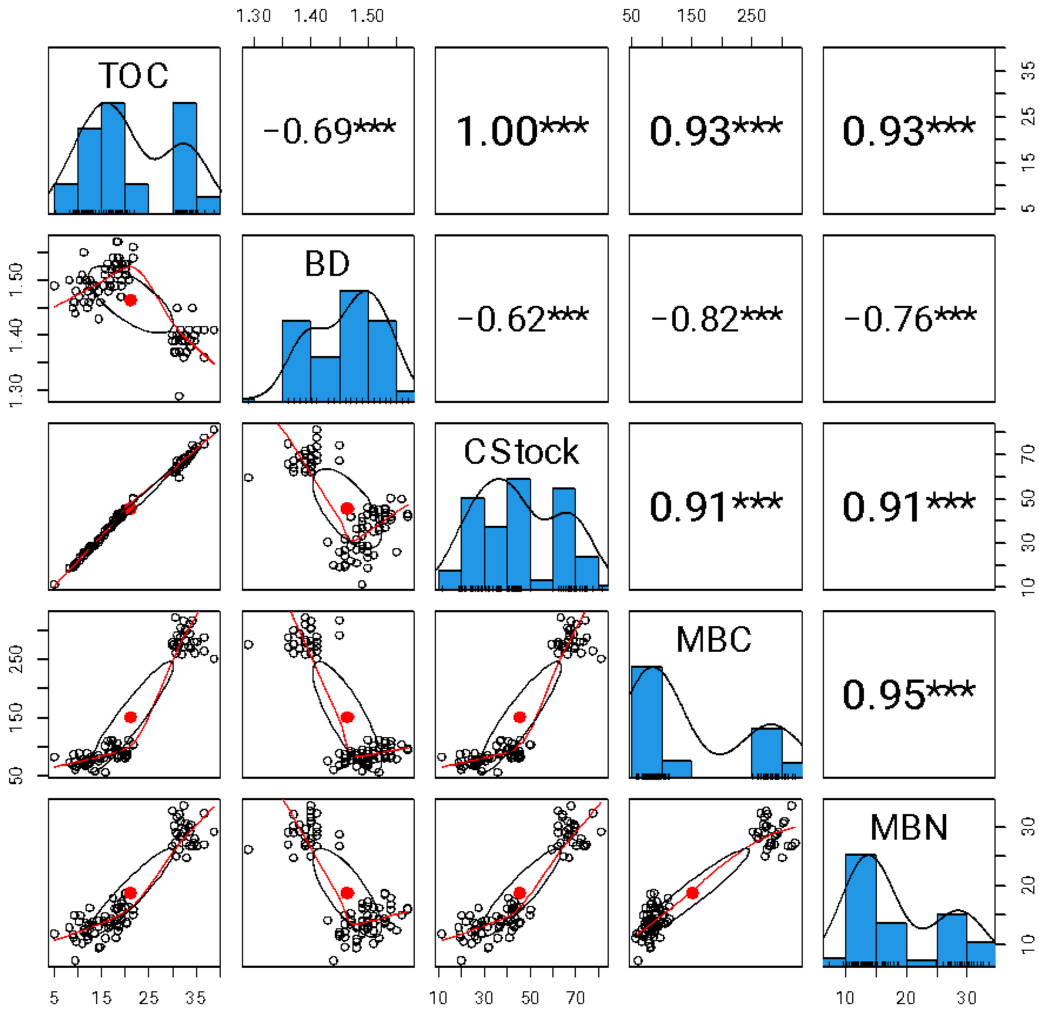


Fig. 1. *Distribution of carbon pools and total organic carbon under different ecosystems and the correlation values with * to specify significant correlations (Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1)*

Table 3. Effects of different ecosystems of Conoor on land degradation index (LDI)

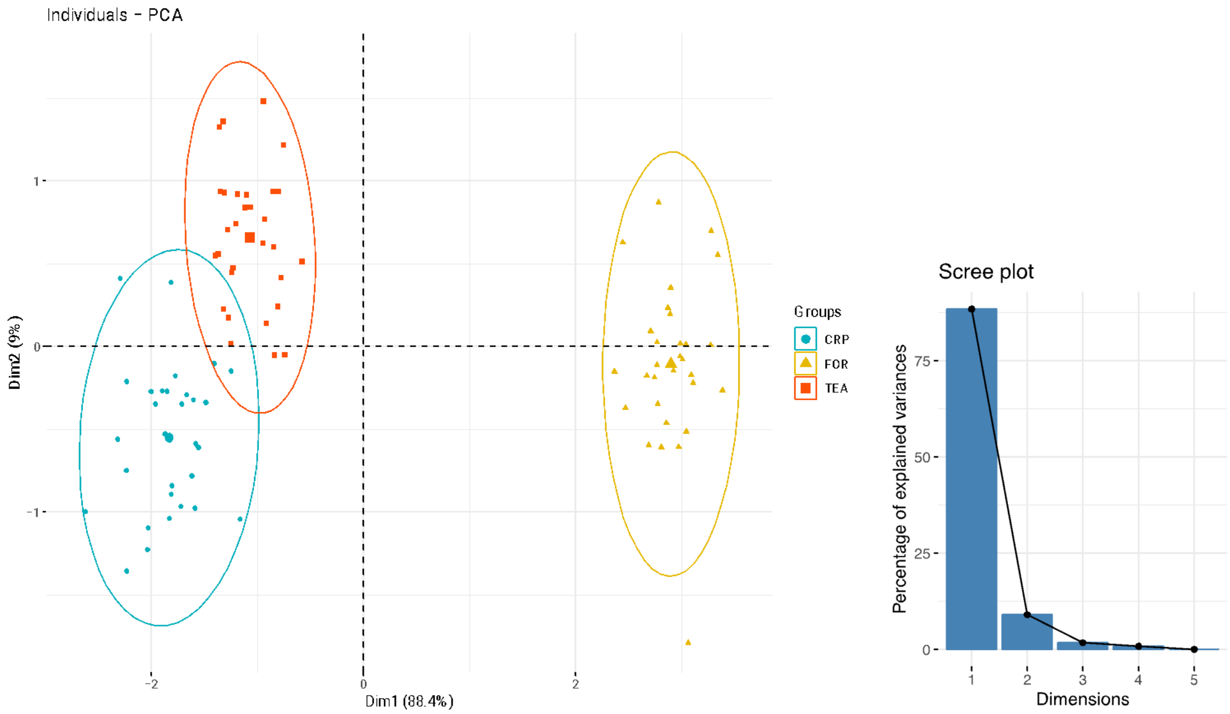
Depth	LDI (Tea plantation)	LDI (Crop land)
0-15 cm	-33.07	-60.59
15 - 30 cm	-33.48	-64.87
30 – 45 cm	-49.40	-59.78

*Reference ecosystem - Forest

TEA ecosystem (Table. 3).

DISCUSSION

Humans produced food at the cost of soil quality depletion (McNeill and Winiwarter 2004). Only a few decades after scientific understanding, this depletion has been linked to soil carbon stocks and carbon pools. Carbon in soil delivers infinite services to human beings. Unfortunately, due to large-scale LUC and intensive farming, the carbon reserve in the terrestrial ecosystem has been affected and resulted in emissions of higher CO_2.
Deforestation of native forest land to other land use has inflicted a severe decline in TOC concentration (Wang *et al.*, 2014). Initially, those native lands (FOR) were treasuring enough carbon in soils, owing to its architecture, such as canopy structure, which helped them in providing additional carbon inputs and maintained the available soil moisture. This ultimately fostered a higher concentration of TOC in FOR soils (Nath *et al.*, 2018). Beginning in the 19th century, Conoor had undergone a major change in its land-use types through deforestation, accompanied by the introduction of plantations and croplands to meet the need of the growing economy (Krishnan, 2015). This ultimately led to a decline in forest cover (Thirumalai *et al.*, 2015) and soil fertility (Iqshanullah, 2019). Thus, it affects the soil structure without proper management practice when the native land gets converted for other land use. This ultimately results in the depletion of macro aggregates (rich in carbon) (Six *et al.*, 2000) and the gain of micro aggregates (poor in carbon). Thus when a larger aggregate is subjected to LUC without any additional carbon input, they tend to degrade and oxidize to CO_2.
Higher TOC in FOR fosters a higher stock and lower BD in different land-use types (Fig 1). The decrease in TOC along the depth leads to a lesser stock and higher BD in sub-surface soils (Hsu *et al.*, 2021). These results corroborate the findings of Getachew *et al.* (2012). The highest carbon stock in FOR than CRP and TEA was in agreement with Stockmann *et al.* (2013), who reported a decline in carbon stocks when the existing forests get converted to plantation (−13%) and cropland (−42%).
Results of PCA (Fig 2) also prove LUC, change in vegetation, anthropogenic disturbances, and climate can have a significant impact on the soil carbon status (Intergovernmental Panel on Climate Change, 2007). It is evident that principal component 1 (TOC) results in 84.2 % variable clustering at the right end of the biplot and makes the native land (FOR) unique. Carbon



Dimensions (1 - TOC, 2 – BD, 3- Carbon stock, 4 – MBC, 5 – MBN)

Fig. 2. *Principal component analysis (PCA) of various carbon pools under different ecosystems of Conoor region.*

stock and carbon pools result in 9 % variability (Fig 2). This portrays that the properties of TEA and CRP were closer when compared to that of FOR which are far apart. Thus TEA and CRP, which are farther from FOR indicate a higher level of degradation upon LUC.

Soil microbial biomass carbon (MBC), a labile carbon pool (Hanson *et al*., 2000) is an index of disturbance and stress in the soils (Hernández *et al*., 1997) and is highly sensitive to LUC. Thus the less disturbed FOR with higher microbial activity due to its deep root system accompanied with litter fall favour higher MBC (Arunachalam *et al*., 1999). Higher MBC in FOR than at TEA and CRP agrees with other reports (dos Santos *et al*., 2019; Kooch *et al*., 2019; Mganga and Kuzyakov 2014). The variation in vegetation composition and agricultural practices such as tillage results in a decline of MBC in TEA and CRP (Van Leeuwen *et al*., 2017) which is in congruent with other findings (Soleimani *et al*., 2019). MBC on the other hand highly depends on substrates which are rich in organic matter. Thus a decrease in TOC causes a decrease in MBC (Wang and Wang 2011; Chen *et al*., 2017; Padalia *et al*., 2018). MBC decreases with depth (Lepcha *et al*., 2020) due to lower TOC in subsoils and it was supported by various other findings (Fall *et al*., 2012; Soleimani *et al*., 2019)

MBN in soils is attributed to prevailing climatic conditions, vegetation, soil types and properties (Anderson and Domsch, 1989; Priha, 1999; Murrieta *et al*., 2007). With its dense structure, the FOR accumulates higher litter and roots, favouring a significant contribution of nitrogen to microbial biomass growth (Diaz-Ravina *et al*., 1988; Jenkinson, 1988). This results in the highest MBN in FOR than in TEA and CRP. In addition, TOC in the soils plays a role in determining MBN (McCulley and Burke, 2004). Thus higher TOC in FOR leads to more stabilization of soil nitrogen and results in higher MBN (Schimel *et al*., 1994).

From the present findings, it is clear that LUC has resulted in the depletion of carbon pools and thus land degradation. In order to estimate the extent of land degradation, LDI (land degradation index) was worked out with FOR as a reference soil (Chidozie *et al*., 2019). Among TEA and CRP, the land degradation in TEA was minimal. However, the TEA and CRP recorded significantly lower values than FOR. Hence, proper strategies are needed to bridge depleted carbon in TEA and CRP. The present study proposes this area to explore the potential of soil further to sequester more carbon.

Conclusion

Forest ecosystems with minimal anthropogenic disturbances resulted in a higher carbon stock, MBC and MBN than in tea and cropland ecosystem. This in turn indicates the most stable nature of accumulated soil carbon in forest ecosystems. The findings suggest that the carbon pools and carbon stocks under the varying depth of soil profile are severely affected by land-use type. Thus the dynamics of carbon turnover should be carefully governed in order to enhance the carbon sequestration potential of the tea and cropland ecosystem. Minimal anthropogenic disturbance coupled with the continuous addition of crop residues in the forest ecosystem has led to higher carbon built-up, and this in turn plays a major role in sustaining the health of the soil. Thus the present study spotlights, the need for an improvement of soil carbon status in the degraded ecosystems of Conoor by adapting suitable carbon management strategies.

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Conflict of interest

The authors declare that they have no conflict of interest.

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