PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 12(2): 1-11
https://doi.org/10.14719/pst.6626

HORIZON
e-Publishing Group
HePG

RESEARCH ARTICLE

Assessing the carbon management index across land use changes in Kolli Hills, Eastern Ghats, Tamil Nadu

Perumal Deepana[1], Selvi Duraisamy[1*], Thiyageshwari Subramaniam[1], Rangasamy Anandham[2], Senthil Alagarswamy[3], Ramalingam Kumaraperumal[4], Manimaran Gajendiran[1], Shanmugam Aravindan [5], Kavinkumar Subramaniyam[6] & Vivek Perumal[7]

*Email: selvi.d@tnau.ac.in

[1]Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[2]Department of Agricultural Microbiology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[3]Department of Crop Physiology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[4]Department of Remote Sensing and GIS, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[5]Department of Genetics and Plant Breeding, Indian Council of Agricultural Research, Central Institute for Cotton Research, Regional Station, Coimbatore 641 003, Tamil Nadu, India

[6]Department of Chemistry, Technical Service Head, Southern Water Tech, Erode 638 052, Tamil Nadu, India

[7]Department of International Business Management, Sheffield Hallam University, Ponds Forge S1 2AP, United Kingdom

OPEN ACCESS

ARTICLE HISTORY

Received: 10 December 2024
Accepted: 19 January 2025

Available online
Version 1.0 : 21 April 2025
Version 2.0 : 19 June 2025

Check for updates

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

CITE THIS ARTICLE

Deepana P, Duraisamy S, Subramaniam T, Anandham R, Alagarswamy S, Kumaraperumal R, Gajendiran M, Aravindan S, Subramaniyam K, Perumal V. Assessing the carbon management index across land use changes in Kolli Hills, Eastern Ghats, Tamil Nadu . Plant Science Today. 2025; 12(2): 1-11. https://doi.org/10.14719/pst.6626

Abstract

Alterations in land patterns in Kolli Hills (KH) of the Eastern Ghats, Tamil Nadu (TN), transitioning from native ecosystems to various land uses, have notably diminished soil carbon concentrations. To measure this reduction, the carbon management index (CMI) was evaluated across key land-use categories, including agricultural system (AS), horticultural system (HS), plantation system (PS), thorn forest (TF), deciduous forest (DF) and evergreen forest (EF). The analysis focused on total organic carbon (TOC), total carbon (TC), total inorganic carbon (TIC) and carbon pools with varying degrees of lability, including less labile carbon (LLC), labile carbon (LC), very labile carbon (VLC) and non-labile carbon (NLC). The findings indicated that EF's carbon pools were markedly higher ($p < 0.05$) than AS and HS. The contribution of LC, VLC, LLC and NLC to TOC was highest in EF and DF, while it was lowest in AS and HS. The TOC at 15 cm depth was highest in the surface soils of EF (106.17 g kg^{-1}), with a gradual decline in concentration with increasing depth. This highlights carbon pool degradation from land-use change, quantified by the CMI. When EF was used as the reference ecosystem, the CMI was higher in DF (51.93) and TF (45.69) at a 30 cm depth, while AS (10.75) and HS (12.46) showed a much lower CMI. These findings highlight the need to implement effective carbon management strategies in KH to restore soil vitality and safeguard biodiversity.

Keywords

carbon management index; carbon pools; Eastern Ghats; Kolli Hills; land use change

Introduction

Soil organic carbon (SOC) is a significant component of soil health and sustainability (1, 2). SOC is critical in global carbon cycling, enhancing soil fertility and structure (3). Three distinct SOC pools have different stability and decomposition rates: (i) the active pool, with LC, has a turnover of days to weeks; (ii) the slow pool is more stable, turning over in decades to centuries; and (iii) the passive pool, containing NLC, lasts thousands of years (4). While SOC is crucial, TIC, primarily composed of carbonates, also significantly influences soil carbon stocks. Although less dynamic, TIC plays a crucial role in regulating CO_2 exchange between the soil and the atmosphere, buffering soil acidity and influencing carbon sequestration in arid or semi-arid regions (5, 6). SOC and TIC comprise TC, a gauge of soil properties' health and functionality. The ratio of these fractions can change depending on soil properties, the climate and the practices used to use the land. Land use changes (LUC) significantly affect the dynamics of SOC, TIC and soil thermal properties. Conversion of natural ecosystems into agricultural or other anthropogenic uses can have a number of negative repercussions, including the destabilization of SOC pools, the reduction of overall soil carbon stores and the increase in greenhouse gas emissions (7, 8). Additionally, changes in land use can affect the dynamics of TIC (9, 10). These modifications can change soil pH, moisture and biological activity. It is necessary to ensure careful monitoring of TC fractions and their lability to understand soil function and direct approaches for carbon sequestration (11, 12). CMI has become a valuable tool for assessing the build-up of SOC and providing early warning signs of soil deterioration. This is accomplished by analyzing the stability and lability of TOC (13).

The KH, which are located in Tamil Nadu (TN) and are part of India's Eastern Ghats (EG), are a location that is both ecologically and culturally significant. Kolli Hills, well-known for its unique biodiversity, traditional farming methods, and unusual terrain, is seeing increasing land-use changes due to plantation forestry, infrastructural development, and agricultural growth (14–16). These changes have made the area vulnerable to soil degradation processes, including nitrogen loss, erosion and carbon depletion, affecting SOC and TOC stocks (17–20). Despite its ecological significance, this region's understanding of soil organic carbon (SOC) is limited. This is particularly true concerning the impacts of various land-use changes on SOC stability, TC concentrations, and TC sequestration potential. The aim is to report this gap by analyzing the CMI in KH across different land alterations, focusing on the relationships between TOC, TIC, and TC. This study aims to: (i) understand how land-use changes influence TOC, TC and TIC dynamics in Kolli Hills; (ii) identify sensitive indicators of soil degradation and carbon lability; and (iii) provide practical recommendations for sustainable soil and land management. Considering the urgent need to battle climate change worldwide through effectively implementing carbon sequestration strategies, this work has wide-ranging implications. This study highlights the importance of protecting soil carbon reservoirs in KH and preserving soil biodiversity and functionality in ecologically similar regions facing similar challenges.

Materials and Methods

Site description

The KH have an area of around 280 km^2 and are located in Tamil Nadu's Eastern Ghats. The KH are is positioned at an elevation of 500 to 1500 m above MSL and spans latitudes 11°00'N to 11°45'N and longitudes 77°00'E to 77°30'E. Laterite overlies the granite and metamorphic charnockite that make up the majority of the bedrock in the area. The terrain has geomorphic features such as plateaus, debris slopes, hills, and slopes that have been depleted. The region experiences temperatures fluctuating from 20 °C to 30 °C, with the southwest monsoon serving as the primary source of rainfall, averaging between 1400 and 2000 mm annually. Local inhabitants, agricultural officers, horticulture officers, assistant agriculture and horticulture officers, forest rangers and foresters provided valuable assistance during the field survey conducted in KH from 2022 - 2023. The report indicates minimal anthropogenic stress on forestlands, including DF, TF and EF. However, human activities have a substantial impact on other ecosystems, including PS, HS and AS. The majority of these ecosystems are rainfed agroecosystems in India's EG. Since the 17^{th} century, the KH have undergone extensive forest conversion to accommodate plantations, agriculture and various economic activities.

Soil sampling and analysis

Six major ecosystems, namely EF, DF, TF, AS, HS and PS, were examined to determine the distribution of TOC, carbon pools, TIC, carbon pool index (CPI), lability index (LI), TC and CMI throughout the Eastern Ghats. Forty samples were taken from each ecosystem's surface and subsurface layers, for a total of 480 soil samples (Fig. 1). Five 1 m^2 quadrats were sampled at each site, with the soil categorized into 2 depth ranges: 0 - 15 cm and 15 - 30 cm. After removing stones and plant debris with a 2.0 mm mesh, the samples were divided into 3 subsamples for in-depth examination. TOC was analyzed using a TOC analyzer (Elementar vario TOC analyzer) (21). TIC was evaluated using diluted hydrochloric acid and TOC was computed by subtracting TIC from TC. Using a modified approach, the oxidizable organic carbon (OOC) fractions were calculated (22). Unlike the stable $K_2Cr_2O_7$ concentration, the OOC fractions were determined using varying H_2SO_4 concentrations - 24 N, 18 N and 12 N applied at 2:1, 1:1 and 0.5:1 respectively (23). Active pools (AP) are the result of adding LC and VLC. The entire NLC and LLC, on the other hand, were referred to as passive pools (PP). CMI is largely supported by research on soil improvement, deterioration and LUC. This model, often called an indicator-cum-evaluation model, demonstrates the effects of LUC on the soil quality of an ecosystem in relation to a reference environment. It is calculated according to standardized method (24). The formula for the CMI is the product of the LI and CPI times 100. The sample TOC is divided by the reference soil's TOC to determine the CPI. The ratio of oxidized to unoxidized car-

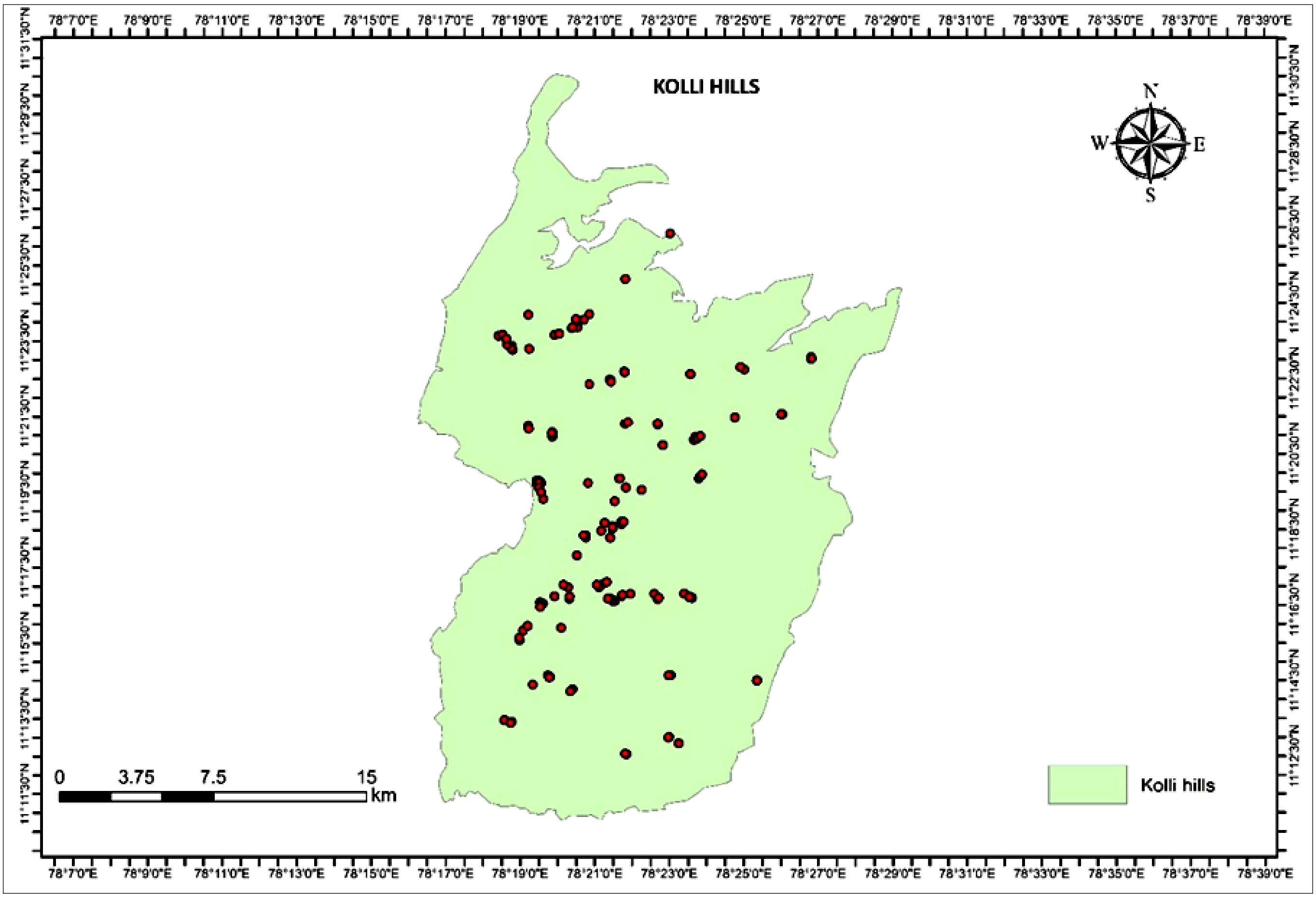

Fig. 1. Location map of Kolli Hills, Eastern Ghats. The red dots indicate Eastern Ghats ecosystem sample locations.

bon in $KMnO_4$ indicates the lability of carbon. The carbon lability of the reference soil is divided by the carbon lability of the sample soil to determine the LI.

Statistical Analysis

ANOVA was performed using distinct ecosystems as fixed treatment effects and sample locations as duplicates. Duncan's Multiple Range Test was used to compare means and identify significant differences among land-use systems at $p < 0.05$. Principal Component Analysis, conducted using R software version 4.1.1, and network maps made with the "graph" package were examples of additional statistical investigations. Additionally, R's built-in "cor" function was used to conduct correlation analysis.

Results

The variations in TOC, TIC and TC across various ecosystems at two soil depths are shown in Fig. 2. The EF system outperformed the others with the greatest TOC of 106.17 g kg^{-1} at 0 - 15 cm. The order of the TOC at 0 - 15 cm in the various ecosystems is as follows: EF, DF, TF, PS, HS and AS. The same pattern was also observed at 30 cm deep. At a 0 - 30 cm depth, the TIC in AS increased even further, reaching 6.03 g kg^{-1} at 0 - 15 cm. This was maximum than that of EF (2.17 g kg^{-1}). The TIC was maximum at 0 - 30 cm for the AS (7.92 g kg^{-1}) > HS (6.98 g kg^{-1}) (Fig. 2). In all ecosystems, the higher TC was found in surface soil (108.34 g kg^{-1}), and its EF was often higher than that of subsurface soil. The greatest TC of the surface soil resulted from the following circumstances: EF (108.34 g kg^{-1}) > DF (86.09 g kg^{-1}) > TF (71.66 g kg^{-1}). The TC of surface soil was higher than that of subsurface soil in all environments. The concentrations of TC were lowest (41.77 g kg^{-1}) in the AS at 0 - 30 cm and higher (96.24 g kg^{-1}) in the EF (Fig. 2).

The study examined 4 distinct carbon pools, LLC, VLC, NLC, and LC, across 6 ecosystems (Table 1). The highest LC content was measured in EF between 0 and 15 cm below the surface and lowest at AS. The soil VLC content ranged from 8.54 to 28.88 g kg^{-1} throughout the different ecosystems down to 30 cm. It was maximum in EF represented by DF (17.98 g kg^{-1}) and TF (16.90 g kg^{-1}) at 0 to 15 cm depth, whereas the concentrations in the latter habitats were noticeably lower. Compared to EF, which exhibited a maximum LLC at 0 to 15 cm, HS (13.22 g kg^{-1}) and AS (7.71 g kg^{-1}) had lower LLCs. At a 0 to 30 cm depth, EF had the highest LLC of 18.03 g kg^{-1} among the various systems (Table 1). The EF had a significantly higher NLC than other ecosystems. At a 0 - 15 cm depth, the EF's maximum NLC concentration was 32.37 g kg^{-1}, more than similar ecosystems. A similar pattern was also observed at a depth of 30 cm.

The CPI in the different ecosystems fluctuated from 0.32 to 1.00 at 0 - 30 cm depth, using the EF as a reference habitat due to its stable, undisturbed nature, rich in soil carbon. Comparing other ecosystems to EF highlights changes in soil carbon stability, aiding in assessing land-use impacts and ecosystem health. The surface soil beneath the DF had a higher CPI (0.63) and a lower AS (0.22) at 0 to 15 cm. For every habitat, the CPI gradually

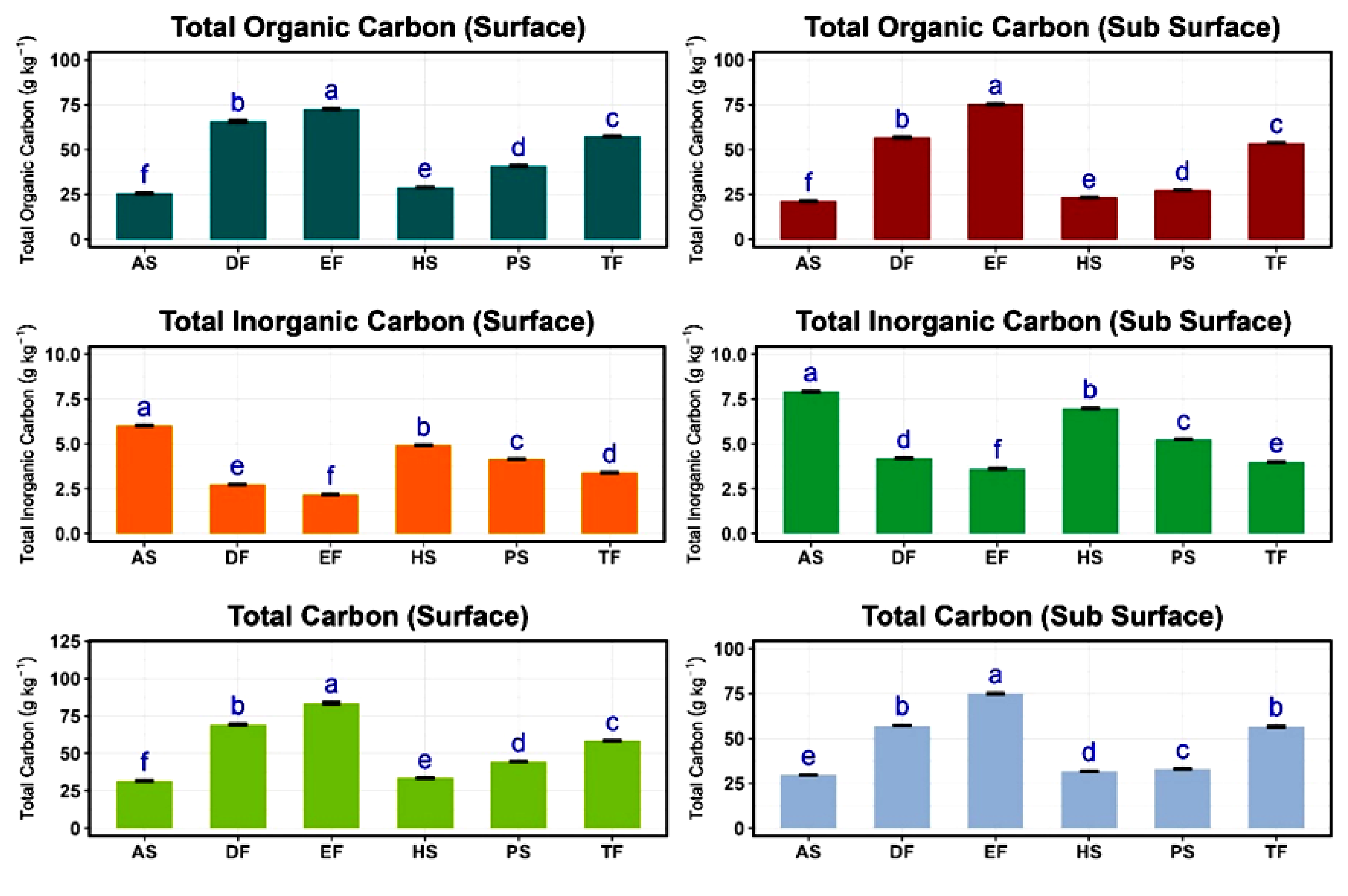

Fig. 2. Total organic carbon, total inorganic carbon, and TC in Eastern Ghats ecosystems at two depths. DMRT results show significant differences ($p < 0.01$) in histograms at depths ranging from 0 to 15 cm and 15 to 30 cm (DF - Deciduous Forest, PS - Plantation System, EF - Evergreen Forest, AS - Agriculture System, TF - Thorn Forest, HS - Horticulture System).

Table 1. Distribution of different carbon pools across various land uses in the Kolli Hills, Eastern Ghats

Ecosystems	Labile carbon ($g\ kg^{-1}$)		Very labile Carbon ($mg\ kg^{-1}$)		Less labile carbon ($g\ kg^{-1}$)		Non labile carbon ($g\ kg^{-1}$)	
	Soil Depth							
	0 - 15 cm	15 - 30 cm	0 - 15 cm	15 - 30 cm	0 - 15 cm	15 - 30 cm	0 - 15 cm	15 - 30 cm
Evergreen Forest	20.90 ± 0.03^{a}	18.77 ± 0.03^{a}	31.81 ± 0.06^{a}	28.88 ± 0.06^{a}	21.09 ± 0.05^{a}	18.03 ± 0.01^{a}	32.37 ± 0.02^{a}	26.94 ± 0.04^{a}
Deciduous Forest	14.69 ± 0.05^{b}	9.81 ± 0.03^{c}	17.98 ± 0.05^{b}	14.06 ± 0.01^{c}	20.47 ± 0.02^{b}	16.85 ± 0.06^{b}	30.21 ± 0.01^{b}	25.16 ± 0.01^{b}
Thorn Forest	13.40 ± 0.03^{c}	11.78 ±	16.90 ± 0.02^{c}	15.49 ± 0.04^{b}	20.22 ± 0.04^{c}	15.69 ± 0.02^{c}	17.73 ± 0.06^{c}	15.69 ± 0.02^{c}
Agriculture System	8.74 ± 0.02^{f}	7.39 ± 0.02^{e}	10.75 ± 0.02^{f}	8.54 ± 0.01^{f}	7.71 ± 0.02^{f}	12.23 ± 0.01^{e}	7.46 ± 0.03^{f}	5.69 ± 0.02^{e}
Horticulture System	10.85 ± 0.02^{e}	7.12 ± 0.01^{f}	14.41 ± 0.01^{e}	12.17 ± 0.02^{d}	13.22 ± 0.02^{e}	6.37 ± 0.01^{f}	8.21 ± 0.01^{e}	5.94 ± 0.01^{d}
Plantation System	11.12 ± 0.01^{d}	8.75 ± 0.01^{d}	15.27 ± 0.03^{d}	10.68 ± 0.04^{e}	17.84 ± 0.05^{d}	13.40 ± 0.05^{d}	9.02 ± 0.01^{d}	4.96 ± 0.02^{f}

The data are presented as mean ± standard error. Values within the same column followed by different letters indicate significant differences. Duncan's multiple range test was employed to compare means and assess the significance of mean variations between ecosystems. Statistical significance was considered at $p < 0.05$.

decreased with depth (Table 2). In the different ecosystems, the CPI sequence was as follows: PS > AS > HS > DF > TF. The lability index (LI) was consistently higher in surface soils than in subsurface soils across all habitats, with the order being DF > TF > PS > HS > AS. As depth increased, LI decreased. DF had the greatest LI (0.66), followed by TF (0.59), as seen in Table 2. The lowest LI (0.32) under AS was recorded at 0 - 15 cm. A similar pattern was also observed between 0 and 30 cm. At 0 to 30 cm depth, the CMI in different ecosystems ranged from 6.56 to 42.51. In comparison to TF (38.91), PS (17.78), HS (10.77), and AS (6.56), the CMI in the DF was 42.51 at a depth of 15 cm and increased even more at 0 - 30 cm. The DF (51.93) > TF (45.69) > PS (19.19) > HS (12.46) > AS (0.75) had the highest CMI at 0 - 30 cm (Table 2).

Carbon fractions and the TOC and the TIC, TC, and SOC index (CPI, LI and CMI), were found to be significantly

Table 2. Carbon Management Index across various land uses in the Kolli Hills, Eastern Ghats

Ecosystems	Carbon pool index		Lability index		Carbon management index	
	Soil depth					
	0 - 15 cm	15 - 30 cm	0 - 15 cm	15 - 30 cm	0 - 15 cm	15 - 30 cm
Evergreen forest	1.00 ± 0.101[a]	1.00 ± 0.004[a]	1.00 ± 0.013[a]	1.00 ± 0.001[a]	100.00 ± 0.06[a]	100.00 ± 0.14[a]
Deciduous forest	0.63 ± 0.002[b]	0.71 ± 0.001[b]	0.66 ± 0.002[b]	0.71 ± 0.003[b]	42.51 ± 0.16[b]	51.93 ± 0.22[b]
Thorn forest	0.46 ± 0.001[c]	0.52 ± 0.003[c]	0.59 ± 0.001[c]	0.51 ± 0.001[c]	38.91 ± 0.07[c]	45.69 ± 0.06[c]
Agriculture system	0.22 ± 0.001[f]	0.32 ± 0.001[d]	0.32 ± 0.001[f]	0.12 ± 0.004[f]	6.56 ± 0.01[f]	10.75 ± 0.03[f]
Horticulture system	0.31 ± 0.001[e]	0.36 ± 0.002[e]	0.38 ± 0.001[e]	0.35 ± 0.001[e]	10.77 ± 0.03[e]	12.46 ± 0.03[e]
Plantation system	0.36 ± 0.001[d]	0.42 ± 0.001[d]	0.53 ± 0.001[d]	0.45 ± 0.002[d]	17.78 ± 0.04[d]	19.19 ± 0.01[d]

The data are presented as mean ± standard error. Values within the same column followed by different letters indicate significant differences. Duncan's multiple range test was employed to compare means and assess the significance of mean variations between ecosystems. Statistical significance was considered at $p < 0.05$.

positively correlated. The carbon fractions and TOC were found to be significantly correlated. A noteworthy positive correlation was discovered between the SOC index and TOC. For surface soil samples, TOC correlated positively with TC ($r^2 = 0.67$), CMI ($r^2 = 0.67$), CPI ($r^2 = 0.65$) and NLC ($r^2 = 0.61$), but negatively with TIC ($r^2 = -0.46$) (Fig. 3). Similarly, in subsurface soil samples, TOC correlated positively with NLC ($r^2 = 0.70$), TC ($r^2 = 0.68$), CPI ($r^2 = 0.67$) and CMI ($r^2 = 0.65$), but negatively with TIC ($r^2 = -0.48$) (Fig. 4). To find important markers of soil quality at 2 depths, soil samples were subjected to PCA. Principal Component Analysis (PCA) is appropriate for this analysis, as it reduces the dimensionality of complex datasets to identify the most important variables that explain the largest possible variance in soil quality across the 2 depths. Dimensionality reduction with PCA makes identifying critical soil quality indicators easier and discern patterns or relationships within the data. CMI, TIC, LI and VLC are significant indicators of soil biological quality since PC1 accounted for 58.1 % of the variation in surface soil samples. The variables VLC, CMI, TIC and LI (Labile Organic Carbon) are significant indicators of soil quality for various reasons. VLC represents highly reactive carbon rapidly decomposed by microbes, reflecting the biological activities in soil and the availability of easily decomposable organic matter. The CMI refers to the management practices of the soil, indicating its effect on carbon storage and showing future potential for maintaining sustainable carbon and soil health management. TIC signifies the presence of inorganic carbon, which may impact soil pH and nutrient availability, mainly in alkaline soils. LI shows signs of easily decomposable organic matter, vital for microbial activity linked with nutrient cycling. Together, these variables give an elaborate understanding of carbon dynamics, microbial health and soil management; hence, they are significant in evaluating soil quality. PC2 explained 11.3 % of the variance and emphasized the importance of LC, NLC and LLC (Fig. 5). Subsurface soil samples showed similar results, with PC1 explaining 52.9 % of the variance and PC2 12.2 % (Fig. 6). According to the variable biplot and PCA analysis across various soil depths, TIC and LI contributed the most, followed by LC and TC. These findings highlight the importance of managing both inorganic and organic carbon components in soil for optimizing soil fertility, microbial activity and carbon sequestration. Soil management practices can be tailored to enhance these carbon pools, ensuring sustainable soil use and improving agricultural productivity while promoting environmental sustainability.

Discussion

Substantial LUC in the KH of the EG in TN has significantly impacted the region's ecologically diverse landscapes. These alterations have significantly influenced the changing aspects of soil carbon. Native ecosystems, especially EF, play a vital role as carbon reservoirs because of the large quantities of TOC that they contain and the stable carbon pools that they contain (25). EF soil carbon is both stable and resistant to decomposition, which highlights its significant function in preserving carbon stores and ensuring soil health. Conversely, changes in land use to AS and HS systems have resulted in the deterioration of macroaggregates, which has led to an upturn in microaggregates and a lessening in soil fertility (26–28). Without the implementation of targeted carbon management techniques, the potential of macroaggregates in AS and HS to undergo further improvement is restricted since they do not include any more carbon inputs. The decay of these aggregates results in carbon dioxide emissions, highlighting the importance of implementing environmentally responsible land management methods to mitigate the effects of these emissions (29–31). Principal Component Analysis (PCA) reveals major differences between undisturbed forests (EF) and disturbed ecosystems. EF clustering results from increased TOC, carbon pools, microbial activity and enzymatic activities, as demonstrated by PCA (32). There were considerable disparities between native forests (EF) and converted land uses such as AS and HS, as evidenced by the fact that TOC and TC accounted for 67.4 and 62.43 % of the variability among land uses respectively. When compared to AS, HS and PS, the concentrations of TC in EF were significantly greater (108.34 g kg^{-1}). The concentrations of TIC were maximum in AS (6.03 g kg^{-1}), shadowed by HS (4.92 g kg^{-1}), and then lower in EF (2.17 g kg^{-1}) respectively. This trend highlights the negative influence of intensive land-use practices on soil carbon stocks (33,

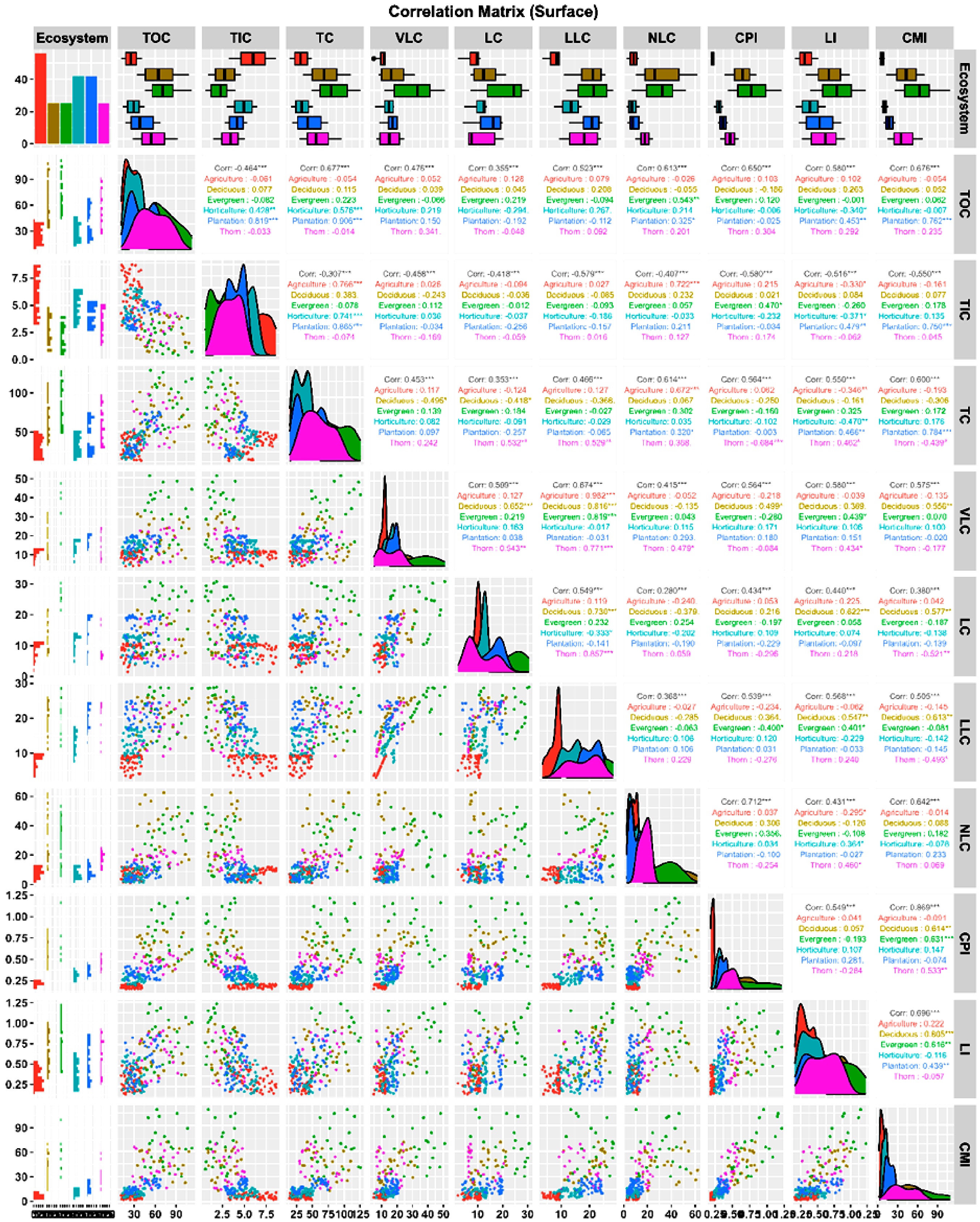

Fig. 3. Relationship between soil total organic carbon and soil characteristics in surface samples of the Eastern Ghats across different ecosystems. Each cell has scatter plots, density distributions and correlation coefficients (Corr) with significant correlations (***: 0.001 **: 0.01 *: 0.05 *: 0.1 *). Ecosystem-specific data is colored. The variables include Carbon Pool Index (CPI), Very Labile Carbon (VLC), Total Organic Carbon (TOC), Lability Index (LI), Labile Carbon (LC), Total Inorganic Carbon (TIC), Carbon Management Index (CMI), Less Labile Carbon (LLC), Total Carbon (TC) and Non-Labile Carbon (NLC).

34). Very labile carbon (VLC) was the predominant type of TOC in both EF and DF. This behaviour can be related to quickly decomposable litter and root exudates, which contribute to greater active pools (AP) in these land uses (35).

On the other hand, native forests had higher contributions from pools that were more stable and resistant to change, such as NLC, which was bigger in EF than in AS and HS carbon sources (36–38). This stability is vital for the enduring storage of carbon and it underlines the degrada-

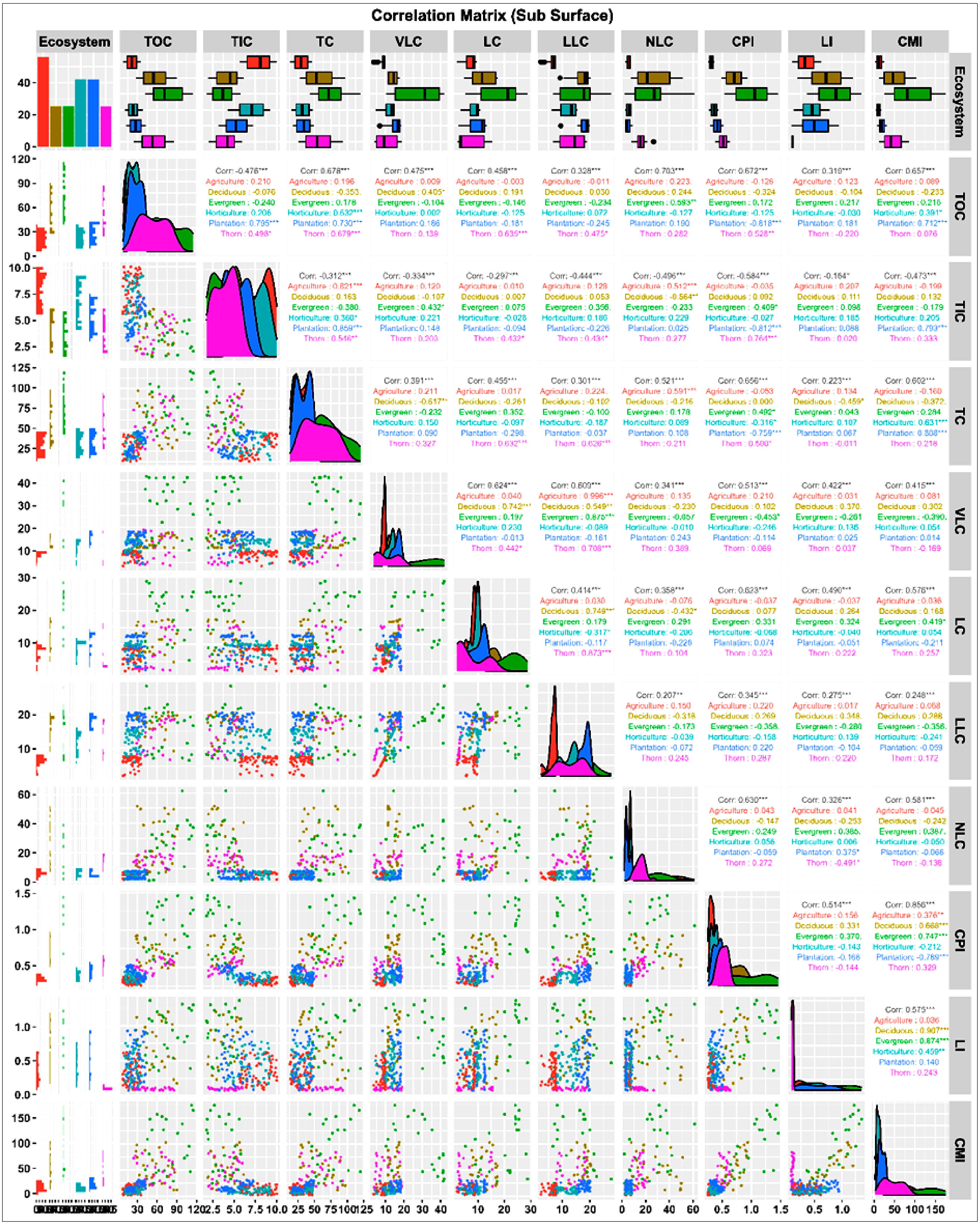

Fig. 4. Relationship between soil total organic carbon and soil characteristics in sub-surface samples of the Eastern Ghats across different ecosystems. Each cell has scatter plots, density distributions, and correlation coefficients (Corr) with significant correlations (***: 0.001 **: 0.01 *: 0.05 *: 0.1 *). Ecosystem-specific data is colored. TOC, TIC, TC, VLC, LC, LLC, NLC, CPI, LI and CMI are variables. The variables include Carbon Pool Index (CPI), Very Labile Carbon (VLC), Total Organic Carbon (TOC), Lability Index (LI), Labile Carbon (LC), Total Inorganic Carbon (TIC), Carbon Management Index (CMI), Less Labile Carbon (LLC), Total Carbon (TC) and Non-Labile Carbon (NLC).

tion found in AS and HS, where unstable VLC predominates and becomes susceptible to additional disturbance and CO_2 releases (39, 40). Given that EF is an undisturbed ecosystem with higher TOC content, the CMI was calculated using EF as the reference ecosystem. LI, CMI and CPI values were significantly lower than AS and HS, showing a loss in the carbon sequestering potential of soils under intense agricultural and horticultural use (41–43). This was the case even though CMI, LI, and CPI values were greater in DF. This data highlights the magnitude of soil degrada-

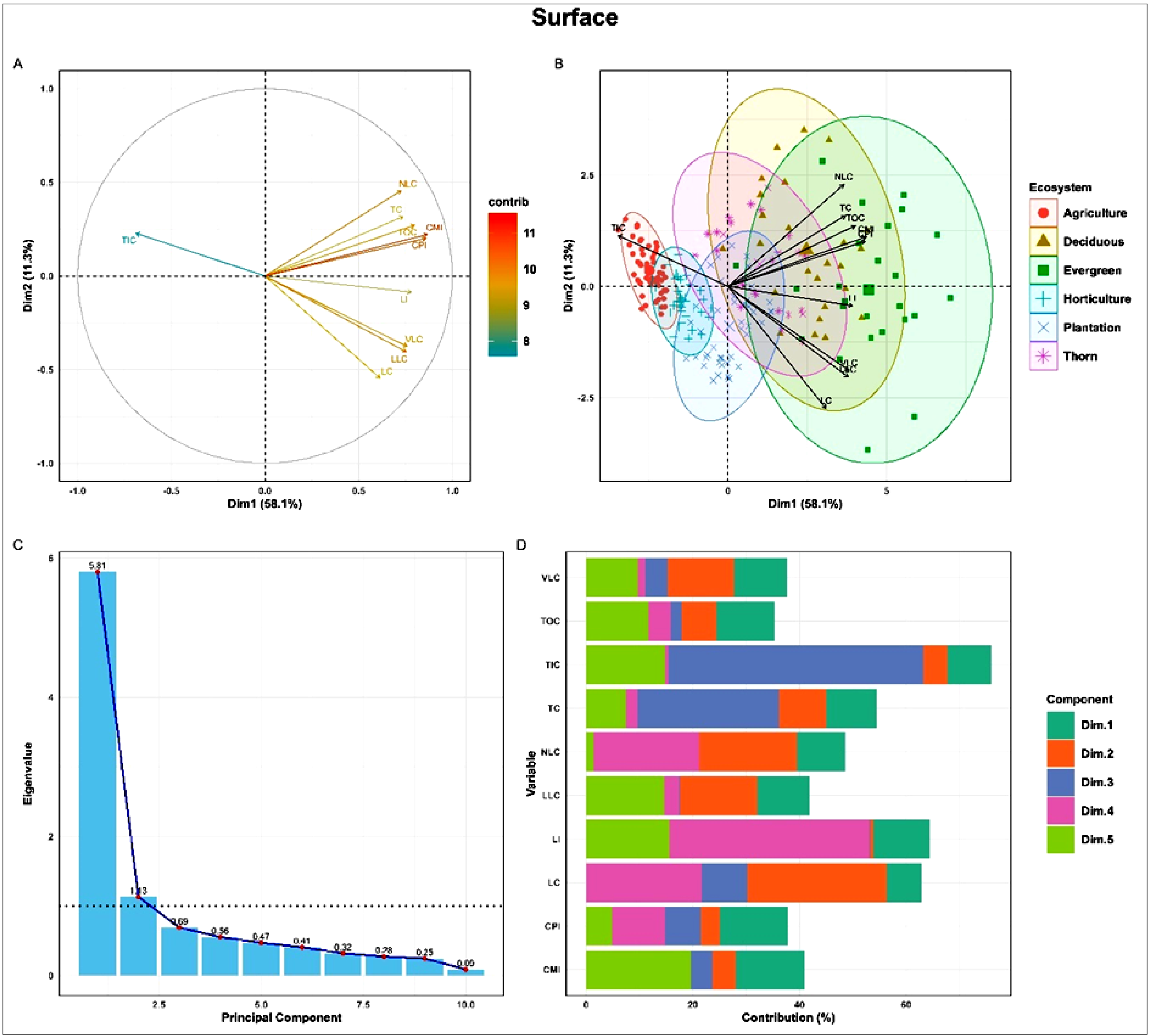

Fig. 5. PCA-based multivariate ecosystem property analysis utilizing surface soil samples. The biplot in Panel A illustrates variables and ecosystems. Panel B exhibits ecosystem distribution highlighting PCA with clustering ellipses. The scree plot in Panel C illustrates each primary component's variance explanation %. Panel D illustrates variable contributions to PCA dimensions.

tion in AS and HS and the pressing requirement for tailored interventions to restore soil carbon dynamics and boost sequestration potential (44). The research highlights the potential for restoration through carbon management systems that imitate the processes in native forests, although degradation was detected (45, 46).

Reducing carbon losses and restoring degraded systems to their former carbon-sequestering capacity is possible by implementing limited tillage, organic inputs and erosion management (47, 48). The findings align with the global efforts to counteract soil degradation, mitigate climate change and preserve biodiversity in ecologically sensitive locations such as the Kolli Hills. For instance, afforestation and reforestation have successfully restored degraded lands and increased soil carbon storage. Conservation agriculture practices such as zero-tillage, crop residue retention and crop rotation are good for improving soil organic carbon levels. Similarly, agroforestry systems that combine trees with crops or livestock provide dual benefits of carbon sequestration and income generation for farmers. The use of organic amendments such as compost, manure or biochar can enhance soil health and carbon content. Erosion control measures like contour farming, terracing and cover cropping prevent the loss of carbon-rich topsoil. Precision agriculture, through data-driven approaches to target fertilization and soil management, reduces carbon losses while optimizing productivity. Restoration of wetlands is also important due to their high potential for organic carbon storage.

This study highlights the enormous impact that LUC has on carbon dynamics. It also highlights the native forests display in preserving the firmness of SOC and the health of ecosystems. There has been considerable carbon degradation and soil fertility loss due to a land use transition to AS and HS. Native forests, such as EF, serve as resilient carbon stores. According to the findings, there is an immediate requirement for conservation-oriented mea-

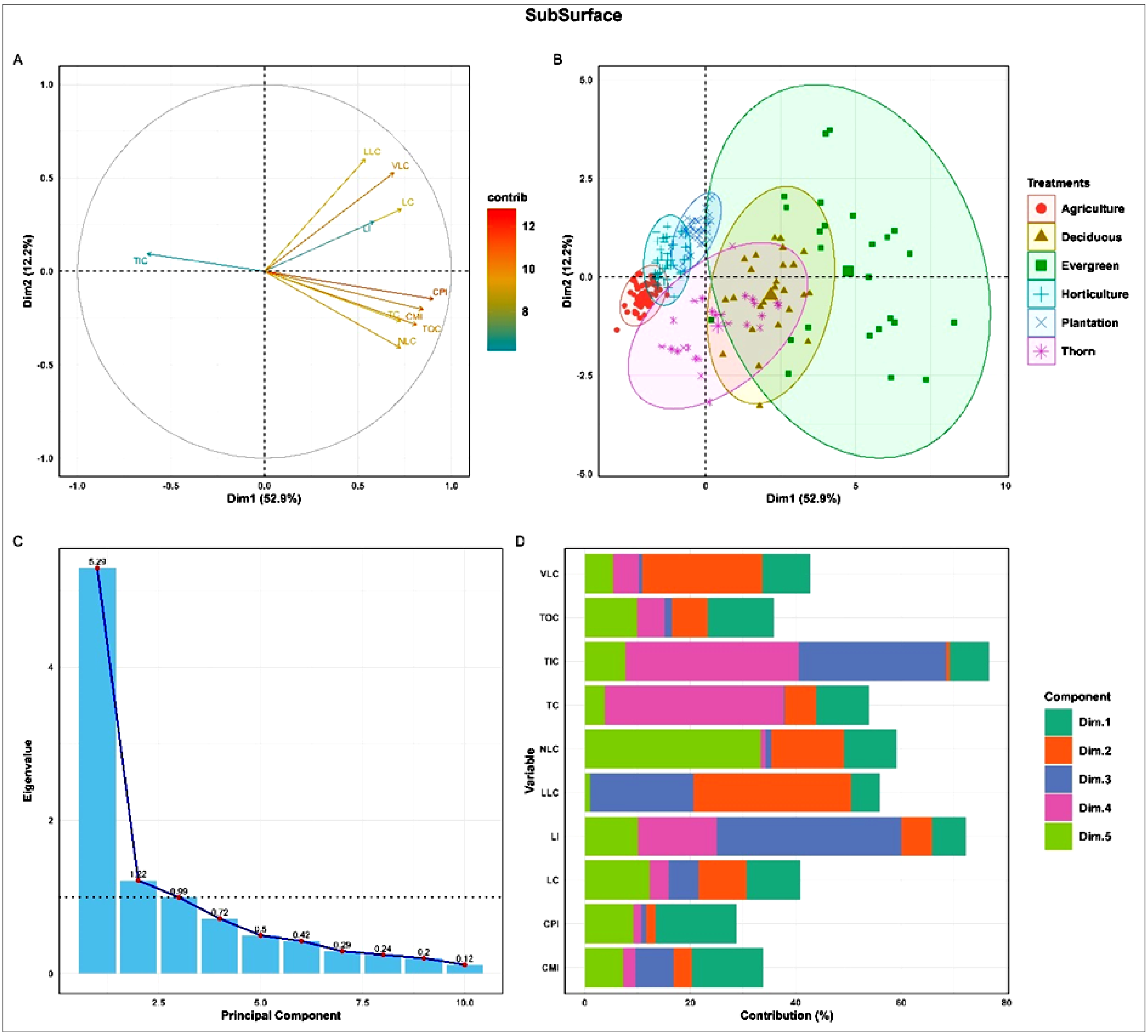

Fig. 6. Multivariate Principal Component Analysis (PCA) on subsurface soil samples for ecosystem characteristics. The biplot in Panel A illustrates variables and ecosystems. Panel B exhibits ecosystem distribution, highlighting PCA with clustering ellipses. The scree plot in Panel C illustrates each primary component's variance explanation %. Panel D illustrates variable contributions to PCA dimensions.

sures to safeguard ecosystem services and offer support for sustainable development. In addition, the study suggests potential rehabilitation measures. Still, it also recommends conducting additional research to refine mitigation techniques and improve the capacity of degraded systems (AS and HS) to sequester carbon. Monitoring the restoration activities over an extended period is necessary to guarantee the viability of soil health in Kolli Hills. The call for long-term monitoring can be strengthened through methodological proposals, such as permanent monitoring sites, remote sensing, isotopic analysis and carbon simulation models (CENTURY, e.g.). Such cross-site studies and socio-economic assessments would ensure this applicability, linking it to a more global aim of relevance and the communities. Experimental trials of innovative practices like biochar and regenerative agriculture could further move toward refining carbon management.

Conclusion

Severe soil carbon degradation in Kolli Hills, Tamil Nadu, results from anthropogenic activities. EF had the highest TOC, carbon pools, and CMI, while AS and HS showed deterioration. Agroforestry, reforestation and organic farming are crucial for restoring soil health and biodiversity. This study highlights carbon cycles, aiding climate change mitigation.

Acknowledgements

This research was funded by the Department of Science and Technology, Government of India. We extend our gratitude to the landowners, the Tamil Nadu Forest Department, Chennai, the Department of Agriculture and Farmers Welfare, Government of Tamil Nadu, Chennai, as well as the Departments of Forest, Agriculture, Horticulture, and Plantation Crops in Kolli Hills, Tamil Nadu, for granting permission to collect soil samples across various ecosystems in Kolli Hills, Eastern Ghats, as part of this study. This research was funded by the Department of Science and

Technology, Government of India, IF220114.

Authors' contributions

PD, SD, TS, and RA conceptualized and supervised the study, including methodology development, formal analysis, original draft preparation, review and editing, and data curation. SA and RK were responsible for project administration, investigation, and manuscript review and editing. MG, SA, KS and VP contributed to data analysis, preparation of figures and tables, and approval of the final draft. All authors reviewed and approved the final version of the manuscript for publication.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Quill Bot and AI assistance in order to enhance the readability and flow of content; after the original drafting. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

References

1. Nath PC, Nath AJ, Reang D, Lal R, Das AK. Tree diversity, soil organic carbon lability and ecosystem carbon storage under a fallow age chronosequence in North East India. Environ Sustain Indic. 2021;10:100122. https://doi.org/10.1016/j.indic.2021.100122
2. Chaplot V, Bouahom B, Valentin C. Soil organic carbon stocks in Laos: spatial variations and controlling factors. Glob Chang Biol. 2010;16(4):1380–93. https://doi.org/10.1111/j.1365-2486.2009.02013.x
3. Deepana P, Duraisamy S, Subramanium T, Anandham R, Alagarswamy S, Kumaraperumal R, et al. Anthropogenic land use impacts carbon dynamics in Kolli hills, Eastern Ghats, India. Environ Earth Sci. 2024;83:625. https://doi.org/10.1007/s12665-024-11928-0
4. Torn MS, Trumbore SE, Chadwick OA, Vitousek PM, Hendricks DM. Mineral control of soil organic carbon storage and turnover. Nature. 1997;389:170–73. https://doi.org/10.1038/38260
5. Salisu MA, Ismail F, Bamiro NB, Luqman H. Sustainable agriculture for food safety, security and sufficiency. In: Raimi L, Olatidoye OP, Said TFH, editors. Agripreneurship and the dynamic agribusiness value chain. Singapore: Springer; 2024. p. 29–60. https://doi.org/10.1007/978-981-97-7429-6_3
6. Sarkar T, Sengupta S, Kanthal S, Kundu S. Climate change mitigation through agroforestry improves natural resource and livelihood security. In: Jatav HS, Rajput VD, Minkina T, Van Hullebusch ED, Dutta A, editors. Agroforestry to combat global challenges. Sustainable development and biodiversity, vol 36. Singapore: Springer; 2024. p. 219–46. https://doi.org/10.1007/978-981-99-7282-1_12
7. Sahoo UK, Singh SL, Gogoi A, Kenye A, Sahoo SS. Active and passive soil organic carbon pools as affected by different land use types in Mizoram, Northeast India. PloS One. 2019;14(7):e0219969. https://doi.org/10.1371/journal.pone.0219969
8. Sanderman J, Hengl T, Fiske GJ. Soil carbon debt of 12000 years of human land use. Proc Natl Acad Sci USA. 2017;114(36):9575–80. https://doi.org/10.1073/pnas.1706103114
9. Lal R, Griffin M, Apt J, Lave L, Morgan MG. Managing soil carbon. Sci. 2004;304(5669):393. https://doi.org/10.1126/science.1093079
10. Lal R, Smith P, Jungkunst HF, Mitsch WJ, Lehmann J, Nair PR, et al. The carbon sequestration potential of terrestrial ecosystems. J Soil Water Conserv. 2018;73(6):145A–52A. https://doi.org/10.2489/jswc.73.6.145A
11. Lal R. Sequestering carbon in soils of agro-ecosystems. Food Policy. 2011;36(S1):S33–S39. https://doi.org/10.1016/j.foodpol.2010.12.001
12. Zhang GS, Ni ZW. Winter tillage impacts on soil organic carbon, aggregation and CO_2 emission in a rainfed vegetable cropping system of the mid–Yunnan plateau, China. Soil Till Res. 2017;165:294–301. https://doi.org/10.1016/j.still.2016.09.008
13. Sainepo BM, Gachene CK, Karuma A. Assessment of soil organic carbon fractions and carbon management index under different land use types in Olesharo Catchment, Narok County, Kenya. Carbon Balance Manag. 2018;13:4. https://doi.org/10.1186/s13021-018-0091-7
14. Matzek V, Lewis D, O'Geen A, Lennox M, Hogan SD, Feirer ST, et al. Increases in soil and woody biomass carbon stocks as a result of rangeland riparian restoration. Carbon Balance Manag. 2020;15:1–5. https://doi.org/10.1186/s13021-020-00150-7
15. Dawson JJ, Smith P. Carbon losses from soil and its consequences for land-use management. Sci Total Environ. 2007;382(2-3):165–90. https://doi.org/10.1016/j.scitotenv.2007.03.023
16. Haynes RJ. Labile organic matter fractions as central components of the quality of agricultural soils: an overview. Adv Agron. 2005;5:221–68. https://doi.org/10.1016/S0065-2113(04)85005-3
17. Padbhushan R, Kumar U, Sharma S, Rana DS, Kumar R, Kohli A, et al. Impact of land-use changes on soil properties and carbon pools in India: A meta-analysis. Front Environ Sci. 2022;9:794866. https://doi.org/10.3389/fenvs.2021.794866
18. Smith P. Land use change and soil organic carbon dynamics. Nutr Cycl Agroecosyst. 2008;81:169–78. https://doi.org/10.1007/s10705-007-9138-y
19. Dawson JJC. Loss of soil carbon to the atmosphere via inland surface waters. In: Lal R, Lorenz K, Hüttl R, Schneider B, von Braun J, editors. Ecosystem services and carbon sequestration in the biosphere. Dordrecht: Springer; 2013. p. 183–208. https://doi.org/10.1007/978-94-007-6455-2_9
20. Poeplau C, Don A. A simple soil organic carbon level metric beyond the organic carbon-to-clay ratio. Soil Use Manag. 2023;39(3):1057–67. https://doi.org/10.1111/sum.12921
21. Nykamp M, Becker F, Hoelzmann P. Total organic carbon quantification in soils and sediments: performance test of a modified sample preparation method. MethodsX. 2024;13:102934. https://doi.org/10.1016/j.mex.2024.102934
22. Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 1934;37(1):29–38. http://doi.org/10.1097/00010694-193401000-00003
23. Chan KY, Bowman A, Oates A. Oxidizible organic carbon fractions and soil quality changes in an oxic paleustalf under different pasture leys. Soil Sci. 2001;166(1):61–67. http://doi.org/10.1097/00010694-200101000-00009
24. Blair GJ, Lefroy RD, Lisle L. Soil carbon fractions based on their degree of oxidation and the development of a carbon manage-

ment index for agricultural systems. Aust J Agric Res. 1995;46 (7):1459–66. https://doi.org/10.1071/AR9951459

25. Thiyageshwari S, Gayathri P, Krishnamoorthy R, Anandham R, Paul D. Exploration of rice husk compost as an alternate organic manure to enhance the productivity of blackgram in typic haplustalf and typic rhodustalf. Int J Environ Res Public Health. 2018;15(2):358. https://doi.org/10.3390/ijerph15020358

26. Smith P, Bustamante M, Ahammad H, Clark H, Dong H, Elsiddig EA, et al. Agriculture, forestry and other land use (AFOLU). In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, et al., editors. Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge (UK): Cambridge University Press; 2014. p. 811–922. https://doi.org/10.1017/CBO9781107415416.017

27. Martinez ML, Perez-Maqueo O, Vazquez G, Castillo-Campos G, Garcia-Franco J, Mehltreter K, et al. Effects of land use change on biodiversity and ecosystem services in tropical montane cloud forests of Mexico. For Ecol Manage. 2009;258(9):1856–63. https://doi.org/10.1016/j.foreco.2009.02.023

28. Kok MT, Alkemade R, Bakkenes M, van Eerdt M, Janse J, Mandryk M, et al. Pathways for agriculture and forestry to contribute to terrestrial biodiversity conservation: A global scenario-study. Biol Conserv. 2018;221:137–50. https://doi.org/10.1016/j.biocon.2018.03.003

29. Six J, Paustian K, Elliott ET, Combrink C. Soil structure and organic matter I. Distribution of aggregate-size classes and aggregate-associated carbon. Soil Sci Soc Am J. 2000;64(2):681–89. https://doi.org/10.2136/sssaj2000.642681x

30. McLauchlan K. The nature and longevity of agricultural impacts on soil carbon and nutrients: A review. Ecosyst. 2006;9:1364–82. https://doi.org/10.1007/s10021-005-0135-1

31. Selvi D, Santhy P, Dhakshinamoorthy M. Efficacy of long-term integrated plant nutrient management on important soil properties of an Inceptisol. Madras Agric J. 2003;90:1. https://doi.org/10.29321/MAJ.10.A00155

32. Gokila B, Manimaran G, Jayanthi D, Sivakumar K, Sridevi G, Thenmozhi S, et al. Long-term fertilization and manuring effects on the nexus between sulphur distribution and SOC in an Inceptisol over five decades under a finger millet–maize cropping system. Sci Rep. 2024;14:9758. https://doi.org/10.1038/s41598-024-60357-3

33. Hussain A, Ali S, Rizwan M, ur Rehman MZ, Qayyum MF, Wang H, et al. Responses of wheat (*Triticum aestivum*) plants grown in a Cd contaminated soil to the application of iron oxide nanoparticles. Ecotoxicol Environ Saf. 2019;173:156–64. https://doi.org/10.1016/j.ecoenv.2019.01.118

34. Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, et al. Soil carbon 4 per mille. Geoderma. 2017;292:59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

35. Filho LJF, de Oliveira HMR, Barros SVM, Santos DAC, de Oliveira TS. From forest to pastures and silvopastoral systems: Soil carbon and nitrogen stocks changes in northeast Amazonia. Sci Total Environ. 2024;908:168251. https://doi.org/10.1016/j.scitotenv.2023.168251

36. Bargali SS, Padalia K, Bargali K. Effects of tree fostering on soil health and microbial biomass under different land use systems in the Central Himalayas. Land Degrad Dev. 2019;30(16):1984–98. https://doi.org/10.1002/ldr.3394

37. Soleimani A, Hosseini SM, Bavani ARM, Jafari M, Francaviglia R. Influence of land use and land cover change on soil organic carbon and microbial activity in the forests of northern Iran. Catena. 2019;177:227–37. https://doi.org/10.1016/j.catena.2019.02.018

38. Jagadesh M, Selvi D, Thiyageshwari S, Kalaiselvi T, Lourdusamy K, Kumaraperumal R. Unravelling the carbon pools and carbon stocks under different land uses of Conoor region in Western Ghats of India. J Appl Nat Sci. 2022;14(3):762–70. https://doi.org/10.31018/jans.v14i3.3596

39. Iqbal A, Hussain Q, Mo Z, Hua T, Mustafa AEZMA, Tang X. Vermicompost supply enhances fragrant-rice yield by improving soil fertility and eukaryotic microbial community composition under environmental stress conditions. Microorganisms. 2024;12(6):1252. https://doi.org/10.3390/microorganisms12061252

40. Yao Y, Gao B, Zhang M, Inyang M, Zimmerman AR. Effect of biochar amendment on sorption and leaching of nitrate, ammonium and phosphate in a sandy soil. Chemosphere. 2012;89(11):1467–71. https://doi.org/10.1016/j.chemosphere.2012.06.002

41. Kalambukattu JG, Singh R, Patra AK, Arunkumar K. Soil carbon pools and carbon management index under different land use systems in the Central Himalayan region. Acta Agric Scand-B Soil Plant Sci. 2013;63(3):200–05. https://doi.org/10.1080/09064710.2012.749940

42. Tang H, Xiao X, Li C, Tang W, Cheng K, Pan X, et al. Effects of different soil tillage systems on soil carbon management index under double-cropping rice field in southern China. Agron J. 2019;111(1):440–47. https://doi.org/10.2134/agronj2018.06.0414

43. Vieira FCB, Bayer C, Zanatta JA, Dieckow J, Mielniczuk J, He ZL. Carbon management index based on physical fractionation of soil organic matter in an Acrisol under long-term no-till cropping systems. Soil Till Res. 2007;96(1-2):195–204. https://doi.org/10.1016/j.still.2007.06.007

44. De Bona FD, Bayer C, Dieckow J, Bergamaschi H. Soil quality assessed by carbon management index in a subtropical Acrisol subjected to tillage systems and irrigation. Aust J Soil Res. 2008;46(5):469–75. https://doi.org/10.1071/SR08018

45. Zhao F, Yang G, Han X, Feng Y, Ren G. Stratification of carbon fractions and carbon management index in deep soil affected by the grain-to-green program in China. Plos One. 2014;9 (6):e99657. https://doi.org/10.1371/journal.pone.0099657

46. Ghosh BN, Meena VS, Alam NM, Dogra P, Bhattacharyya R, Sharma NK, et al. Impact of conservation practices on soil aggregation and the carbon management index after seven years of maize–wheat cropping system in the Indian Himalayas. Agric Ecosyst Environ. 2016;216:247–57. https://doi.org/10.1016/j.agee.2015.09.038

47. Mandal M, Chattarjee ND. Land use alteration strategy to improve forest landscape structural quality in Radhanagar forest range under Bankura district. Eurasian J Forest Sci. 2020;8(1):1–10. https://doi.org/10.31195/ejejfs.580431

48. Manimaran G, Jayanthi D, Janaki P, Amirtham D, Gokila B. Long term impact of fertilization and intensive cropping on maize yield and soil nutrient availability under sandy clay loam Soil (Inceptisol). Int J Plant Soil Sci. 2022;34(20):795–801. https://doi.org/10.9734/ijpss/2022/v34i2031223