



RESEARCH ARTICLE

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

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Abstract

Alterations in land patterns in Kolli Hills(KH) of the Eastern Ghats, Tamil Nadu, 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: (1) the active pool, with LC, has a turnover of days to weeks; (2) the slow pool is more stable, turning over in decades to centuries; and (3) 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 CO₂ 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 is a gauge of the health and functionality of soil properties. 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 km² and are located in Tamil Nadu's Eastern Ghats. The KH are positioned at an elevation of 500 to 1,500 meters 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 to 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 17th 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 m² 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 three 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 K₂Cr₂O₇ concentration, the OOC fractions were determined using varying H₂SO₄ 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 very labile carbon (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

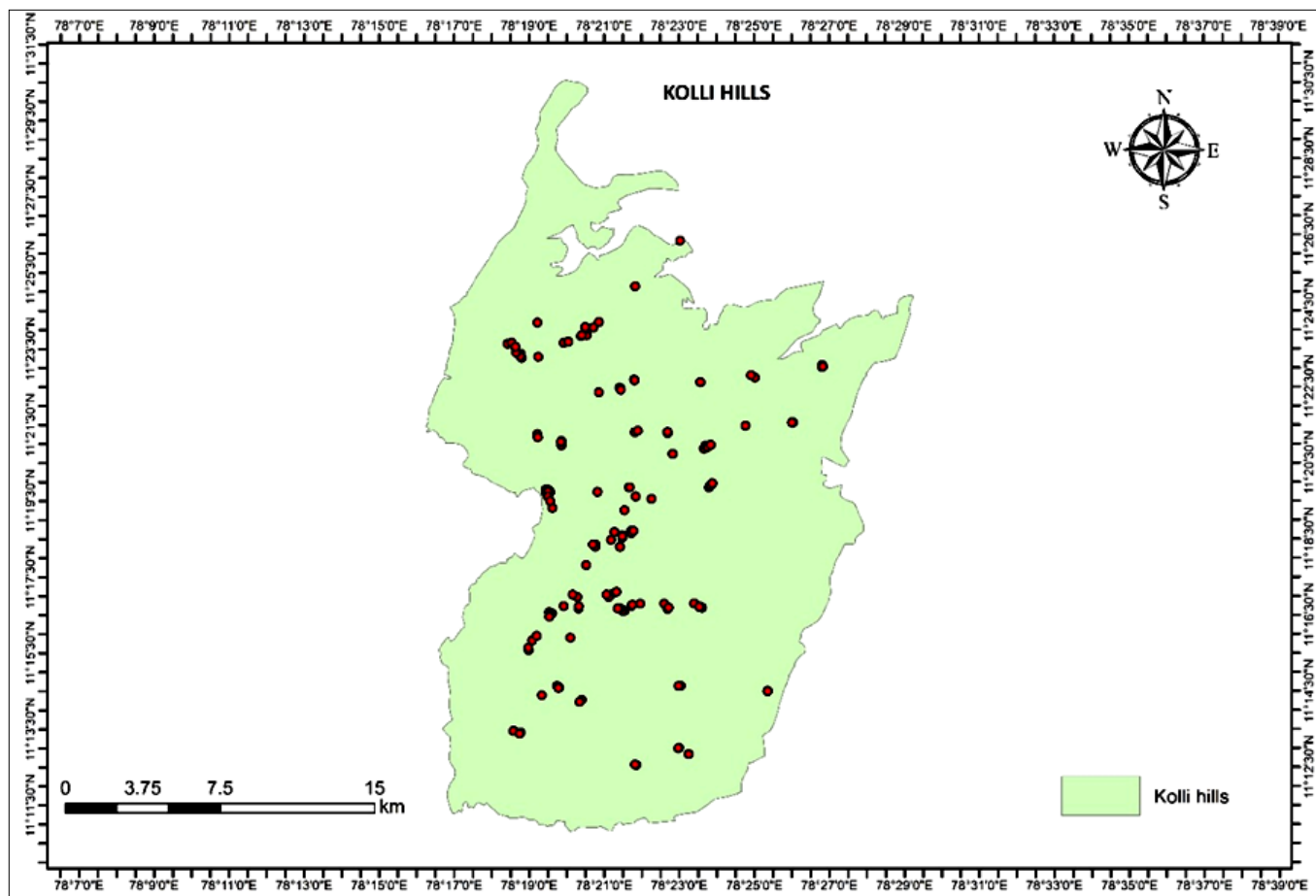


Fig. 1. Location map of Kolli Hills, Eastern Ghats. The red dots indicate Eastern Ghats ecosystem sample locations.

reference soil's TOC to determine the CPI. The ratio of oxidized to unoxidized carbon 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 Lability Index (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 to 15 cm. The order of the TOC at 0 to 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 four distinct carbon pools, LLC, VLC, NLC, and LC, across six 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

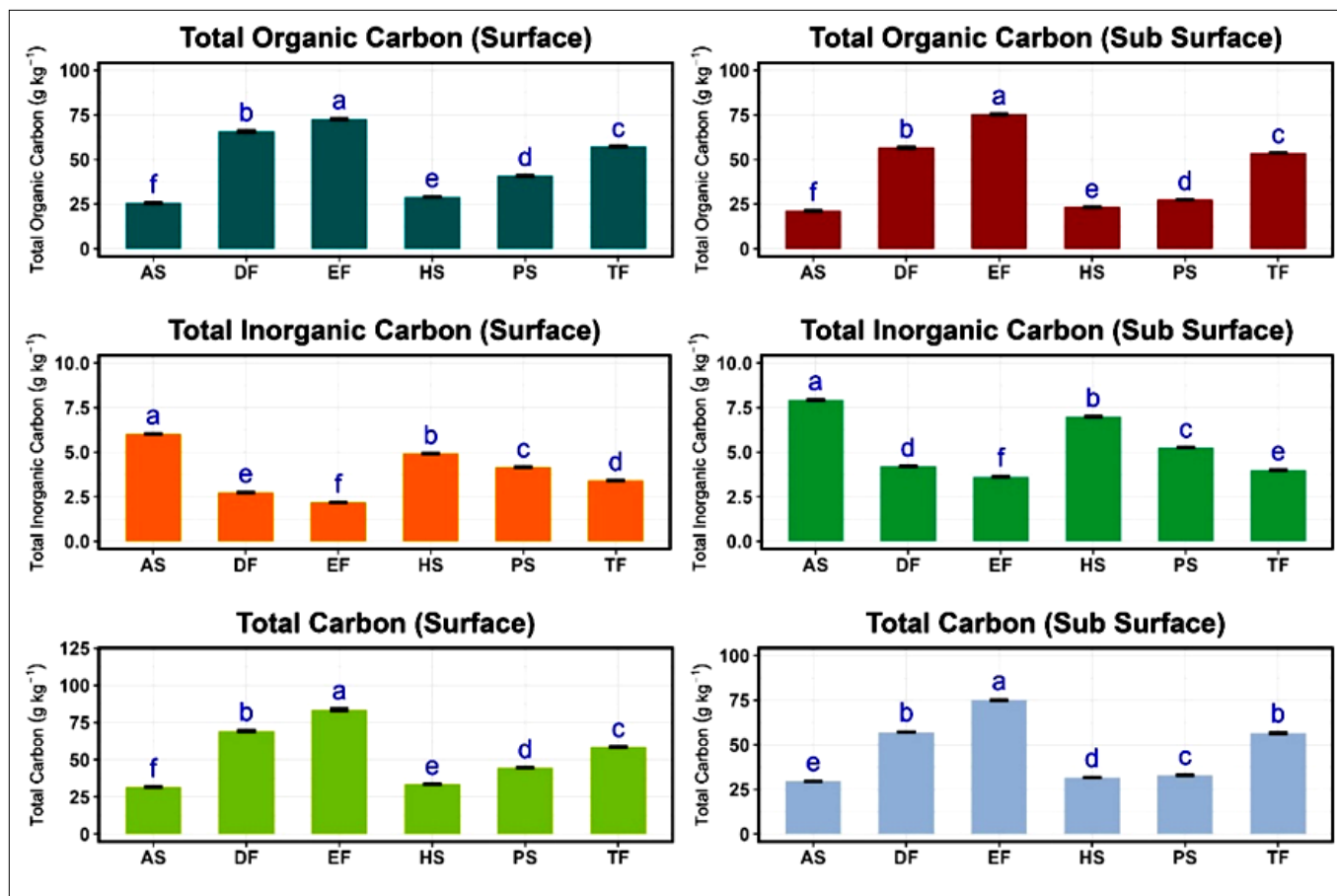


Fig. 2. Total organic carbon, total inorganic carbon, and TC in Eastern Ghats ecosystems at two depths. DMRT results show significant differences ($p < 0.01$) in histograms at depths ranging from 0 to 15 cm and 15 to 30 cm (DF - Deciduous Forest, PS - Plantation System, EF - Evergreen Forest, AS - Agriculture 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±0.02 ^b	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 $p < 0.05$.

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 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 two 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 (32), as demonstrated by PCA. 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

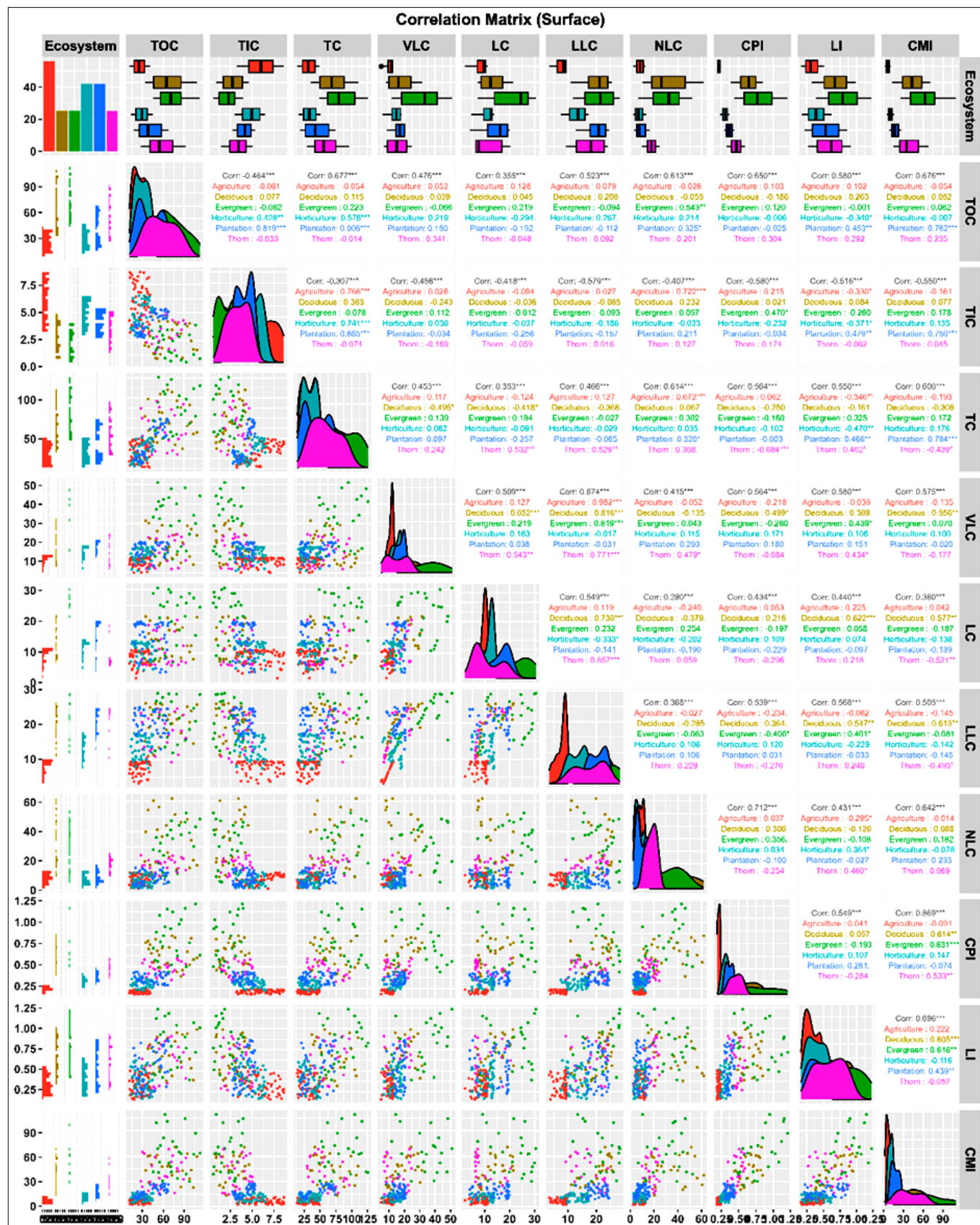


Fig. 3. Relationship between soil total organic carbon and soil characteristics in surface samples of the Eastern Ghats across different ecosystems. Each cell has scatter plots, density distributions, and correlation coefficients (Corr) with significant correlations (***: 0.001 **: 0.01 *: 0.05 *: 0.1 *). 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).

carbon stocks (33, 34). Very labile carbon (VLC) was the predominant type of TOC in both EF and DF. This behavior 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 (36-38) carbon sources. This stability is vital for the enduring storage of carbon, and it underlines the degrada-

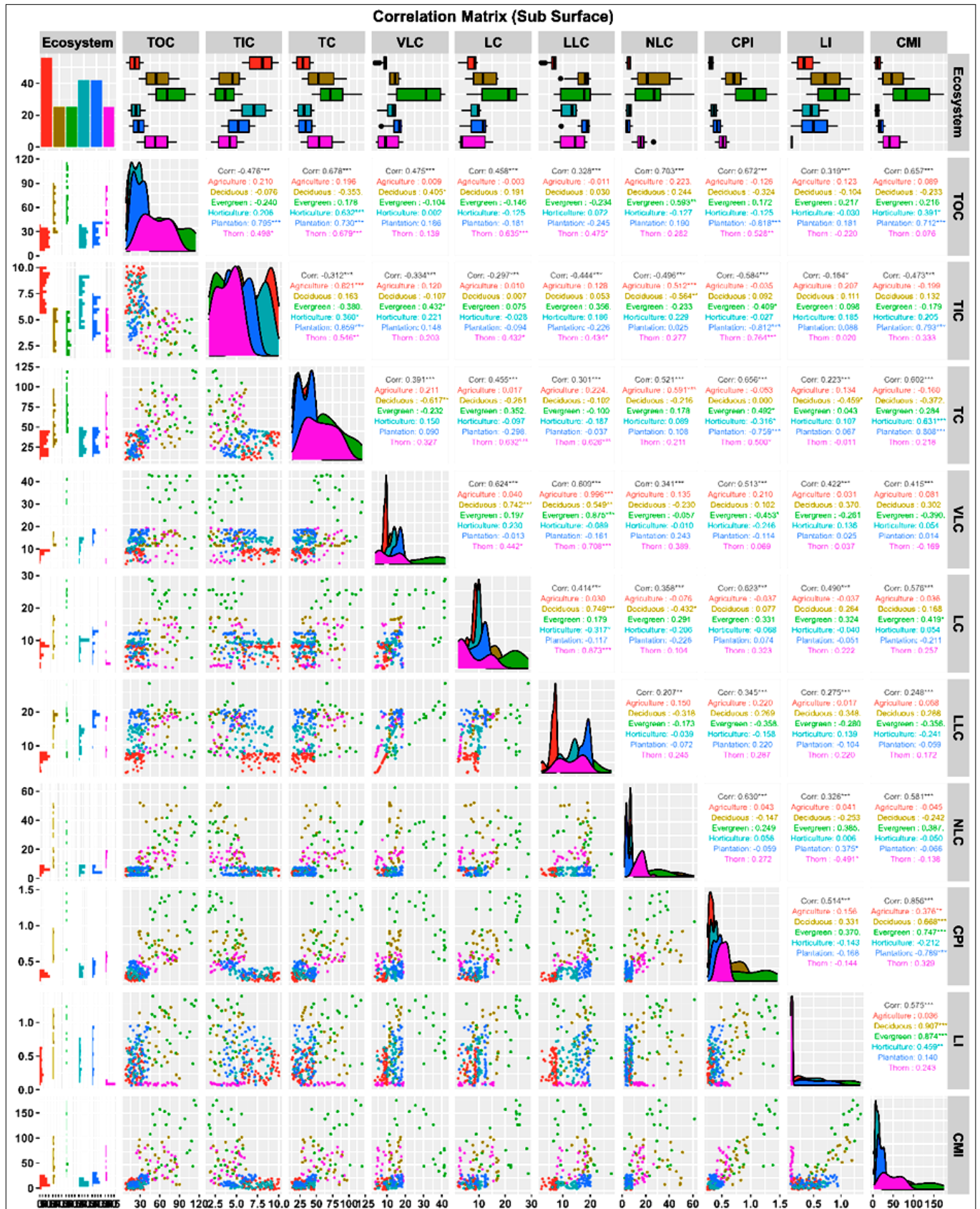


Fig. 4. Relationship between soil total organic carbon and soil characteristics in sub-surface samples of the Eastern Ghats across different ecosystems. Each cell has scatter plots, density distributions, and correlation coefficients (Corr) with significant correlations (***: 0.001 **: 0.01 *: 0.05 *: 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 CO₂ 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-

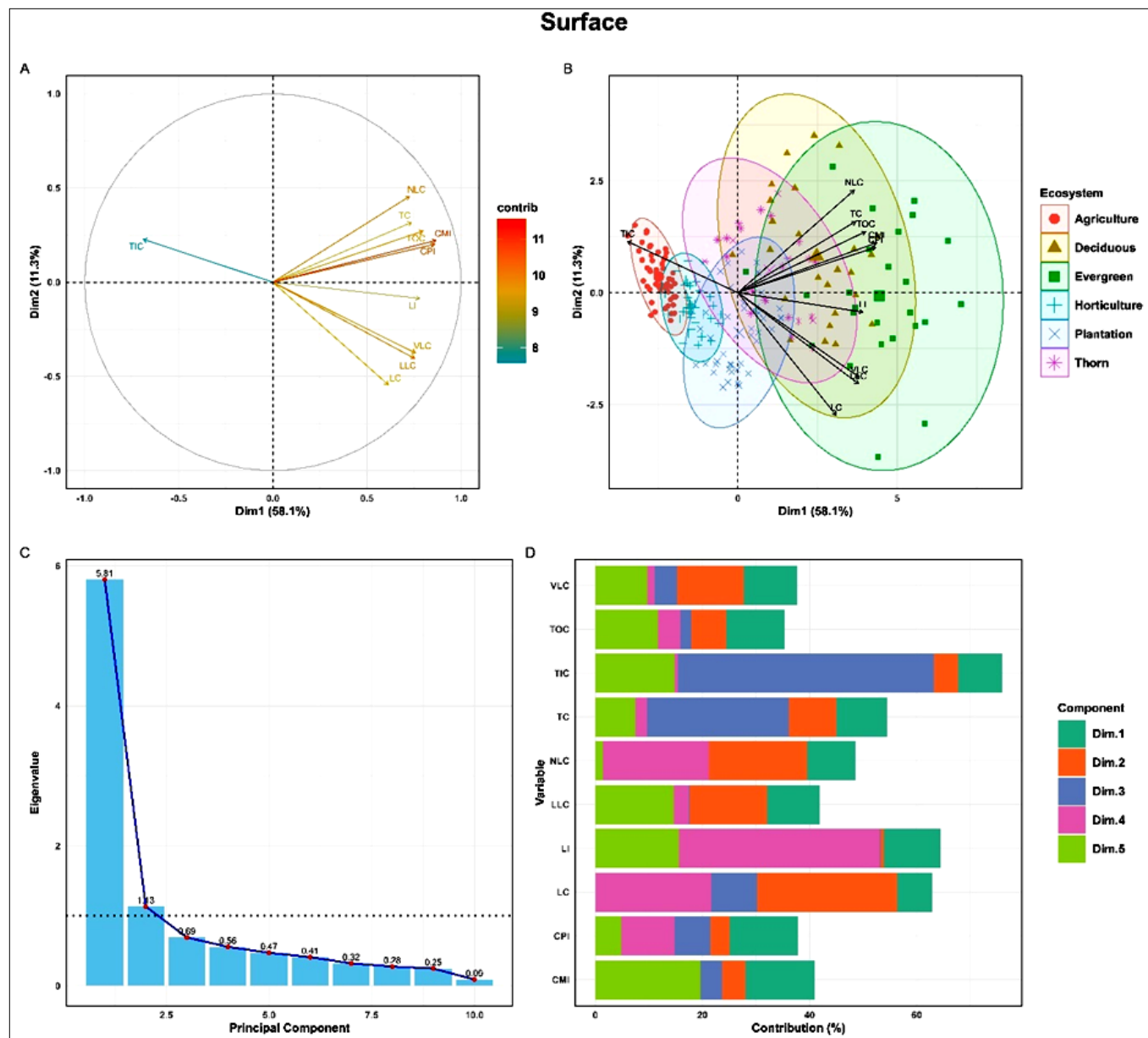


Fig. 5. PCA-based multivariate ecosystem property analysis utilizing surface soil samples. The biplot in Panel A illustrates variables and ecosystems. Panel B exhibits ecosystem distribution highlighting PCA with clustering ellipses. The scree plot in Panel C illustrates each primary component's variance 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(45, 46), although degradation was detected.

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-

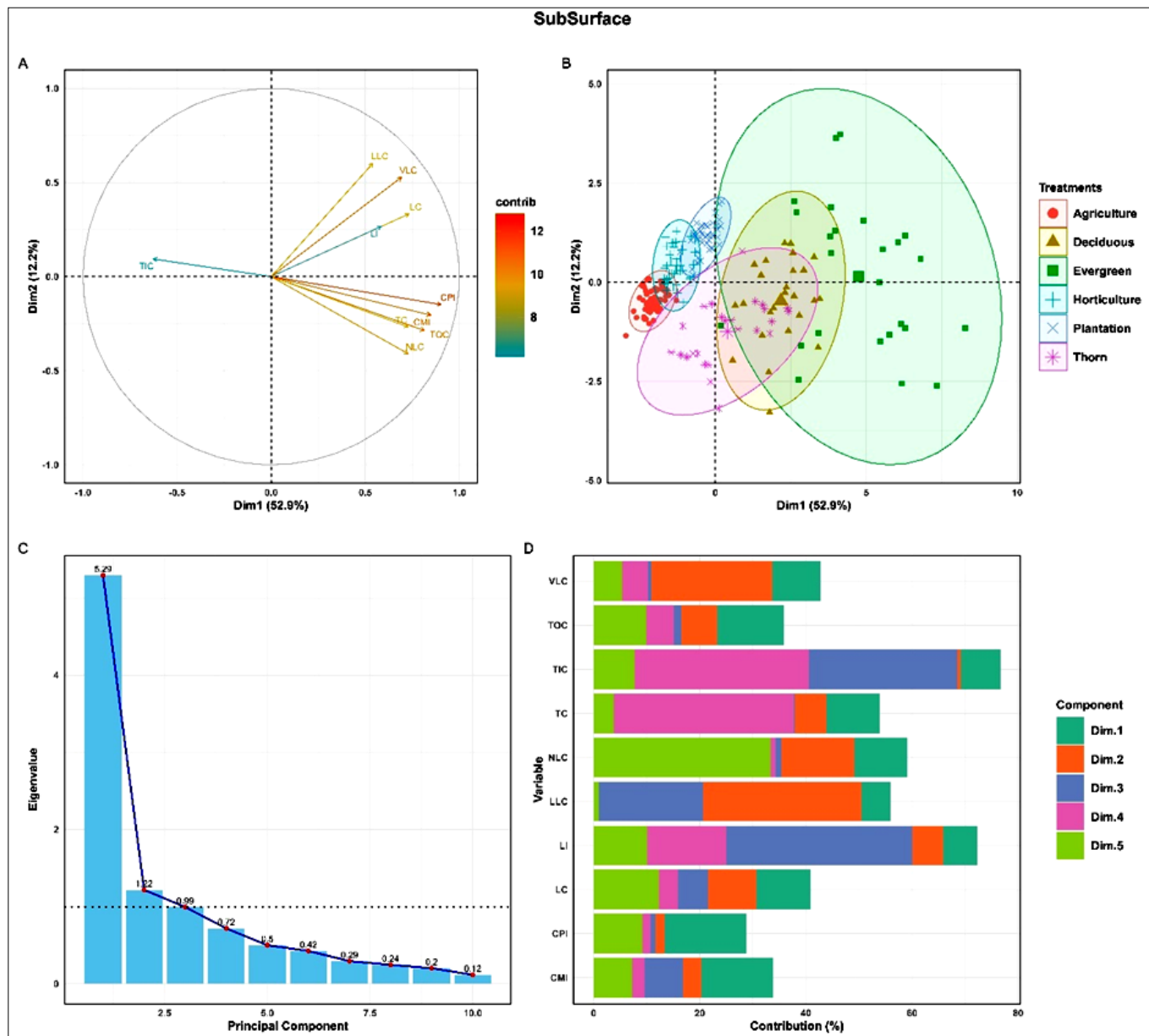


Fig. 6. Multivariate Principal Component Analysis (PCA) on subsurface soil samples for ecosystem characteristics. The biplot in Panel A illustrates variables and ecosystems. Panel B exhibits ecosystem distribution, highlighting PCA with clustering ellipses. The scree plot in Panel C illustrates each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

asures 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.

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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. KS, VP, MG, and SA 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 author(s) used Quill Bot and AI assistance in order to enhance the readability and flow of content; after the original drafting. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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