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Research Article

Carbon management Index under different land uses of Conoor region of Western ghats in Tamil Nadu

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Abstract
The increased land-use change (LUC) from native lands to other land use at the Conoor region of western ghats in Tamil Nadu has severely declined soil carbon concentration. Therefore to quantify this decline, Carbon Management Index (CMI) was worked out under major land uses {(Forest (FOR), cropland (CRP), tea plantation (TEA)} using total organic carbon (TOC) and carbon pools under varying degrees of lability {a) NLC (non-labile carbon) b) VLC (very labile carbon) c) LC (labile carbon) d) LLC (less labile carbon)}. Results portray that the carbon pools were significantly ($p < 0.05$) higher in FOR than in TEA and CRP. The contribution of active pools {(very labile carbon (VLC) and labile carbon (LC)} towards TOC was higher in TEA and CRP, whereas in FOR, the passive pool {(less labile carbon (LLC) and non-labile carbon (NLC)} was higher. TOC (0-45 cm) was concentrated on the surface soils of FOR (32.88 g kg^{-1}), CRP (11.87 g kg^{-1}) and TEA (18.84 g kg^{-1}) and it gradually declined with the increase in depth. The decline in TOC was maximum between 0 – 15 and 15 – 30 cm depth in CRP (30.62%) and FOR (22.17%), whereas it was maximum (37.16%) between 15 -30 and 30 -45 cm depth in TEA. Therefore, LUC spotlights the degradation of carbon pools and its extent was quantified using the carbon management index (CMI). The CMI (0 – 45 cm) recorded at CRP (12.93) and TEA (32.62) signals the need for an implementation of carbon management strategies at Conoor to keep the soils alive and protect biodiversity.

Keywords: Carbon management index, Carbon pools, Conoor, Land-use change, Soil organic carbon

INTRODUCTION

Soils organic carbon (SOC), an ecosystem engineer, directly influences the global carbon cycle (Nath *et al.*, 2021). They have the ability to maintain quality and restore sustainability in the soil (Chaplot *et al.*, 2010; Srinivasarao, 2020a). SOC has been fostered in soils with varying degrees of decomposition rate and stability (Regnier *et al.*, 2013). Based on this, they are classified as 1) an active pool, which turns over a period of a few days; 2) slow pool; turnover lasts up to centuries and it represents the stabilized form of carbon; 3) passive pools - the most stabilized and persists for over thousands of year (Trumbore, 1997).

The native forest land, owing to its minimal disturbances, encompasses the most stable form of carbon and sequesters 25% of the global carbon emissions (Wei *et al*., 2013). Unfortunately, due to deforestation of these native land, the land-use change (LUC) has altered the carbon pools, with the depletion of soil carbon concentration (Sahoo *et al*., 2019). Various studies have also showcased the inverse relationship between soil carbon concentration and LUC (Golchin *et al*., 1995). Thus in the global carbon cycle, organic carbon is crucial in deciding whether the soils should act as a carbon sink or source. The soil with the stabilized recalcitrant carbon acts as a sink (Paustian *et al*., 2019) and this process shows a tremendous promise of reducing the carbon footprint. But upon LUC, the soil carbon loses its stability and serves as a source. Increasing LUC of native forest land (Sanderman *et al*., 2017) has degraded 33% of global soils (Food and Agriculture Organization, 2019) and this, in turn, has led to the increased concentration of CO_2 in the atmospheric (143.3 × 109 to 148.8 × 109 tn) (Lal *et al*., 2018; Ramesh *et al*., 2019). Therefore the soil which earlier served as a sink of carbon has now become the source and this in turn, warns the global community to curb it through the implementation of suitable strategies (Ross *et al*., 2016).

Although the TOC varies with land uses, it is not susceptible to short-term changes as the labile fractions. As a result, calculating the liability of TOC in each land use serves an early predictor of soil deterioration. Thus the lability of the TOC { carbon management index (CMI)} has been utilised in diverse land uses to evaluate a land use's potential to increase soil quality in order to apply more sensitive indicators (Sainepo *et al*., 2018).

Nestled in the western ghats, Conoor is a part of UNESCO's World Heritage site and biodiversity hotspot. Owing to the large-scale conversion of native land to other land use (Saravanan *et al*., 2021) the Conoor region has become highly susceptible to natural hazards (Chandrasekaran *et al*., 2013). At this juncture, the Conoor, undergoing large-scale LUC, has no prior studies on soil carbon pools. Hence this study attempted to address the unexplored carbon pools of the Conoor region and provide insights to manage the carbon efficiently using the Carbon Management Index (CMI) to keep the soils of Conoor alive and protect biodiversity.

MATERIALS AND METHODS

Site description

Covering an area of about 22%, Conoor region of western ghats in Tamil Nadu is situated between 11 ^{0} 20 'North, 11^{0}25' North latitude, 76^0 44' East and 77^0 00' East longitudes, at an altitude of 1500 to 2546 m amsl (above mean sea level). Predominant bedrock is the charnockite group (metamorphic rock) overlying the laterite with geomorphic features such as a denudational hill, denudational slope, debris slope and plateau. This region receives rainfall from the southwest monsoon with average annual rainfall between 1400 – 2000 mm year -1 and the temperature range between 0 to 28 °C.

A field investigation (2021 -2022) was carried out with the help of local people to survey the different ecosystems of Conoor. This region witnessed a rapid LUC from native forest land to cultivation, plantation and commercial activities. Farmers revealed that tea, carrot, garlic, potato, beans, and cauliflower are the most common crops grown here as rainfed with large-scale tillage, pesticides and fertilizers.

Soil sampling

Soil sampling was carried out in FOR, TEA and CRP ecosystems of Conoor. Samples in each location were collected randomly (90 samples) from five different quadrats and in three depth classes ("0-15", "15-30", "30 – 45" cm). Those collected samples were pooled to get 3 bulk samples per plot. They were sieved to separate debris and rock fragments and finally packed into the laboratory. Triplicates of each sample were analyzed. TOC was analyzed with a TOC analyzer (Elementar) (Jackson, 1973).

Carbon pools have been categorized based on varying degrees of lability, *viz*, a) NLC (non-labile carbon) b) VLC (very labile carbon) c) LC (labile carbon) d) LLC (less labile carbon) and are estimated by modifying the concentration of H_2SO_4 (12N, 18N, 24N) (Chan et al. 2001) in the original Walkley and Black method, Walkley and Black (1934). Active pool (AP) of carbon is the combination of VLC and LC, whereas the Passive pool (PP)) of carbon is the combination of LLC and NLC

Carbon management index (CMI)

CMI is an assessment tool which predicts how the land-use change impacts the quality of soil in comparison to the reference land use (Blair *et al.*, 1995).

The index is formulated as follows:

$$\mathrm{CMI} = \mathrm{CPI} * \mathrm{LI} * 100 \tag{1}$$

CPI - carbon pool index, LI - lability index

Statistical analysis

Analysis of variance (ANOVA) has been carried out with the sampling sites as replicates or random effects and the various ecosystems as 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"*, creating network maps using the package "*qgraph*", and computing the PCA (Principal Component Analysis). For visualization R packages like *ggplot, Complex Heatmap, Factoextra, FactoMineR, and dendextend* were used.

RESULTS

VLC (g kg^{-1}) in each land uses differed significantly ($p < 0.05$). VLC under different land uses of Conoor follows FOR > TEA > CRP. VLC recorded in FOR at 0-15 cm (10.23 g kg^{-1}) was the highest. The overall (0-45 cm) VLC in each land uses was TEA – 6.19 g kg^{-1}, CRP – 4.26 g kg^{-1}, and FOR – 8.33 g kg^{-1}. The concentration of VLC has decreased along with the depth of the soil profile. This decrease was maximum between 0 -15 cm to 15 - 30 cm depth in TEA (30%) and CRP (34%), whereas it was between 15 - 30 cm and 30-45 cm depth in FOR (22%) ecosystem (Fig 1, Table 1).

LC (g kg^{-1}) under different land uses of Conoor was significantly different ($p < 0.05$) and follows FOR (6.92 g kg^{-1}) > TEA (3.95 g kg^{-1}) > CRP (2.50 g kg^{-1}). LC recorded in Conoor ranged between 1.75 g kg^{-1} to 8.84 g kg^{-1}. The average LC (0-45 cm) in each land uses are; TEA – 3.95 g kg^{-1}, CRP – 2.50 g kg^{-1}, and FOR – 6.92 g kg^{-1}. The concentration of LC was maximum at the surface and it decreased with depth increment (Fig 1, Table 1). LC in CRP followed a similar trend as VLC, but in the case of TEA, the decrease in LC was maximum (47%) between 15 - 30 cm and 30-45 cm depth and in FOR it was between 0 -15 cm to 15 - 30 cm depth (33%).

LLC (g kg^{-1}) found in Conoor was significantly different ($p < 0.05$) in each land uses. LLC follows FOR > TEA > CRP. LLC in FOR was 42% higher than TEA and 66% higher than CRP. LLC ranged between 1.75 g kg^{-1} to 8.84 g kg$^{-1,}$ with the lowest in CRP and highest being recorded at FOR. The overall (0-45 cm) LLC in each land uses are; TEA – 3.82 g kg^{-1} , CRP – 2.23 g kg^{-1}, and FOR – 6.59 g kg^{-1}. The concentration of LLC decreased along with the depth, which was in line with LC (Fig 1, Table 1).

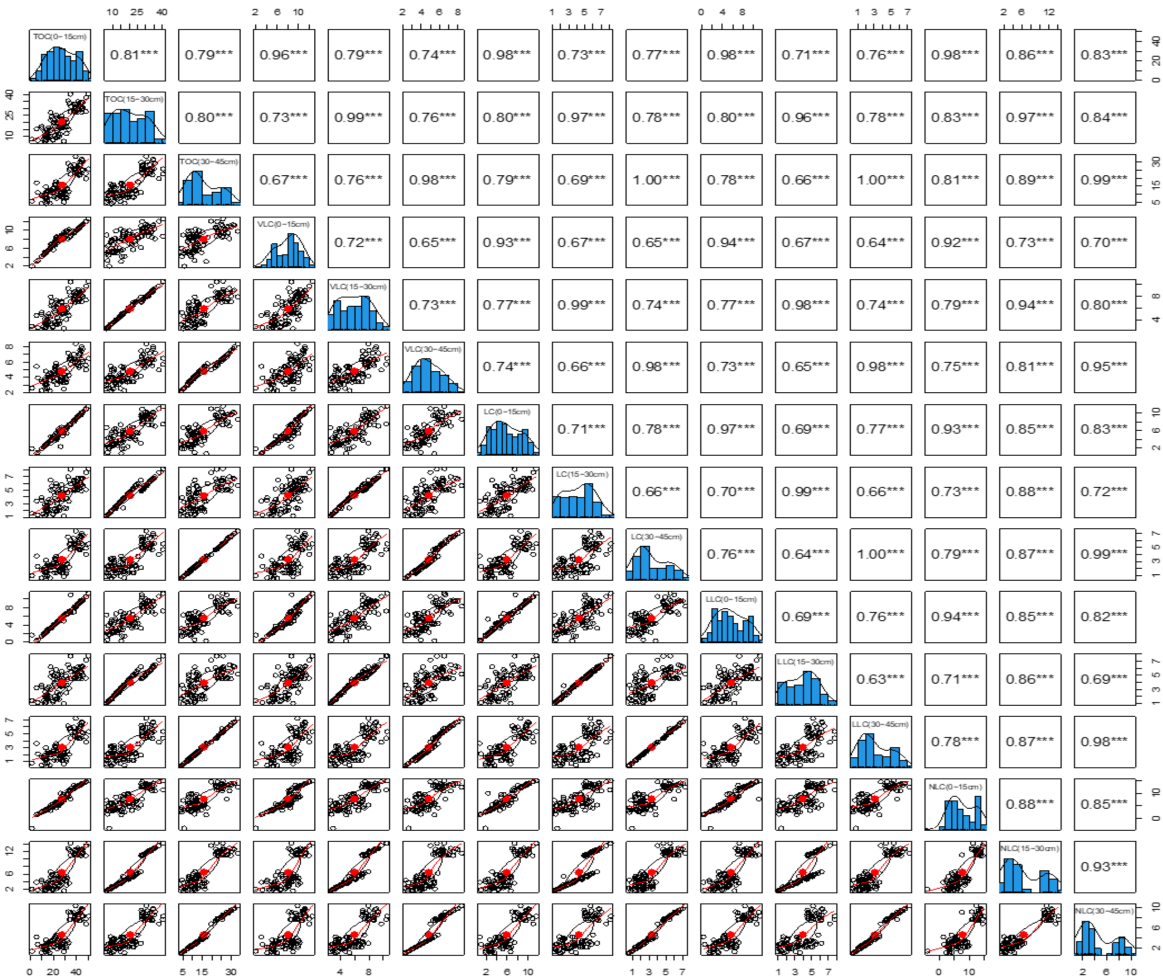


Fig. 1. *Distribution of carbon pools and total organic carbon under different ecosystems and the correlation values with * to specify significant correlations (Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1)*

Table 1. Distribution of various carbon pools under different land uses of Conoor

Ecosystems	VLC (g kg^{-1})			LC (g kg^{-1})		
	0-15 cm	15 -30 cm	30 - 45 cm	0-15 cm	15 -30 cm	30 - 45 cm
Crop land	5.55^{c}	3.67^{c}	3.56^{c}	3.32^{c}	2.29^{c}	1.89^{b}
Tea Plantation	8.35^{b}	5.83^{b}	4.39^{b}	5.18^{b}	4.37^{b}	2.31^{b}
Forest	10.23^{a}	8.28^{a}	6.48^{a}	9.08^{a}	6.05^{a}	5.62^{a}
Ecosystems	LLC (g kg^{-1})			NLC (g kg^{-1})		
	0-15 cm	15 -30 cm	30 - 45 cm	0-15 cm	15 -30 cm	30 - 45 cm
Crop land	2.89^{c}	2.03^{c}	1.75^{b}	3.64^{c}	2.70^{c}	2.32^{c}
Tea Plantation	5.11^{b}	4.20^{b}	2.15^{b}	6.73^{b}	4.72^{b}	3.15^{b}
Forest	8.84^{a}	5.55^{a}	5.37^{a}	12.75^{a}	11.96^{a}	8.41^{a}
Ecosystems	AP (g kg^{-1})			PP (g kg^{-1})		
	0-15 cm	15 -30 cm	30 - 45 cm	0-15 cm	15 -30 cm	30 - 45 cm
Crop land	8.87^{c}	5.96^{c}	5.45^{c}	6.54^{c}	4.73^{c}	4.07^{c}
Tea Plantation	13.53^{b}	10.20^{b}	6.71^{b}	11.84^{b}	8.93^{b}	5.31^{b}
Forest	19.31^{a}	14.33^{a}	12.10^{a}	21.60^{a}	17.51^{a}	13.79^{a}

Values in the same column followed by different letters are significantly different ($p < 0.05$); NLC (non-labile carbon); VLC (very labile carbon); LC (labile carbon); LLC (less labile carbon; AP (active pools); PP (passive pools)

Table 2. Effects of different land use of Conoor on carbon management index

Ecosystem	0-15 cm	15 - 30 cm	30 – 45 cm
		CPI	
Crop land	0.38^{c}	0.34^{c}	0.37^{c}
Tea ecosystem	0.62^{b}	0.60^{b}	0.46^{b}
*Forest ecosystem	1.00^{a}	1.00^{a}	1.00^{a}
		LI	
Crop land	0.37^{c}	0.38^{c}	0.34^{c}
Tea ecosystem	0.57^{b}	0.72^{b}	0.41^{b}
*Forest ecosystem	1.00^{a}	1.00^{a}	1.00^{a}
		CMI	
Crop land	13.78^{c}	12.68^{c}	12.34^{c}
Tea ecosystem	35.38^{b}	43.35^{b}	19.12^{b}
*Forest ecosystem	100.00^{a}	100.00^{a}	100.00^{a}

Values in the same column followed by different letters are significantly different ($p<0.05$). CPI (Carbon Pool Index), LI (Lability Index), CMI (Carbon Management Index);*Reference ecosystem

There was a significant ($p < 0.05$) difference observed in NLC (g kg^{-1}) among each land use of Conoor. NLC in Conoor follows FOR (11.04 g kg^{-1}) > TEA (4.87 g kg^{-1}) > CRP (2.89 g kg^{-1}). NLC in Conoor varied from 2.32 g kg^{-1} to 12.75 g kg^{-1}. The overall average NLC (0-45 cm) among each land uses is as follows; TEA – 4.87 g kg^{-1}, CRP – 2.89 g kg^{-1}, FOR – 11.04 g kg^{-1}. NLC recorded in FOR was 56% higher than TEA and 74% higher than CRP. The concentration of NLC was maximum at the surface and it decreased with depth increment (Fig.1). NLC in CRP and TEA followed the similar trend of LLC, but in the case of FOR, the decrease in LC was maximum (30%) between 15 - 30 cm and 30-45 cm depth (Table 1).

The active pool (sum of VLC and LC) of carbon was higher in FOR (15.25 g kg^{-1}) followed by TEA (10.15 g kg^{-1}) and CRP (6.76 g kg^{-1}). Passive pool (sum of LLC and NLC) of carbon in different ecosystem follows FOR (17.63 g kg^{-1}) > TEA (8.69 g kg^{-1}) > CRP (5.11 g kg^{-1}). The contribution of AP toward TOC was higher in CRP and TEA, whereas the contribution of PP toward TOC was higher in FOR (Fig 1, Table 1).

TOC in each ecosystem of Conoor followed FOR > TEA > CRP. FOR (32.88 g kg^{-1}) was significantly higher than other land uses. The concentration of TOC under various land uses of Conoor differed significantly ($P < 0.05$), with the highest (40.91 g kg^{-1}) being recorded at FOR in 0-15 cm depth (Fig 1). TOC (0-45 cm) found in FOR was 64% higher than CRP and 43% higher than TEA. TOC in TEA was 37% higher than CRP. The TOC concentration was found to decrease with the increase in depth.

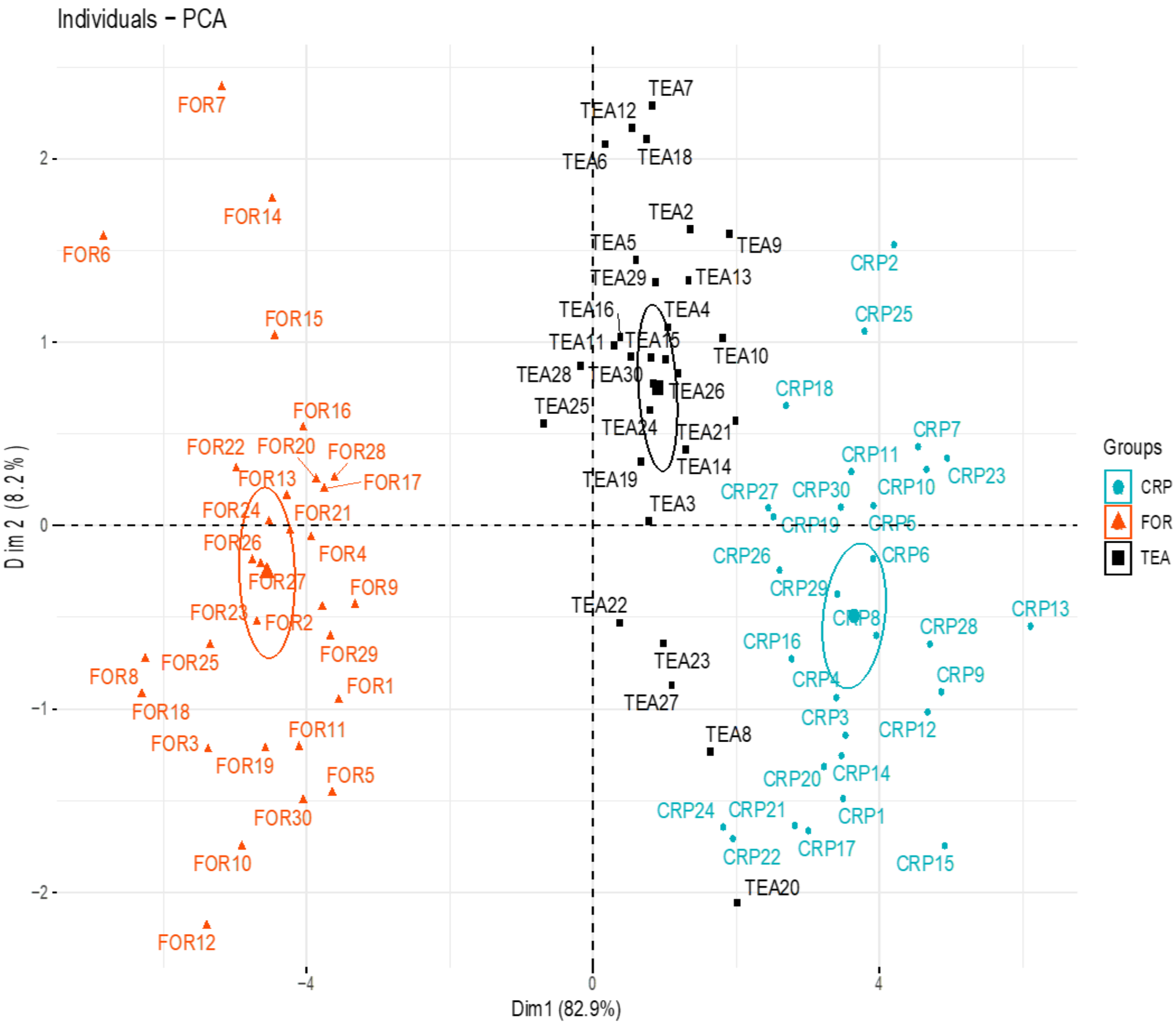
Various carbon pools under different oxidizability were positively correlated with TOC. The correlation between the carbon pools and TOC was highest at 0-15 cm depth and decreased along the soil profile depth (Fig 1).

FOR ecosystem with the highest TOC was selected as a reference ecosystem. Carbon pool index (CPI) ranged from 0.34 to 0.62. It was significantly higher in TEA than in CRP. CPI in TEA followed 0.62 (0-15 cm) > 0.60 (15-30cm) > 0.46 (30 -45cm) and in CRP 0.34 (15-30cm) > 0.37 (30 -45cm) > 0.38 (0-15 cm). LI ranged from 0.34 to 1.00 and LI in TEA and CRP (0-45 cm) was 0.57 and 0.36, which was 43% and 64% lower than FOR. CMI ranged from 12.34 to 100. CMI recorded in TEA was higher than CRP, but compared to FOR, the CMI in TEA and CRP was much less (Table 2).

DISCUSSION

Land-use change from native forest land to other land resulted in the degradation of soil and its organic carbon concentration (Jendoubi *et al*., 2019). Native lands (FOR), owing to their carbon inputs and tree architecture, sequester enough carbon within their ecosystem, resulting in higher TOC in FOR soils (Nath *et al*., 2018) than in other ecosystems. Since the 19th century, Conoor in Nilgiris has witnessed a large-scale land-use change, which has declined the forest cover (Hailu *et al*., 2020) and ultimately the soil fertility (Iqshanullah, 2019) due to the degradation of macro aggregates which in turn results in the gain of micro aggregates. Macro aggregates without additional carbon input in CRP and TEA have no scope for further improvement unless appropriate carbon management strategies are provided. Thus, with inputs, they tend to degrade by oxidized and get converted to carbon dioxide.

The results of PCA portray the variable clustering of native land (FOR), owing to its higher concentration of variable pools of TOC makes them unique (Fig 1, Table



Dimensions (1 - TOC, 2 – VLC, 3- LC, 4 – LLC, 5 – NLC)

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

1). TOC alone accounts for 82.9% of variability among the land uses (Fig 2). LUC thus impacts the concentration of soil carbon and its pools (VLC, LC, LLC, NLC) in TEA and CRP, clustered farther apart from FOR. This indicates the level of degradation in TEA and CRP which is incongruent with the findings of Stockmann *et al.* (2013) and Nath *et al*. (2021), who reported the degradation of soil quality and carbon due to the conversion of native forests to other land use types.

Among the variable pools of carbon which are significantly higher in FOR, their contribution towards TOC varied among the land use type. VLC contributed a major share to TOC in CRP and TEA compared to other fractions. This may be due to the easily decomposable litters and root exudates (Zhang *et al.* 2020) in CRP and TEA than FOR. Since the fertilizer application in Conoor was higher in TEA and CRP, it could have also resulted in variability among the active carbon pools in TEA and CRP when compared to FOR, which is more stable and recalcitrant (NLC). This was congruent with other studies reported (Sahoo et al., 2019). Thus when the land is subjected to disturbance, it alters the carbon dynamics, with an increase in unstable VLC. VLC, upon further disturbance due to cultivation and other anthropogenic activities, gets converted to CO_2 and enters the atmosphere. With the higher VLC, AP was higher than PP in CRP and TEA. The stable native land with higher recalcitrant pools makes PP higher than AP in FOR land use.

Thus LUC has altered the carbon dynamics among the land uses in Conoor. In order to estimate the dynamics of carbon among each land uses, the carbon management index (CMI) was worked out (Sainepo *et al*., 2018) with a native forest as a reference ecosystem (due to its undisturbed natural settings and higher TOC concentration). Though CMI was higher in TEA than CRP, it was far less than FOR. This indicated the level of degradation in CRP and TEA due to their reduction in the carbon sequestering potential. Henceforth, this necessitates the implementation of appropriate strategies to bridge carbon depletion in TEA and FOR. However, this work has not focussed on improving the carbon sequestration potential of soils. The present study proposes an area to explore further in future studies for this area.

Conclusion

Carbon pools and CMI under different land uses of the Conoor region of western ghats in Tamil Nadu portray the degradation of carbon inflicted by anthropogenic activities. Owing to the minimal disturbances, FOR registered the highest concentration of TOC, carbon pools and CMI than TEA and CRP. The recalcitrant carbon pool was higher in FOR than in TEA and CRP. At the same time, the active pools of carbon were found to be higher in TEA and CRP. The lower CMI in TEA and CRP necessitates implementing carbon management strategies to rehabilitate the degraded TEA and CRP to keep the soil alive and protect biodiversity.

Conflict of interest

The authors declare that they have no conflict of interest.

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