SOIL ORGANIC CARBON STOCKS IN NATURAL FORESTS OF DONGNAI CULTURE AND NATURE RESERVE, SOUTHEASTERN VIETNAM

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Abstract. Even minor fluctuations in the carbon content in forest soil can significantly impact atmospheric carbon concentrations and future global climate patterns. Therefore, investigating the variation characteristics of soil organic carbon (SOC) in tropical forests is essential for comprehending the carbon sequestration potential of forest soil. This study delves into SOC dynamics within the natural forest types of Dongnai Culture and Nature Reserve in southeastern Vietnam. Nine 1000 m^2 plots were sampled across rich, medium, and poor forests. Soil samples were collected from depths ranging from 0 to 60 cm. The findings revealed increased SOC content from poor to rich forests, with a decrease in depth. The total carbon (C) stocks ranged from 92.20 Mg C ha^{-1} in poor forests to 124.30 Mg C ha^{-1} in rich forests within the top 60 cm. Over 81% of soil C was concentrated in the upper 40 cm. Factors such as soil water content and slope gradient emerged as crucial determinants affecting SOC distribution. These results underscore the potential of forest management practices to augment SOC levels, thereby offering valuable insights for estimating carbon stocks in the forest ecosystems of southeastern Vietnam.
Keywords: *environmental change, Pearson correlation, soil layers, soil samples, tropical forest*

Introduction

Soil is a significant carbon (Carbon - C) reservoir within terrestrial ecosystems, playing a crucial role in the global carbon cycle (Rice et al., 2023; Xu et al., 2019b). Global estimates indicate that soil organic carbon (Soil Organic Carbon - SOC) stocks (Soil Organic Carbon stocks - CS) reach a median of around 1460.5 Pg C (Scharlemann et al., 2014), surpassing the atmospheric carbon content by a factor of two (Friedlingstein et al., 2020) and exceeding the accumulation of carbon in terrestrial plant biomass by approximately threefold (Zhang et al., 2015; Hou et al., 2019).

Forest ecosystems play a paramount role in the global carbon cycle, hosting more than half of the carbon found in terrestrial environments (Hui et al., 2017; Wang et al., 2019). Among the components of forests, SOC plays a pivotal role as a primary

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absorber of carbon dioxide (Carbon Dioxide - CO_2), contributing significantly to carbon storage in terrestrial ecosystems, with estimates ranging from 16% to 26% (Liu et al., 2016; Wang et al., 2019; Wu et al., 2015). Remarkably, SOC pools within forest ecosystems represent a substantial portion, comprising approximately 73% of the global SOC, with over 60% of forest carbon stocks sequestered in the soil (Liu et al., 2016; Wang et al., 2019; Wu et al., 2015). Forest soils demonstrate remarkable capability for organic carbon storage and sequestration compared to other terrestrial ecosystems (Guan et al., 2019). Consequently, even minor changes in forest soil carbon pools can exert significant impacts on atmospheric CO_2 levels and greenhouse gas concentrations (Wang et al., 2023a; Zhou et al., 2023). Thus, accurately estimating SOC storage and comprehensively understanding its controlling factors are crucial to anticipate the feedback of carbon stocks to global environmental changes (Wang et al., 2023b; Yang et al., 2008).

The Dongnai Culture and Nature Reserve is recognized as the largest reserve in the southern region of Vietnam, covering a forested area of 65,980.61 ha, which represents approximately 65.6% of the total natural land (MARD, 2023; Dongnai Culture and Nature Reserve, 2023). Alongside its diverse forest vegetation and the presence of endemic, rare, and protected plant species, the tropical natural forest ecosystems within this reserve play a crucial role in providing various environmental services, including mitigating adverse impacts on carbon cycles through the absorption and storage of C. Recent studies have highlighted the correlation between changes in SOC in tropical forests and global climate change (Eglinton et al., 2021; Zhao et al., 2023). Consequently, there is growing academic interest in gaining a deeper understanding of the dynamics of SOC accumulation and its controlling parameters within natural forest ecosystems (Hemingway et al., 2019; Zhao et al., 2023), assisting in accurate prediction of carbon stock reserves and their implications for future climate change and forest management.

Over the last decade, the scientific community has made concerted efforts to evaluate changes in SOC within tropical forests, as evidenced by several studies (Kafy et al., 2023; Piao et al., 2009; Huang et al., 2010; Kumar et al., 2016; Toai et al., 2016; Thanh and Chien, 2019; Hai et al., 2015; and Zhou et al., 2023). Despite these endeavors, little attention has been paid to understand the dynamics of SOC in natural forest ecosystems in Vietnam. Specifically, the variability of SOC in the southeastern region of Vietnam remains largely unexplored. This study addresses this knowledge gap by focusing on the Dongnai Culture and Nature Reserve. The primary objectives are twofold: (i) to investigate variations in SOC and CS and (ii) to identify the controlling parameters influencing CS variation across three forest types (rich, medium, and poor forest). Through these objectives, our research seeks to provide essential insights into the carbon sink dynamics of tropical natural forest soils, offering valuable information for informed forest management practices and facilitating the implementation of payment schemes for forest environmental services.

Materials and methods

Study site

Field measurements were conducted within the Dongnai Culture and Nature Reserve, located in Dongnai province, southeastern Vietnam. This reserve spans from 11°05’10” to 11°22’31” N latitude and 106°54’19” to 107°09’03” E longitude (*Fig. 1*).

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Characterized by a tropical monsoon climate, the study area experiences two distinct seasons: the rainy season prevailing from May to October, followed by the dry season from November to April of the subsequent year (Quy et al., 2022). The mean annual precipitation reaches 2572 mm, with an average annual temperature around 26.4°C, and the average annual humidity standing at 80% (Huong et al., 2020).

The study area boasts diverse topography, ranging from 20 to 368 m a.s.l., with slopes varying between 3 and 35°. Predominantly characterized by Yellow-red Feralit soil, the soil layer in the region is generally moderate to highly fertile (Dongnai Culture and Nature Reserve, 2023). Encompassing an area of approximately 100,571.57 ha, the reserve comprises 65,980.61 ha of forested land, 2,071.08 ha of non-forested areas, and the remaining 32,519.88 ha is occupied by Tri An Lake. Notably, the natural forest covers 59,983.38 ha, representing 90.91% of the total forested area within the Dongnai Culture and Nature Reserve.

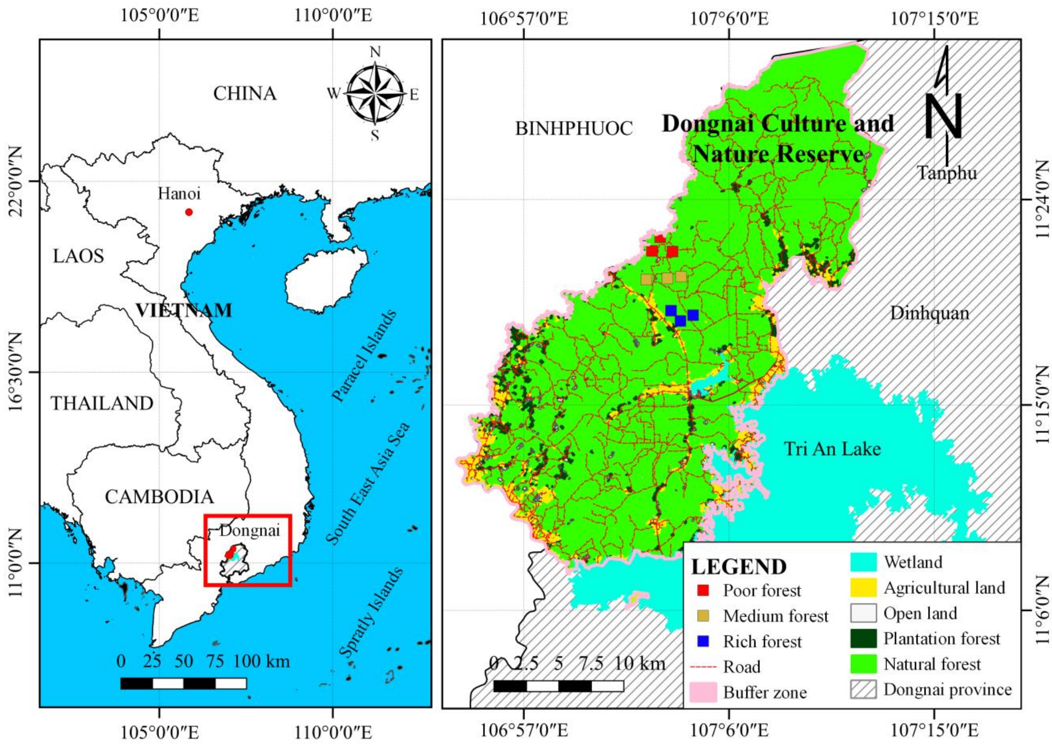

Figure 1. *Map of plots in Dongnai Culture and Nature Reserve in southeastern Vietnam*

The forest vegetation within the reserve comprises a rich variety, including tropical evergreen broadleaved forest, tropical evergreen broadleaved semi-deciduous forest, tropical broadleaved deciduous forest, and plantation forest. These natural forest ecosystems exhibit diverse species composition and high population density, hosting 1401 species belonging to 623 genera and 156 families. Notably, 30 species are listed in the Vietnam Red Data Book, while 18 species are endemic to the region, such as *Lithocarpus vestitus* Hick. & Cam., *Anisoptera costata* Korth., *Aquilaria crassna* Pierre ex Lec., *Afzelia xylocarpa* (Kurz) Craib., *Sindora siamensis* Teysm. ex Miq. var. *siamensis*, *Pterocarpus macrocarpus* Kurz., and *Markhamia stipulata* (Wall.) Seem. ex Schum. (Hung and Potokin, 2019; Thinh and Okolelova, 2014).

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Data collection

Sampling design

For the data collection phase of this study, we selected three natural forest types—poor, medium, and rich forests—all sharing identical climate and soil conditions. The classification of these forest types was guided by the forest types map and Circular No. 33/2018/TT-BNNPTNT issued by the Ministry of Agriculture and Rural Development (MARD, 2018), which provides guidelines for forest survey, inventory, and monitoring. The classification criteria were based on the standing volume of each forest type, with rich forests having a standing volume exceeding 200 m^3 ha^{-1}, medium forests falling within the range of 100 to 200 m^3 ha^{-1}, and poor forests having a volume of 50–100 m^3 ha^{-1} (MARD, 2018).

In this study, the geographical coordinates of survey plots were meticulously recorded and categorized according to their standing volume. Plots located in areas with low volume (poor forest) were documented at the following coordinates: 107°03’01.91” E, 11°22’20.64” N; 107°02’40.49” E, 11°21’42.55” N; and 107°03’32.87” E, 11°21’43.34” N. Conversely, plots in areas with medium forest volume were located at 107°02’21.44” E, 11°20’27.13” N; 107°03”19.37” E, 11°20’30.31” N; and 107°03’55.91” E, 11°20’35.88” N. Finally, plots in regions classified as rich forest were positioned at 107°03’29.72” E, 11°19’6.96” N; 107°04’26.04” E, 11°18’54.25” N; and 107°03’55.91” E, 11°18”38.38’ N.

The fieldwork was conducted between May and November 2023. During this period, we established three sample plots measuring 40 m × 25 m in each forest type (*Fig. A1*), totaling nine study plots across the study area. All tree species with a diameter at breast height (Diameter at Breast Height - DBH) equal to or greater than 6.0 cm were identified by species name and measured within these plots, following established protocols (Piao et al., 2018; Hsu et al., 2020). Key parameters recorded during these measurements included tree density (tree density - N), DBH, and total height of trees (Total height of trees - H). Additionally, we noted environmental characteristics such as forest canopy closure, slope, and elevation above sea level to provide a comprehensive context for our study. The measurements of Tree DBH were taken utilizing LUFW606PM d-tape (Lufkin Executive Diameter Tape - Mexico), while tree height was determined using SUUNTO PM-5 (Suunto PM-5 hand-held clinometers - Germany). Canopy cover assessments were conducted at the center and twenty evenly distributed points within each plot by capturing hemispherical photographs of the canopy, which were subsequently analyzed using the GLAMA application (Gap Light Analysis mobile application). Slope data were recorded at each plot using a Terrinox CP-11 compass. Elevation measurements were initially obtained using a Garmin 60™ GPS device at the lower left corner of each plot and then calculated for other corners within each plot using an inclinometer, with the mean elevation registered accordingly.

To assess the biomass of the understory (comprising shrubs and herbs) within each study plot, we employed a destructive sampling method, collecting data from five 2 m × 2 m quadrats. Litter biomass contribution was determined by gathering samples from five quadrats measuring 1 m × 1 m, positioned at each corner and the center of the plot. All biomass samples were carefully collected and oven-dried at 65°C until reaching a constant weight, ensuring accurate measurements of understory and litter biomass components.

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Soil sampling

During the data collection phase, soil samples were extracted from each plot, reaching a depth of 60 cm. The sampling points were strategically chosen at every sample plot's four corners and the center. The soil collection process involved obtaining samples from three distinct depth levels: 0-20 cm, 20-40 cm, and 40-60 cm. To assess soil bulk density (Bulk Density - BD) across these layers (0-20 cm, 20-40 cm, and 40-60 cm), stainless steel cylinders with a volume of 100 cm^3 were employed. Subsequently, the cored soil was oven-dried at 105°C until achieving a constant weight. The calculation of soil bulk density involved dividing the oven-dried soil's mass by the core's volume, following the methodology outlined by Blake and Hartge (1986).

To ensure accurate representation, soil samples from the same depth layer within a particular plot were mixed in equal volume proportions, air-dried naturally, and stored at room temperature (25°C). Before analysis, these samples underwent a meticulous preparation process involving the removal of plant roots and other debris through a 2-mm-mesh sieve after being smashed. Soil water content (Soil Water Content - SWC), expressed as a percentage, was determined by subjecting 20 grams of soil from each sample to oven-drying at 105°C for 24 h, following protocols outlined by Duan et al. (2020) and Chau et al. (2024).

The soil pH was measured at a soil-to-water mass ratio of 1:2.5 using a Sartorius PB-10 pH meter, following the procedures outlined by Duan et al. (2020) and Chau et al. (2024). Furthermore, SOC content was quantified using the H_2SO_4-$K_2Cr_2O_7$ oxidation method, following the methodology established by Nelson and Sommers (1996).

Data analysis

Soil C storage

The SOC storage across three soil depths (0-20 cm, 20-40 cm, and 40-60 cm) was estimated using parameters including SOC, BD, and soil depth. The calculation for carbon sequestration (Carbon Sequestration - CS) in megagrams per hectare (Mg. ha^{-1}) was carried out according to *Equation 1*, as prescribed by Xu et al. (2019a):

$$CS = SOC_i \times BD_i \times D_i/10 \quad \text{(Eq.1)}$$

where CS represents the soil carbon storage in soil layer i (Mg. C. ha^{-1}); BD_i is the soil bulk density of soil layer i (g cm^{-3}); SOC_i is the soil organic carbon content of soil layer i (g. kg^{-1}), and D_i is the soil thickness of soil layer i (cm).

Forest stand characteristics

The stand basal area (Basal Area - BA, m^2. ha^{-1}) is defined by *Equation 2*, as outlined by Bettinger et al. (2017):

$$BA = 0.7854 \times (DBH/100)^2 \quad \text{(Eq.2)}$$

where BA represents basal area (m^2. ha^{-1}); DBH denotes the diameter at breast height of trees (cm).

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The stand volume (Volume - V) was calculated using *Equation 3* (Khoa et al., 2024):

$$V = BA \times H \times F \quad \text{(Eq.3)}$$

where V represents stand volume ($m^{3\cdot}$ ha^{-1}); BA stands for stand basal area; H denotes total height of trees; F signifies stand form factor. The study adopted a value of F = 0.45 for natural forests (Khoa et al., 2024).

Diversity indices

Species richness (S) is defined as the number of different species represented in an ecological community, landscape, or region. It is essentially the count of distinct species (Gaston and Spicer, 2013).

The Shannon-Weiner index (H') was developed to quantify species diversity (Shannon, 1948):

$$H' = -\sum_{i=1}^{s} p_i \times \ln(p_i) \quad \text{(Eq.4)}$$

where H' represents the Shannon-Weiner index; p_i denotes the proportion of individuals belonging to species i; ln stands for the natural logarithm.

The Margalef index (D) was used to estimate species richness (Margalef, 1958):

$$D = (S - 1) / \ln(N) \quad \text{(Eq.5)}$$

where D represents the Margalef index of species richness; S is the number of species; N is the total number of individuals.

Species evenness was determined to calculate the Pielou index (J') (Pielou, 1966):

$$J' = H' / \ln(S) \quad \text{(Eq.6)}$$

where J' represents Pielou's measure of species evenness; H' is the Shannon-Wiener index; S is the total number of species in the sample.

Important value index

The primary species composition in a community comprises all species with an important value index (Important Value Index - IVI) ≥ 5%. To ascertain the species composition of the community, the IVI for each species in the plot was calculated, and the dominant species were selected based on their importance value (Huong, 2022). The IVI was calculated by *Equation 7*:

$$IVI = (N\% + BA\% + V\%)/3 \quad \text{(Eq.7)}$$

In tropical rainforests, the composition of tree species is diverse, with the dominant tree species (those with IVI > 5%) typically not exceeding ten species. The cumulative value of these species groups is expected to be ≥ 50% (Trung, 1979, 1999). Here, N%, BA%, and V% denote the relative density, relative basal area, and relative volume of the species, respectively. The value V is computed as BA×H×F, where F = 0.45, H represents the total height of the tree (H, m), and BA is the basal area (BA, $m^{2\cdot}$ ha^{-1}).

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Statistical analysis

The statistical analysis in this study utilized R statistical software (R Core Team, 2018) and SPSS 22.0 software (IBM Corp., 2020). Prior to analysis, the data underwent tests for normal distribution and homogeneity of variance via the Shapiro-Wilk and Levene tests, respectively (Gerschlauer et al., 2019). The two-way analysis of variance (ANOVA) was employed to evaluate significant differences in the impacts of forest types and soil layers on SOC and CS, followed by Duncan's Least Significant Difference (LSD) test at a significance level of $p < 0.05$ (Gerschlauer et al., 2019; Zhou et al., 2023). To characterize the relationship between CS and various variables—such as forest characteristics (C, M, BA, DBH, H, N, S, D, Lit, UB, H' and J'), soil attributes (SWC, BD and pH) and topographical factors (slope, elevation) — Pearson correlation analysis was conducted. Subsequently, based on the correlation analysis findings, a stepwise multiple regression analysis was performed to identify the potential effects of environmental variables on CS (Fan et al., 2018; Gerschlauer et al., 2019).

Results

Characteristics of the three forest types

Structural characteristics

The results depict diverse growth patterns observed among trees in the three forest types. The average DBH of trees ranged from 11.8 cm to 19.9 cm, while their average H varied from 10.8 m to 17.4 m, depending on the forest type (*Table 1*). Additionally, *Table 2* presents the structural characteristics of the three forest types, including stand density (N), basal area (BA), volume (V), important value index (IVI) of dominant species, and species composition. The study findings indicate that the rich forest type demonstrates the highest species richness, with 37 species documented, followed by the medium forest type with 34 species, and the poor forest type exhibiting the lowest species diversity, with 32 species recorded.

Table 1. *Characteristics of the three typical forests in Dongnai Culture and Nature Reserve*

Forest types	**Slope (°)**	**Elevation (m a.s.l.)**	**Canopy density**	**DBH (cm)**	**H (m)**	**Density (trees· ha^{-1})**
Poor forest	9.7	76.3	0.71 ± 0.01^a	11.8 ± 0.55^a	10.8 ± 0.43^a	766 ± 80^b
Medium forest	5.7	82.0	0.78 ± 0.03^b	15.3 ± 0.55^b	13.3 ± 0.69^b	683 ± 20^b
Rich forest	3.3	72.7	0.87 ± 0.02^c	19.9 ± 0.21^c	17.4 ± 0.16^c	576 ± 25^a

Data is presented as the mean ± standard deviation (SD). Different letters indicate significant differences at p < 0.05 following ANOVA LSD analysis. DBH refers to the diameter at breast height (1.3 m), while H represents the total height of the tree

The data presented in *Table 2* highlight the number of dominant species (with an IVI greater than 5%) within the different forest types: rich forest (four species), poor forest (five species), and medium forest (seven species). Notably, among these dominant species, *Hopea recopei* was found in both rich and medium forests, while *Lagerstroemia crispa* was present across all three forest types. *L. crispa* exhibited significant dominance, with its prevalence decreasing from the poor forest (24.86%) to the medium forest (6.64%), and finally to the rich forest (5.77%). Of particular interest

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was the presence of one dominant endangered, precious, and rare woody species, *Dipterocarpus dyeri* (according to IUCN, 2024; MOST, 2007), within the rich forest. This species had a tree density of thirty-seven trees per hectare, accounting for 6.51% of the total, with an IVI of 13.59%.

Table 2. *Basic characteristics of forest types and dominant species*

Forest types	Species name	Density (trees· ha^{-1})	N (%)	BA (%)	V (%)	IVI (%)
Poor forest	*Lagerstroemia crispa* Pierre ex Laness.	140	18.21	27.78	28.60	24.86
	Grewia tomentosa Roxb. ex DC	40	5.20	11.00	11.69	9.30
	Litsea pierrei Lec.	37	4.81	6.59	9.47	6.96
	Diospyros venosa Wall. ex A.DC.	77	10.01	4.45	3.28	5.91
	Garcinia gaudichaudii Planch. & Triana	27	3.51	6.36	6.80	5.56
	Total (five dominant species)	321	41.7	56.2	59.8	52.6
	Others (twenty-seven species)	448	58.3	43.8	40.2	47.4
	Total (thirty-two species)	769	100	100	100	100
Medium forest	*Xerospermum noronhianum* (Blume) Blume	70	10.25	13.69	14.96	12.97
	Hopea recopei Pierre.	33	4.83	12.60	17.38	11.60
	Pterospermum megalocarpum Tardieu	43	6.30	10.41	10.17	8.96
	Xerospermum microccarpum Pierre.	47	6.88	8.31	7.67	7.62
	Lagerstroemia crispa Pierre ex Laness	47	6.88	6.16	6.89	6.64
	Diospyros sylvatica Roxb.	53	7.76	6.04	6.05	6.61
	Litsea pierrei Lec.	33	4.83	6.33	5.74	5.63
	Total (seven dominant species)	326	47.7	63.6	68.9	60.0
	Others (twenty-seven species)	357	52.3	36.4	31.1	40.0
	Total (thirty-four species)	683	100	100	100	100
Rich forest	*Hopea recopei* Pierre.	137	24.12	24.36	25.49	24.66
	Dipterocarpus dyeri Pierre ex Laness.	37	6.51	15.40	18.86	13.59
	Vitex tripinnata (Lour.) Merr.	27	4.75	7.71	8.43	6.97
	Lagerstroemia crispa Pierre ex Laness	27	4.75	6.17	6.38	5.77
	Total (four dominant species)	228	40.1	53.6	59.2	51.0
	Others (thirty-three species)	340	59.9	46.4	40.8	49.0
	Total (thirty-seven species)	568	100	100	100	100

N, stand density; V, volume; BA, basal area; IVI, important value index

The average number of individuals per species was seventeen trees per species in the rich forest, 20 trees per species in the medium forest, and twenty-four trees per species in the poor forest. The tree density of the dominant species was highest in the medium forest, accounting for 47.7%. Consequently, the BA and V associated with these dominant species (seven species) were most significant in the medium forest type, representing 63.6% and 68.9%, respectively.

Diversity of the three forest types

Diversity indices were calculated for all analyzed forest types, with the results presented in *Figure 2*. The analysis revealed that the study area comprises twenty-nine families, forty-two genera, and forty-eight species. Interpretation of the findings showed that rich forests are particularly valuable in terms of biodiversity, considering both

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richness and evenness. These forests exhibit the highest values of species richness, Shannon index, and Margalef index while recording the lowest value of the Pielou index compared to other forest types surveyed. In contrast, poor forests displayed the lowest values of species richness (S), Shannon index (H'), and Margalef index (D), along with the highest value of the Pielou index (J'). Further analysis showed that the D values ranged from 2 to 8, and the H' values ranged from 2 to 3, indicating a moderate level of species richness in the study area's forest types. With the J' values hovering close to 1, the uniformity of woody plant species richness in the study area was notably consistent.

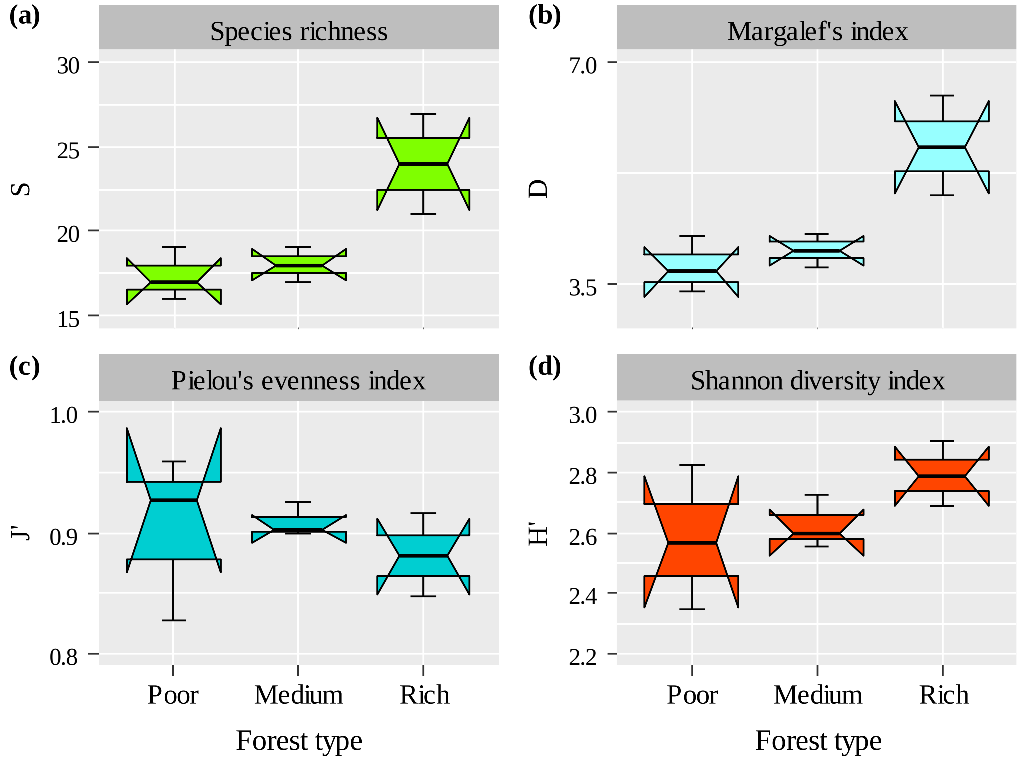

Figure 2. *Diversity indices of three forest types*

Understorey and litter biomass characteristics in the three forest types

The abundance of understory plants was found in forest types such as *Goniothalamus vietnamensis* Ban, *Myxopyrum smilacifolium* Blume, *Rhapis excelsa* (Thunb.) A. Henry, *Dracaena angustifolia* (Medik.) Roxb., *Cyclea barbata* Miers (Lour.) Merr., *Curculigo disticha* Gagnep., *Homalomena pierreana* Engl., *Peliosanthes teta* Andrews, *Coscinium fenestratum* (Gaertn.) Colebr., *Fibraurea tinctoria* Lour, *Telectadium dongnaiense* Pierre ex Costantin, *Tacca integrifolia* Ker-Gawl, *Drynaria bonii* Christ, *Ancistrocladus cochinchinensis* Gagn., and some other species. There was a significant difference in litter biomass between rich, medium, and poor forests ($p < 0.05$), with the highest values in the rich forest (7.72 Mg. ha^{-1}) and the lowest in the poor forest (4.58 Mg. ha^{-1}). The biomass of understory plants ranged from 0.59 Mg. ha^{-1} in the poor forest to 0.78 Mg. ha^{-1} in the medium forest, and did not differ between the different forest types ($p > 0.05$). However, reached the highest in the rich forest (1.10 Mg. ha^{-1}). Notably, understory plant biomass exhibited significant differences when comparing the poor and medium forests to the rich forests (*Table 3*).

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Table 3. *Biomass characteristics of understory and litter in three forest types*

Forest types	Litter (Mg·ha^{-1})	Understory plants (Mg·ha^{-1})
Poor	4.58 ± 0.6^{a}	0.59 ± 0.1^{a}
Medium	6.24 ± 0.2^{b}	0.78 ± 0.1^{a}
Rich	7.72 ± 0.5^{c}	1.10 ± 0.2^{b}

Different letters illustrate a significant difference between distinct stands at p < 0.05 following ANOVA LSD analysis

Soil characteristics of the three forest types

Soil BD in all forest types increased significantly as soil depth increased ($p < 0.05$, *Fig. 3a*). Soil BD value in the upper 0-20 cm soil layer was 1.2-1.4 times significantly lower than in the 40-60 cm soil layer. The soil BD values in poor forests were significantly higher than those in the rich and medium forests for all soil depths ($p < 0.05$).

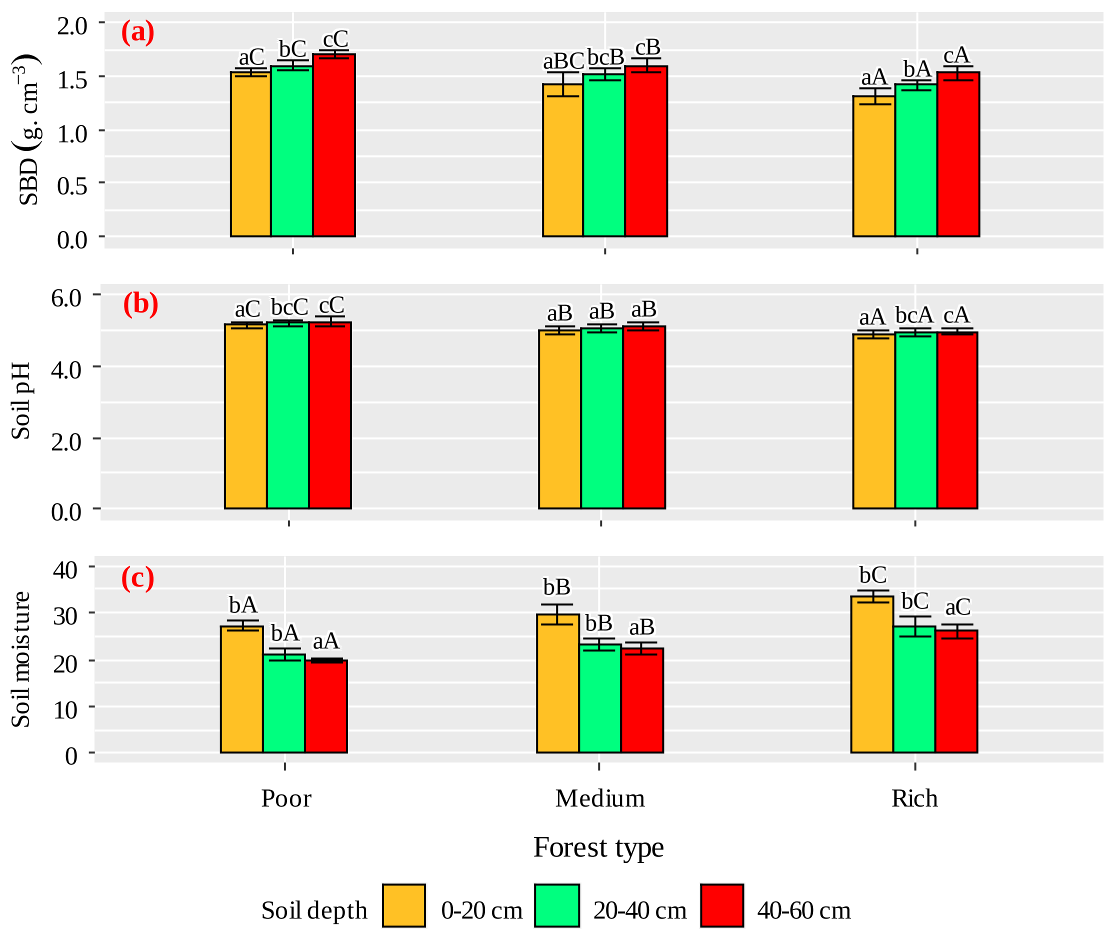

Figure 3. *Soil Bulk density (a), soil pH (b) and soil water content (c) in soil depths. Capital letters denote significant differences between soil layers within different forest types (p < 0.05). Lowercase letters denote significant differences between sampled soil layers within the same forest type (p < 0.05). Different letters indicate significant differences at p < 0.05 based on ANOVA LSD analysis*

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Soil pH value decreased with soil depth but was not significantly different among forest types at all soil depths ($p > 0.05$, *Fig. 3b*). The pH in the three soil layers (0-20 cm, 20-40, and 40-60 cm) followed a significant changing trend with forest types ($p < 0.05$). The soil pH was 5.15, 5.01, and 4.88 in 0-20 cm soil depth; 5.21, 5.06, and 4.94 in 20-40 cm soil depth; and 5.25, 5.12, and 4.97 in 40-60 cm soil depth in the poor, medium, and rich forests, respectively.

SWC also decreased with soil depth (*Fig. 3c*). Nevertheless, no significant difference existed among forest types at 0-20 and 20-40 cm soil layers ($p > 0.05$). The values in rich forests were significantly higher than in medium and poor forests at three soil depths ($p < 0.05$).

Soil organic C content and storage of the three forest types

Regardless of forest types, the SOC concentration decreased significantly as soil depth increased ($p < 0.05$, *Fig. 4a*). In the 0-20 cm soil layer, SOC ranged from 1.58 to 2.21 g. kg^{-1}, which was significantly higher than that of the other soil depths ($p < 0.05$). Significant differences were found among the three forest types of various soil layers for SOC values ($p < 0.05$). In the 0–20, 20–40 and 40–60 cm soil layers, the average SOC content was highest in the rich forests, followed by that in the medium and poor forests.

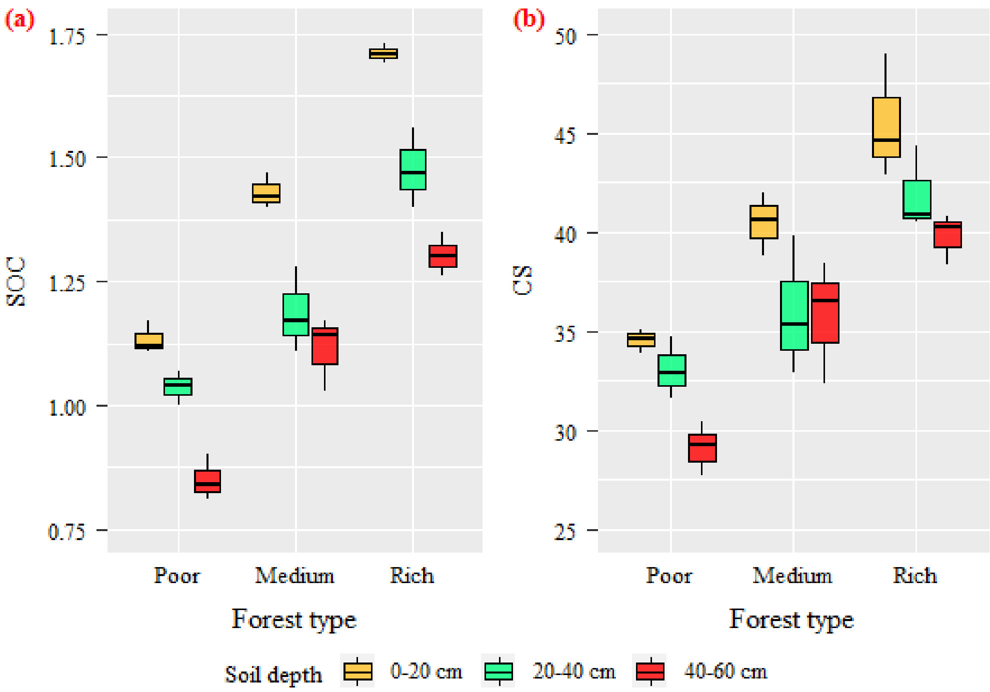

Figure 4. *Soil carbon concentration (a) and soil carbon storage (b) in soil depths*

The CS in 60 cm depth was 92.23, 109.03, and 124.32 Mg· ha^{-1} for the poor, medium, and rich forests, respectively, demonstrating a rapid increase from poor to rich forests (*Fig. 4b*), and the CS in each soil depth had significant differences among different forest types ($p < 0.05$). Under different forest types, SOC stocks decreased rapidly with the increase of soil depth, ranging from 53.06 Mg· ha^{-1} at 0–20 cm to 20.22 Mg· ha^{-1} at 40–60 cm. More than 81% of CS was stocked within the upper 40 cm of the soil profile from each forest type (*Fig. 4b*).

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Effects of environmental factors on soil C storage in three forest types

The Pearson correlation results showed the relationship between the CS and the various influential environmental factors (*Fig. 5*). The CS was significantly positively correlated with the SWC ($p < 0.001$), and significantly negatively correlated with the BD ($p < 0.001$) and pH ($p < 0.01$). The CS was highly positively correlated with the Sl ($p < 0.001$), but not correlated with the Elv ($p > 0.05$). The CS was strongly positively correlated with the C ($p < 0.001$), M ($p < 0.001$), BA ($p < 0.001$), DBH ($p < 0.001$), H ($p < 0.001$), Lit ($p < 0.001$), and UB ($p < 0.01$), and significantly negatively correlated with the N ($p < 0.01$). The D ($p < 0.001$), and S ($p < 0.01$) were significantly positively correlated with the CS. However, no significant correlations were established between H' and CS ($p > 0.05$), and J' ($p > 0.05$).

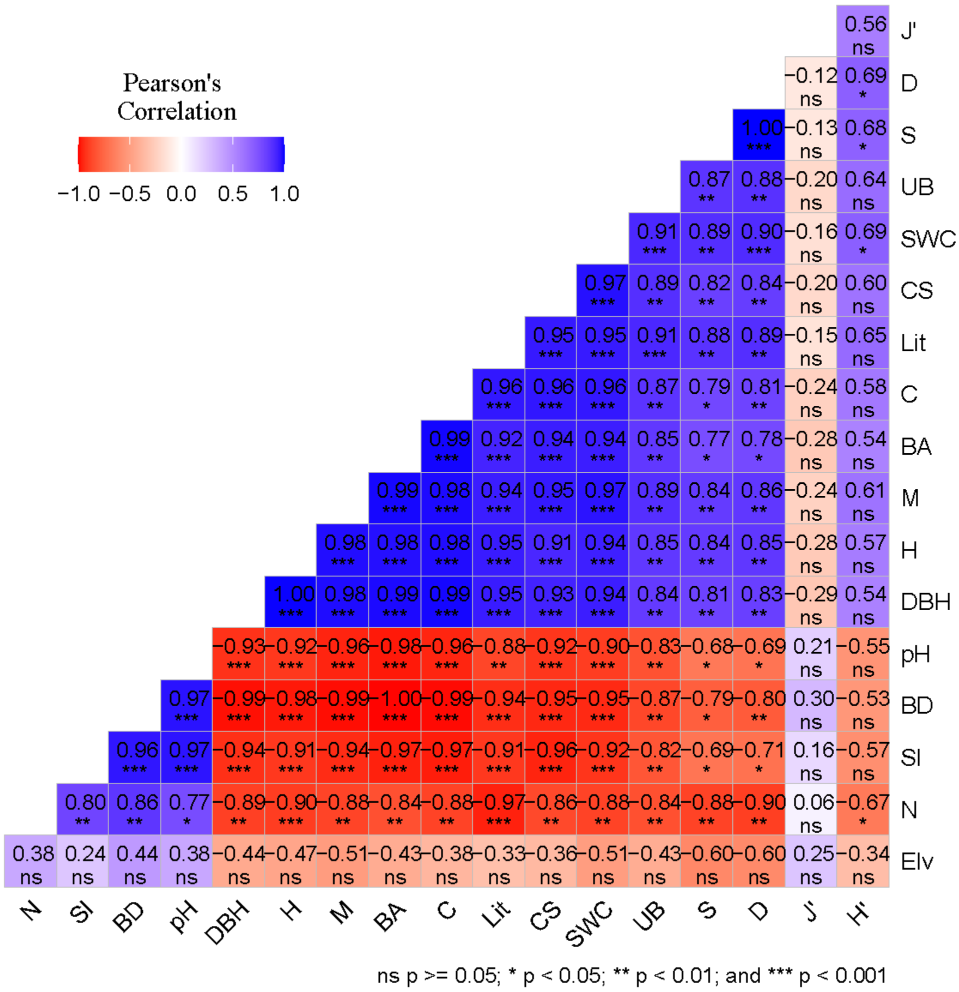

Figure 5. *Pearson correlation of the soil organic carbon and environmental factors. CS, soil carbon storage; N, stand density; M, stand volume; BA, basal area; DBH, diameter at breast height (1.3 m); H, tree height; C, canopy density; Lit, litter biomass; UB, understorey biomass; Sl, slope; Elv, elevation; BD, bulk density; SWC, soil water content; S, species richness; H', Shannon's diversity index; D, Margaler's diversity index; J', Pielou index*

To explore the best predictive variables that influence CS, we conducted stepwise multiple regression analysis with environmental parameters (SWC, BD, pH, C, M, BA,

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DBH, H, N, Sl, S, D, Lit, and UB) as independent variables and CS as the dependent variable. The regression model shows that SWC and slope are the two most important parameters controlling the uptake of soil organic C, and these factors have a significant positive effect (*Table 4*).

Table 4. *Results of stepwise multiple linear regression analyses showing the dependence of soil organic C storage on environmental variables*

Dependent variable	Explanatory variable	Coefficient estimate	SE	t-value	*p*-value	R^2	VIF
CS	Constant	43.245	26.660	1.622	0.156		
	SWC	3.077	0.852	3.613	0.011	0.975	6.771
	Slope	-2.126	0.842	-2.523	0.045		6.771

CS, soil carbon storage; SE, standard error of the coefficient estimate; VIF, variance inflation factor. The values of VIF < 10 denote there is no multicolinearity to the research data

Discussion

Characteristics of the three forest types

The structural characteristics of forests play a crucial role in understanding their ecological dynamics and management implications (Kuuluvainen, 2009). Our results provide insights into the varied growth patterns exhibited by trees in different forest types. The observed range in average DBH, from 11.8 cm to 19.9 cm, reflects variations in tree size and age distribution across the studied ecosystems. Similarly, the variations in average H, ranging from 10.8 m to 17.4 m, signify differences in vertical structure and canopy development among the forest types. Our study also elucidates the structural attributes of the forests, including N, BA, V, IVI of species, and species composition. Notably, the rich forest type stands out for its high S, housing 37 identified species, followed by the medium forest type with 34 species, and the poor forest type exhibiting the lowest species diversity, with only 32 species identified. This disparity in species composition highlights the influence of environmental factors and disturbance regimes on forest structure and diversity distribution (Dieler et al., 2017; Tomao et al., 2020). The findings underscore the importance of considering structural characteristics when assessing forest health, productivity, and conservation priorities. Forests with greater S tend to exhibit higher structural complexity, which, in turn, can support a wide array of ecological functions and services, including habitat provision, carbon sequestration, and watershed protection (Hakkenberg et al., 2016; McElhinny et al., 2005). Understanding and managing these structural attributes is essential for promoting sustainable forest management practices and enhancing ecosystem resilience in the face of environmental change (Mori et al., 2017; Rist and Moen, 2013).

Soil organic C storage in the three forest types

In this study, we found that the CS in the rich forest (124.32 Mg. ha^{-1}) were higher than those in the medium (109.03 Mg. ha^{-1}) and poor forests (92.23 Mg. ha^{-1}), with statistically significant disparities evident among the three forest types (*Fig. 4*). Studies conducted by Xiao et al. (2020) have underscored the substantial influence of alterations in plant species, soil properties, and environmental factors across diverse forest ecosystems on CS. The variations in SOC sequestration among the different forest types

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may stem from divergent patterns of C input or output (Yang et al., 2008), possibly linked to differences in the quality and quantity of litter and roots (*Table 3*). The slower rate of litter decomposition observed in the rich forest compared to the medium and poor forests, as indicated by Thanh and Chien (2019), may be attributed to differences in chemical composition and environmental conditions. This phenomenon could elucidate the heightened CS observed in the rich forest.

The mean CS of 108.53 Mg. ha^{-1} reported in this study is significantly higher than the 62.00 Mg. ha^{-1} reported for tropical evergreen broadleaved forests in the Central Highlands of Vietnam (Hai et al., 2015), but notably lower than those reported for the tropical evergreen broad-leaved forests in southern Vietnam (114.68 Mg. ha^{-1}) and the Chinese evergreen broadleaved forests (257.57 Mg. ha^{-1}) (Zhou et al., 2000). However, it falls within the range of 121.00-123.00 Mg. ha^{-1} reported for tropical forests (Lal, 2004). These variations may be attributed to differences in sampling depths within the soil profile, variations in tree species and tree density, and differences in the management history of the ecosystem, as well as climatic, geographical, geological, and environmental factors across the research areas (Saimun et al., 2021; Sharma and Kakchapati, 2018).

Consistent with prior research findings (Toai et al., 2016; Thanh and Chien, 2019), the SOC and CS exhibit similar vertical distribution characteristics across the three types of forests, showing a declining trend with increasing soil depth. This phenomenon can be attributed to the impact of plant litter and roots on soil carbon, which decreases with greater soil depth (Xiao et al., 2020). As most litter and fine roots are concentrated in the surface soil, C storage is primarily concentrated there. More than 81% of the C was found in the top 40 cm of soil across all forest types (*Fig. 4*). These findings are consistent with previous studies (Zou and Song, 2023), which observed higher SOC in the topsoil compared to the subsoil.

Factors influencing soil organic C stocks

Previous studies have demonstrated that variations in CS are regulated by topographic features and soil properties (Mayes et al., 2014; Fang et al., 2018; Johnson et al., 2015). Our results indicate that forest characteristics, soil properties, and topographical features significantly influence CS in three forest types (rich, medium, and poor forest) within the Dongnai Culture and Nature Reserve (*Fig. 5*). Among the factors assessed, SWC and slope emerge as the most critical regulatory parameters of CS (see *Table 4*). Scholars have highlighted SWC as a crucial physical indicator affecting CS in previous reports, as it regulates organic matter input and microbial activity (Dalsgaard et al., 2016), consequently influencing the accumulation of SOC. Additionally, topographical variations can create distinct microclimates, influencing plant development and soil characteristics (Lozano-García et al., 2016). Slope, being a stable topographical parameter compared to factors like temperature and precipitation (Zhou et al., 2023), significantly influences SOC quantity by affecting litter decomposition rates and soil microorganism activity (Nahidan et al., 2015). Furthermore, forest structural parameters (N, DBH, H, BA, M, and C) and diversity indices (S and D) may also impact the shift in CS in various forest types (*Fig. 5*).

Conclusions

The results of the present study have furnished quantitative data to enhance our understanding of SOC stocks and their modulating factors in tropical natural forest soils

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within the Dongnai Culture and Nature Reserve in the southeastern region of Vietnam. The average CS for each forest type in the study area was determined to be 92.2 Mg C ha^{-1} for poor forests, 109.0 Mg C ha^{-1} for medium forests, and 124.3 Mg C ha^{-1} for rich forests. A significant decrease in soil organic carbon content was observed with increasing soil depth. Specifically, more than 81% of soil C at a depth of 0–60 cm was concentrated in the upper 40 cm of the soil profile. Slope and SWC emerged as the primary factors influencing CS in natural forests. These findings offer new insights that will significantly contribute to our knowledge of CS in tropical natural forests. Furthermore, the information derived from this study can be applied in initiatives such as payment for forest environmental services and forest management activities.

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APPENDIX

(a) Poor forest

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(b) Medium forest

(c) Rich forest

Figure A1. *Illustrations of three forest types and their corresponding soil profiles*

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