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ORIGINAL ARTICLE

Assessment of soil property alteration caused by unsustainable reclamation activities[1]

Avaliação da alteração da propriedade do solo causada por atividades de recuperação insustentáveis

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HIGHLIGHTS:

Distinct differences in soil properties were observed among forest, cultivation, and bare land areas.
Bare and cultivated land exhibiting higher sand and clay contents compared to forest land in the surface soil layer (SSL).
The SSL was affected by unsustainable reclamation activities, leading to notable changes in soil properties.

ABSTRACT: Unsustainable reclamation activities (URAs) have been increasingly conducted to respond to the rising global food demand, leading to severe repercussions on land environments. A total of 120 soil samples representing 12 sites were randomly selected in the three distinct land types (PMFs, PALs, and BHLs) to a depth of 60 cm. The impacts of URAs on soil properties and functions (SPFs) across the Nghe An mountainous province, Vietnam were assessed using the SPSS software (version 26.0) through a one-way analysis of variance (ANOVA). The findings indicated the distinct differences in soil particle size (SPS) among different land types (DLTs). Pristine and mixed forests (PMFs) exhibited the lowest sand ratios, ranging from 31.4 to 35.2%, while bare hills and lands (BHLs) recorded the highest sand ratios, ranging from 49.7 to 55.1%. High bulk density (BD) was observed in BHLs (1.36 ± 0.07 kg dm^{-3}) and PMFs (0.89 ± 0.02 to 1.13 ± 0.03 kg dm^{-3}) while perennial and annual lands (PALs) varied from 1.17 ± 0.04 to 1.25 ± 0.08 kg dm^{-3}. PMFs showed low values for total soil porosity (TSP), and soil water content (SWC) with respective ranges of 32.97-36.18% and 4.72-6.15% while PALs and BHLs exhibited high values for TSP (39.25-43.19%; 43.97-49.62%), and SWC (7.39-10.07%; 9.98-12.74%). Cation exchange capacity (CEC), Ca^{2+}, K^{+}, and Mg^{2+} were recorded higher in PALs compared to PMFs and PALs while total organic contents (TOCs) detected little variation among DLTs. Overall, the URAs enhanced the adverse effects on the SPFs across the study area.

Key words: reclamation, degradation, soil particle size, properties, function

RESUMO: As atividades de recuperação insustentáveis (URAs) têm sido cada vez mais realizadas para responder à crescente procura global de alimentos, levando a graves repercussões nos ambientes terrestres. Um total de 120 amostras de solo representando 12 locais foram selecionadas aleatoriamente nos três tipos distintos de terra (PMFs, PALs e BHLs) a uma profundidade de 60 cm para avaliar os impactos das URAs na província de Nghe An Mountain, no Vietnã. A análise estatística dos parâmetros do solo foi realizada no software SPSS (versão 26.0) por meio de análise de variância unidirecional (ANOVA). As descobertas indicam diferenças distintas no tamanho das partículas do solo (SPS) entre os diferentes tipos de terreno (DLTs). Florestas virgens e mistas (PMFs) exibiram as menores proporções de areia, variando de 31,4 a 35,2%, enquanto colinas e terras nuas (BHLs) registraram as maiores proporções de areia, variando de 49,7 a 55,1%. Elevado densidade global (BD) foi observado em BHLs (1,36 ± 0,07 kg dm^{-3}) e PMFs (0,89 ± 0,02 a 1,13 ± 0,03 kg dm^{-3}) enquanto terras perenes e anuais (PALs) variaram de 1,17 ± 0,04 a 1,25 ± 0,08 kg dm^{-3}. Os PMFs apresentaram baixos valores de porosidade total do solo (TSP) e teor de água do solo (SWC) com respectivas faixas de 32,97-36,18% e 4,72-6,15% enquanto PALs e BHLs exibiram valores elevados para TSP (39,25-43,19%; 43,97-49,62%). e SWC (7,39-10,07%; 9,98-12,74%). A capacidade de troca catiônica (CEC), Ca^{2+}, K^{+} e Mg^{2+} registrou altos valores nos PALs em comparação aos PMFs e PALs, enquanto o conteúdo orgânico total (TOCs) detectou pouca variação entre os DLTs. No geral, as URAs aumentaram os efeitos adversos nas propriedades e funções do solo (SPFs) em toda a área de estudo.

Palavras-chave: recuperação, degradação, tamanho de partícula do solo, propriedades, função

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Introduction

Unsustainable reclamation activities (URAs) have raised concerns due to their significant risks of soil degradation, leading to severe consequences for land ecosystems (Borrelli et al., 2017; Feng et al., 2019). The detrimental effects of URAs on soil functionality and environmental decline have been widely acknowledged (Nelofer et al., 2016; Souza et al., 2016; Marty et al., 2017; Huang et al., 2021). Consequently, researchers have given considerable attention to understanding the variation in soil properties and functions (SPFs) (Souza et al., 2016; Deng et al., 2019). Studies have highlighted the detrimental effects of URAs on soil nutrient uptake for agricultural expansion (Qi et al., 2018; Phung & Dang, 2023). The URAs are also expected to significantly influence ecosystem processes, leading to alterations in soil functions (Nosrati & Collins, 2019; Mihelič et al., 2021). Consequently, the variation in SPFs, an inevitable consequence of URAs, has garnered considerable attention worldwide (Joshi & Negi, 2015; Phung & Dang, 2023). Conversion of forests into agricultural ecosystems can lead to significant changes in SPFs (Garrett et al., 2018).

URAs not only affect the nutrient composition of the soil but also disrupt the ecological balance. Therefore, it is essential to establish a stronger connection between these ideas and emphasize the variation in SPFs caused by URAs (Souza et al., 2016; Deng et al., 2019).

In Nghe An province, the increasing demands of socio-economic development have resulted in various challenges related to land degradation due to the consequences of URAs (Dung et al., 2021; Dinh & Shima, 2022). However, the effects of URAs on the land environment across Nghe An mountainous province have not been thoroughly investigated, hindering the effective management of soil resources and the sustainable exploitation of natural forests. There is a lack of assessment regarding the impacts of URAs on SPFs, further impeding the effective management of land resources and the maintenance of a balanced land-forest ecosystem (Dung et al., 2021; Nguyen et al., 2023). Therefore, this study aims to assess the impacts of URAs on SPFs in Nghe An mountainous province, serving as a representative case where forest lands are extensively exploited for agricultural expansion activities and infrastructure development.

Materials and Methods

Nghe An province is situated in the North Central region of Vietnam, covering an estimated area of 16,400 km^2 (Dinh & Shima, 2022). The study area is located between 18° 41' 29" N - 18° 59' 20" N latitude and 103° 02' 20" E - 105° 29' 19" E longitude, altitude of the study area ranging from 10 to over 1,000 m above mean sea level, with the altitude gradually decreasing from north to south and from west to east (Figure 1). The province exhibits a diverse topography of mountains, plains, mountains and midlands, with mountains occupying around 75% of the total land area (Dinh & Shima, 2022). The terrain presents gradual slopes from north to south and from west to east (Nguyen et al., 2021). The study area encompasses

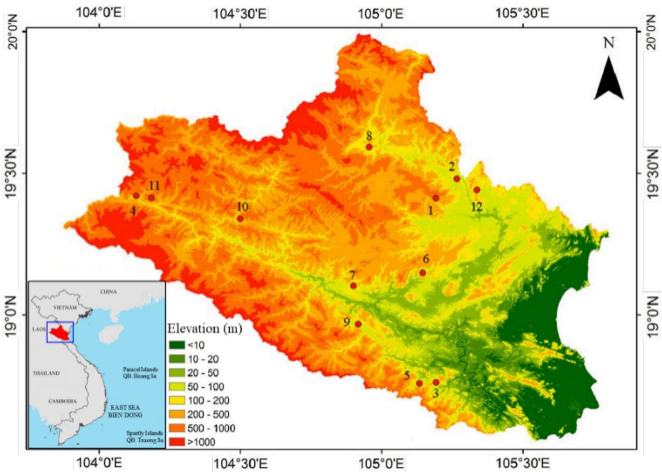

Figure 1. Topographic map of the study area and collected sample spatial sites

a rich variety of flora, comprising pristine and bamboo forests, acacia forests, and cassava plantation paddies (Dung et al., 2021). Nghe An province is home to primeval forests that serve as critical habitats for numerous plant and animal species, contributing significantly to the biological diversity and natural heritage of the region (Nguyen et al., 2021). The province experiences a tropical monsoon climate, characterized by distinct wet and dry seasons (Dinh & Shima, 2022). The mean annual temperature in Nghe An is approximately 24 °C, with recorded temperatures ranging from 40 °C during the hottest periods to around 2 °C during the coldest periods (Nguyen et al., 2021). The study area has a mean annual precipitation of approximately 1,800 mm, which plays a crucial role in sustaining the land and supporting its diverse ecosystems (Figure 2).

A total of 120 soil samples representing 12 sites were randomly selected in the three distinct land types, including pristine and mixed forests (PMFs), perennial and annual lands (PALs), and bare hills and lands (BHLs), to a depth of 60 cm. These land types were selected based on their physiographic conditions, slope gradients (Figure 1) and climatic features (Figure 2).

The PMFs consisted of four positions 1, 2, 3, and 4, the PALs included four positions 5, 6, 7, and 8 and the BHLs encompassed four positions 9, 10, 11, and 12 (Table 1). The history of land use changes for each land type across the study area is also described in detail in Table 1. Each soil sample,

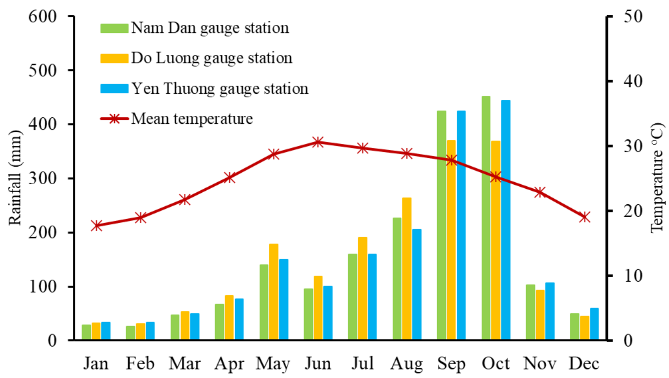

Figure 2. Historical mean monthly temperature and rainfall data of the study area in the period 2000-2022

Table 1. General characteristics of the soil samples across the study area

Site	Latitude (N)	Longitude (E)	Typical groups	Land-use change history
1	19° 24' 53.89"	105° 11' 52.80"	Pristine and mixed forests (PMFs)	The PMFs consisted of mixed trees from the pine family (*Fokienia hodginsii*, *Cunninghamia lanceolata*, and bamboo). The forest remained untouched and was never subjected to reclamation activities, resulting in the formation of a continuous canopy cover.
2	19° 29' 03.65"	105° 15' 35.07"		
3	18° 45' 47.61"	105° 11' 17.81"		
4	19° 25' 24.07"	104° 07' 32.34"		
5	18° 45' 32.22"	105° 07' 43.54"	Perennial and annual lands (PALs)	The PMFs underwent reclamation, and the land was subjected to rotational planting of acacia and cassava. During the acacia phase, the under-story of the PMF was densely populated with grass, with an average height ranging from 0.75 to 2.5 m.
6	19° 09' 00.44"	105° 08' 24.31"		
7	19° 06' 11.13"	104° 53' 43.88"		
8	19° 35' 47.82"	104° 56' 58.95"		
9	18° 58' 14.45"	104° 54' 40.03"	Bare hills and lands (BHLs)	In the 2000s, the PMFs underwent further reclamation, leading to the conversion of the land into bare hills and bare lands. These areas are characterized by a lack of vegetation and a noticeable absence of surface layer coverage.
10	19° 20' 31.18"	104° 29' 37.76"		
11	19° 24' 58.49"	104° 08' 54.76"		
12	19° 26' 40.70"	105° 18' 07.40"		

weighing approximately 500 g, was collected using Kopecky rings with a diameter of 10 cm. Samples were collected at five different depth layers, including 0-5, 5-10, 10-20, 20-40, and 40-60 cm depths.

The collected samples were divided into two parts. One part was stored in plastic bags to preserve potential moisture for the analysis of soil particle size (sand, silt, and clay), soil BD, and soil water content (SWC). The other part was air-dried for 24 hours, sieved, and used for determining cation exchange capacity (e.g., Ca^{2+}, K^+, and Mg^{2+}) and total organic contents (TOCs) (e.g., total nitrogen (TN), total phosphorus (TP), and total carbon (TC)). Soil particle size classified following the United States (2014), which categorizes soil particles into sand, silt, and clay (EMBRAPA, 2018). SWC was determined using the dielectric permittivity method (Zawilski et al., 2023), while soil BD was defined as the ratio of dry soil weight (g) after drying in the oven for 24 hours at 105 °C to the soil volume of 100 cm^3, as given in Eq. 1.

$$\text{Bulk density} = \frac{\text{dry soil weight}}{\text{soil volume}} \quad (1)$$

The total soil porosity was calculated using soil bulk density and the soil particle density as described by Eq. 2.

$$\text{Total soil porosity} = \left(1 - \frac{\text{soil bulk density}}{\text{soil particle density}}\right) \times 100 \quad (2)$$

Soil pH was determined using a soil-to-water suspension ratio of 1:2.5. The TOCs, including total nitrogen (TN) and total carbon (TC) were analyzed using dry combustion methods while total phosphorus (TP) was quantified by applying Olsen's sodium bicarbonate extraction method for 8 hours at 560 °C (United States, 2014; Marty et al., 2017). CEC including Ca^{2+}, K^+, and Mg^{2+} were quantified through ammonium acetate extraction buffered at pH 7 (Locatelli et al., 2023).

The soil properties were analyzed using a one-way analysis of variance (ANOVA) to assess the differences in soil characteristics among the various land types across the entire study area. This statistical analysis was performed using the SPSS Statistics software (version 26.0). The ANOVA was applied to compare the mean differences in soil parameters, such as sand, clay, silt, soil BD, STP, SWC, soil pH, and nutrient contents (Ca^{2+}, Mg^{2+}, K^+, TP, TN, TC) across the study area. The statistical significance of the observed differences was evaluated using the Pearson's test at significant levels of $\alpha = 0.05$ and 0.01. All sample mean values and standard errors were analyzed using the SPSS software. The ANOVA results hope to provide an insight into how the soil properties varied within the Nghe An mountainous province, which is crucial for understanding the overall soil conditions and their potential implications for land use and management practices in the region.

Results and Discussion

Table 2 provides an overview of the important statistical characteristics of the SPFs throughout the study area. The analysis of soil particle size (SPS) revealed that the mean contents of sand, clay, and silt were 42.9, 43.8, and 13.3%, respectively. Overall, the soil texture in the Nghe An mountainous province is characterized by a predominance of sand and clay particles. This indicates that the soils in the study area have a sandy clay texture, with the clay component being the dominant fraction. The main reason for the high proportion of sand and clay in the surface layer is likely due to the study area experiencing high mean annual rainfall, particularly heavy and prolonged rainfall during the study period, which is directly influenced by storms. Additionally, the steep terrain of the area has facilitated favorable conditions for the transportation of small-sized silt particles on the surface layer. A study on the potential risks of soil erosion in North-Central Vietnam conducted by Nguyen et al. (2023) reported that the erosion in the surface layer across Nghe An (Vietnamese mountain province), Vietnamese closely related to climatic conditions and terrain features.

The high clay content, coupled with the relatively low sand proportion, suggests that the soils in the Nghe An mountainous province tend to have a fine-grained, cohesive nature, which can significantly influence their water-holding capacity and nutrient retention. Similar results were reported by Nelofer et al. (2016), who observed that soil samples typically exhibit higher proportions of sand and clay in the surface soil layer (SSL).

The soil pH was found to range from 4.52 to 4.96, indicating slightly acidic soil conditions. Among the analyzed soil properties, several showed relatively low variability (Islam et al., 2020), as indicated by the CV of sand (18.76%), clay (11.80%), soil BD (11.74%), soil pH (3.25%), Ca^{2+} cation (3.25%), and TC (13.27%). On the other hand, moderate variability was observed for silt (25.71%), SWC (29.57%), K^+ cation (21.82%),

Table 2. Statistical characteristics of the soil properties across the study area

Properties	Unit	Min	Max	Mean	SD	CV (%)	Skewness	Kurtosis
Sand	%	31.2	49.7	42.9	8.05	18.76	-0.071	-1.615
Clay	%	13.9	36.3	43.8	5.16	11.80	0.169	-1.723
Silt	%	11.2	26.5	13.3	3.42	25.71	0.336	-1.359
BD	kg dm^{-3}	0.83	1.42	1.20	0.14	11.74	-0.940	0.307
STP	%	36.2	50.9	43.8	5.06	12.40	0.084	-1.052
SWC	%	4.72	12.74	8.51	2.52	29.57	-0.089	-1.227
Soil pH	-	4.45	4.96	4.73	0.15	3.25	-0.389	-0.665
Ca^{2+}	$cmol_c$ kg^{-1}	0.05	0.23	0.14	0.06	3.25	-0.016	-1.186
Mg^{2+}	$cmol_c$ kg^{-1}	0.04	0.14	0.09	0.03	32.21	0.099	-0.057
K^+	cmo_{lc} kg^{-1}	0.05	0.09	0.07	0.02	21.82	0.375	0.000
TP	g kg^{-1}	0.08	0.18	0.13	0.03	23.03	-0.050	-0.965
TN	g kg^{-1}	0.89	2.78	1.68	0.54	34.18	0.544	-0.347
TC	g kg^{-1}	12.98	21.34	17.82	2.36	13.27	-0.697	-0.019

Min - Minimum; Max - Maximum; SD - Standard deviation; CV - Coefficient of variation; SWC - Soil water content; BD - Soil bulk density, STP - Soil total porosity, TN - Total nitrogen; TP - Total phosphorus; TC - Total carbon

Mg^{2+} cation (32.21%), and TOC (TP: 23.03%, and TN: 34.18%). Notably, the highest CV was observed for TN content, reaching up to 34.18%, followed by Mg^{2+} cation at 32.21%. This suggests significant spatial variation among the collected soil samples. Overall, TN content and Mg^{2+} cation exhibited moderate spatial variation, as evidenced by their CV values exceeding 30%.

Looking at the skewness values, most of the soil properties exhibit a relatively symmetrical distribution, with skewness values close to zero (Table 2). This implies that the data are roughly balanced around the mean, except for silt (0.336). SWC shows a slightly negative skewness (-0.089), indicating a higher frequency of lower moisture levels in the study area. This could be attributed to factors such as climate and soil type. In terms of kurtosis, most soil properties display negative values varying from -1.723 to -1.359. This suggests a platykurtic distribution, meaning that the distributions have flatter peaks compared to a normal distribution. On the other hand, some properties like soil pH and TP exhibit slightly negative kurtosis values (-0.665 and -0.965), indicating a more peaked distribution.

Figure 3 illustrates the results of the SPS analysis conducted on different land types (DLTs) at depths ranging from 0 to 60 cm. The analysis revealed significant variations in the percentages of sand, silt, and clay between pristine and mixed forests (PMFs), perennial and annual lands (PALs), and bare hills and lands (BHLs). The mean percentages of sand, silt, and clay in PMFs were found to be 33.5, 17.5, and 49.0%, respectively. In comparison, PALs exhibited higher

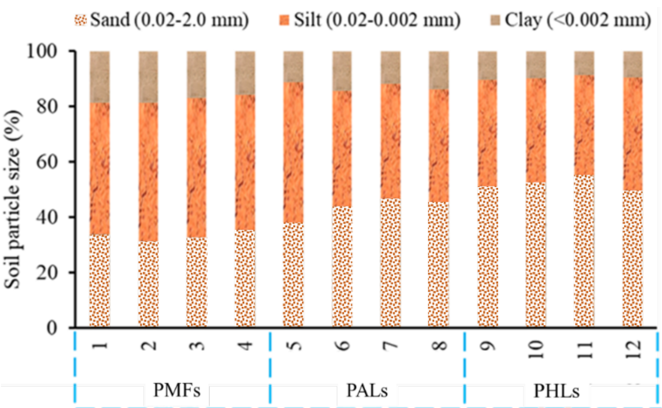

Figure 3. The soil particle size varies among sample sites with different land-use (PMFs - Pristine and mixed forests; PALs - Perennial and annual lands; BHLs - Bare hills and lands) histories

percentages of sand (43.4%), lower percentages of silt (12.8%), and similar percentages of clay (43.8%). BHLs displayed the highest percentages of sand (52.1%), lower percentages of silt (9.6%), and similar percentages of clay (38.3%). Dinh & Shima (2024), who conducted a study on the impacts of land use and management practices on soil properties in the Lam River Basin, observed that the surface layer of PALs has higher proportions of sand and clay compared to silt.

Specifically, PMFs, characterized by the presence of *Fokienia hodginsii*, *Cunninghamia lanceolata*, and bamboo, exhibited the lowest percentage of sand, ranging from 31.4 ± 2.58% to 35.2 ± 3.14%. PALs showed percentages of sand ranging from 37.8 ± 3.29% to 46.7 ± 4.15%, while BHLs recorded the highest percentage of sand at 50.6 ± 3.87% (Table 3). PMFs have a lower sand ratio compared to PALs and BHLs, primarily due to the removal of vegetation in BHLs through anthropogenic activities (Dinh & Shima, 2024). The cover loss has made it easier for silt and clay to be washed away during heavy rainfall events (Nguyen et al., 2023).

Soil BD is closely linked to soil porosity and plays a crucial role in soil water retention and permeability (Nguyen et al., 2021). In the study area, soil BD ranged from 0.89 ± 0.04 to 1.36 ± 0.07 kg dm^{-3}. Figure 4A illustrates the range of soil BD values for PALs, which varied from 1.17 ± 0.04 to 1.25 ± 0.08 kg dm^{-3}. In contrast, PMFs displayed a narrower range of 0.89 ± 0.02 to 1.13 ± 0.03 kg dm^{-3}. The highest soil BD value of 1.36 ± 0.07 kg dm^{-3} was observed in the BHLs. These findings indicate that soil BD exhibited lower variation in the PMs, where the land has not been significantly affected by anthropogenic activities (Dinh & Shima, 2022). Conversely, significant changes in soil BD were observed in the PALs and BHLs (Table 3).

In a study conducted by de Souza et al. (2016), the effects of URAs on soil properties were investigated. The study revealed that anthropogenic activities can cause significant compaction in the SSL while having a lesser impact on the soil profiles. STP plays a vital role in soil aeration, water permeability, and vegetable growth, making it an important indicator of soil fertility that influences various other soil properties, as highlighted by Zhou et al. (2019). URAs have been found to have a negative impact on soil porosity and other soil functions. Similar results were observed for TSP. In the PMFs, TSP exhibited lower values ranging from 32.97 ± 3.75 to 36.18 ± 4.38%. In contrast, higher values ranging from 39.25 ± 4.11 to 43.19 ± 3.73% were recorded

Table 3. Soil particle size (SPS), soil bulk density (BD), total soil porosity (TSP), soil water content (SWC), and standard deviation (SD) among different used land types

Site	SPS			BD	TSP	SWC
	Sand (%)	Clay (%)	Silt (%)	(kg dm^{-3})	(%)	(%)
	(Mean ± SD)			(Mean ± SD)	(Mean ± SD)	(Mean ± SD)
1	33.8 ± 2.97 a	18.7 ± 1.64 a	47.5 ± 3.14 a	0.97 ± 0.02 a	34.84 ± 3.98 a	4.72 ± 0.01 a
2	31.4 ± 2.58 b	18.7 ± 1.45 a	49.9 ± 4.22 b	1.12 ± 0.03 a	36.18 ± 4.38 a	5.98 ± 0.02 b
3	32.6 ± 2.21 a	16.8 ± 1.82 b	50.6 ± 3.87 a	0.89 ± 0.04 b	32.97 ± 3.75 b	6.15 ± 0.03 a
4	35.2 ± 3.14 a	15.9 ± 1.35 a	48.9 ± 4.39 a	1.13 ± 0.03 a	35.16 ± 3.21 a	4.97 ± 0.03 a
5	37.8 ± 3.29 a	11.3 ± 0.78 a	50.9 ± 3.93 a	1.22 ± 0.05 a	39.25 ± 4.11 b	8.91 ± 0.71 b
6	43.9 ± 4.97 a	14.3 ± 1.25 b	41.8 ± 4.02 b	1.25 ± 0.08 b	41.17 ± 5.12 a	7.39 ± 0.51 a
7	46.7 ± 4.15 b	11.9 ± 1.06 a	41.4 ± 3.78 b	1.17 ± 0.04 a	40.67 ± 4.08 a	9.18 ± 0.64 b
8	45.3 ± 6.11 b	13.8 ± 0.86 a	40.9 ± 4.21 a	1.23 ± 0.06 b	43.19 ± 3.73 b	10.07 ± 0.78 a
9	50.9 ± 4.59 a	10.3 ± 1.14 a	38.8 ± 2.98 b	1.35 ± 0.09 b	45.34 ± 4.19 a	9.98 ± 0.29 a
10	52.4 ± 3.14 b	9.8 ± 0.76 b	37.8 ± 3.19 a	1.29 ± 0.05 a	43.97 ± 3.78 b	11.15 ± 0.23 b
11	55.1 ± 6.15 b	8.7 ± 1.02 a	36.2 ± 2.78 a	1.32 ± 0.06 b	47.13 ± 4.21 a	10.93 ± 0.25 a
12	49.7 ± 3.92 a	9.6 ± 0.95 a	40.7 ± 3.37 b	1.36 ± 0.07 a	49.62 ± 5.08 a	12.74 ± 0.72 a

Means followed by different letters indicate a significant level (α = 0.05) among soil sample sites by one-way ANOVA

in the plantation forest and acacia land areas (Figure 4A). The BHLs displayed the highest TSP values, reaching up to 49.62 ± 5.08%. These findings indicate a significant difference in TSP among the collected sample positions, as illustrated in Figure 4B. The SWC exhibited varying ranges at the collected sample positions (Figure 4C). In the PMFs, the SWC ranged from 4.72 ± 0.01% to 6.15 ± 0.03%. In the PALs, the SWC ranged from 7.39 ± 0.51% to 10.07 ± 0.78%. The BHLs displayed SWC ranging from 9.98 ± 0.29% to 12.74 ± 0.72% (Table 3).

Soil pH is an important factor that influences other soil properties, as highlighted by Oraon et al. (2018). In the study area, the soil pH ranged from 4.45 to 4.92 (Table 4). No significant differences in soil pH values was observed between the collected sample positions throughout the study area. However, a slight increase in soil pH was observed with increasing soil depth. The SSL exhibits relatively acidic pH values, which can be attributed to the decomposition of nutrient-rich organic matter (Souza et al., 2016). A similar study conducted by Nelofer et al. (2016) indicated that soil pH is typically low in the SSL due to concentrated decomposition of plants and animals. This decomposition process generates an increased concentration of organic acids, consequently lowering the overall pH in the SSL (Dinh & Shima, 2024). The results are consistent with the conclusions of Hong et al. (2019) that climatic factors and soil inorganic carbon govern the pH variables in the SSL. A study conducted in the Mun Basin by Zhao et al. (2018) reveals that precipitation is one of the key causes enhancing the washing away of calcium and magnesium ions from the surface soil layer, consequently leading to a decrease in soil pH. Overall, a slight upward trend in soil pH with increasing soil depth was observed across the study area. This finding aligns with the study conducted by Suleiman et al. (2017), which reported that mildly acidic soil conditions are favorable for the SSL.

The CEC and TOCs play crucial roles in soil fertility and nutrient availability (Qi et al., 2018; Dinh & Shima, 2024). Figure 5 shows that, the CEC values varied among different land use types, with notable differences observed between the PALs and BHLs. The PALs exhibited higher CEC values, with Ca^{2+}, Mg^{2+}, and K^{+} cations ranging from 0.05 ± 0.001 to 0.23 ± 0.022 g kg^{-1}, 0.04 ± 0.001 to 0.14 ± 0.015 g kg^{-1}, and 0.05 ± 0.001 to 0.09 ± 0.003 g kg^{-1}, respectively. In contrast, the BHLs

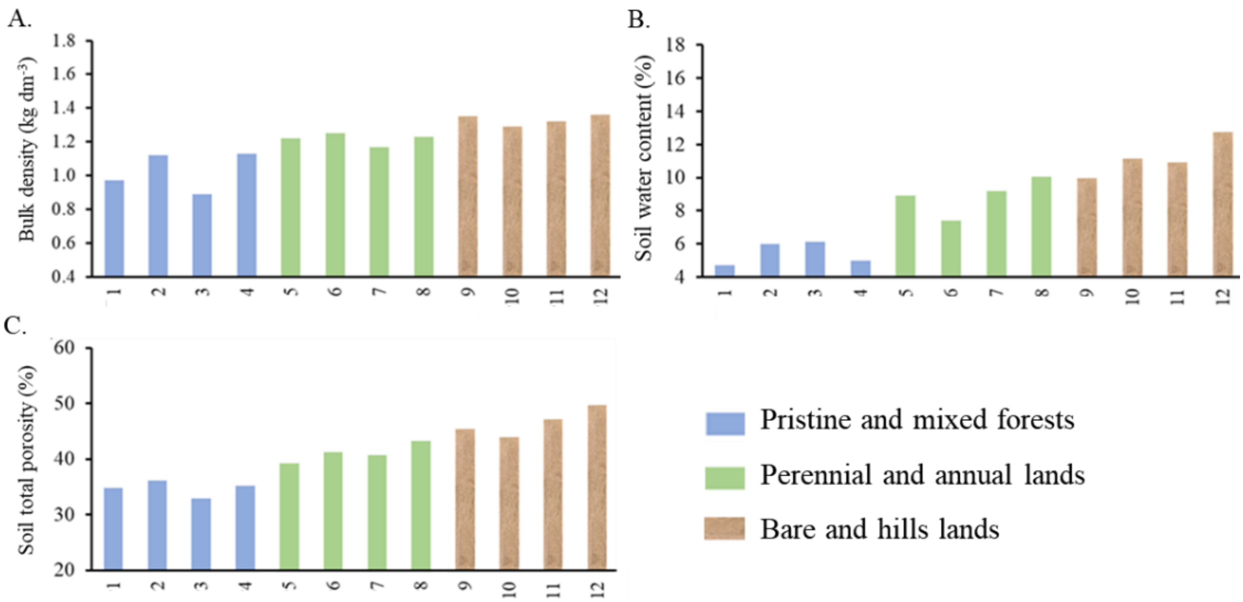

Figure 4. Analysis results of (A) soil bulk density, (B) soil total porosity, and (C) soil water content in the different sample spatial sites across the study area

Table 4. Soil pH, cation exchange capacity and total organic contents among land use types

Site	Soil pH	CEC ($cmol_c$ kg^{-1})			TOC (g kg^{-1})		
		Ca^{2+} (Mean ± SD)	Mg^{2+} (Mean ± SD)	K^+ (Mean ± SD)	TP (Mean ± SD)	TN (Mean ± SD)	TC (Mean ± SD)
1	4.45	0.05 ± 0.001 a	0.04 ± 0.001 a	0.06 ± 0.001 a	0.17 ± 0.012 a	2.35 ± 0.102 a	19.72 ± 2.151 a
2	4.58	0.08 ± 0.002 a	0.07 ± 0.002 a	0.08 ± 0.002 a	0.16 ± 0.013 a	2.11 ± 0.114 b	16.98 ± 1.124 a
3	4.72	0.06 ± 0.001 b	0.05 ± 0.001 a	0.09 ± 0.003 a	0.18 ± 0.009 b	2.78 ± 0.217 b	18.27 ± 2.011 a
4	4.49	0.09 ± 0.003 a	0.08 ± 0.003 b	0.05 ± 0.001 b	0.15 ± 0.012 a	2.07 ± 0.197 a	17.99 ± 1.287 b
5	4.67	0.21 ± 0.018 b	0.11 ± 0.012 b	0.09 ± 0.002 a	0.14 ± 0.011 b	1.75 ± 0.125 a	21.34 ± 1.972 b
6	4.82	0.19 ± 0.021 a	0.13 ± 0.011 a	0.08 ± 0.001 a	0.11 ± 0.006 b	1.59 ± 0.113 a	18.97 ± 1.658 a
7	4.79	0.23 ± 0.022 a	0.09 ± 0.002 b	0.09 ± 0.003 a	0.13 ± 0.009 a	1.38 ± 0.098 b	20.31 ± 1.997 a
8	4.96	0.18 ± 0.002 b	0.14 ± 0.015 a	0.07 ± 0.002 a	0.14 ± 0.011 a	1.63 ± 0.141 a	19.43 ± 1.379 b
9	4.68	0.12 ± 0.001 a	0.09 ± 0.001 b	0.05 ± 0.001 b	0.11 ± 0.005 a	1.14 ± 0.095 b	17.68 ± 1.327 a
10	4.85	0.15 ± 0.002 a	0.13 ± 0.012 a	0.07 ± 0.003 b	0.09 ± 0.011 b	1.32 ± 0.114 a	15.97 ± 1.113 b
11	4.92	0.16 ± 0.003 a	0.09 ± 0.001 a	0.06 ± 0.002 a	0.08 ± 0.006 a	1.09 ± 0.103 a	12.98 ± 1.092 a
12	4.79	0.13 ± 0.001 b	0.08 ± 0.002 b	0.05 ± 0.001 a	0.11 ± 0.008 b	0.89 ± 0.075 b	14.19 ± 1.217 b

CEC - Cation exchange capacity; TOC - Total organic contents; SD - Standard deviation; TN - Total nitrogen; TP - Total phosphorus; TC - Total carbon; Means followed by different letters in each column indicate a significant difference (α = 0.05, 0.01) among different land use types, determined by one-way ANOVA

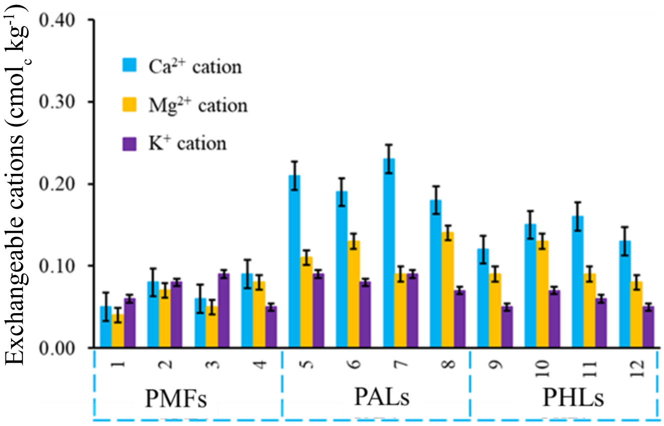

Figure 5. The exchangeable cations in the sample spatial sites across the study area

showed comparatively lower exchangeable cation values (Table 4). These findings suggest that the PALs have a greater ability to retain and exchange essential cations, which could potentially enhance nutrient availability for plant growth. Furthermore, the TOCs results indicate variations among the different land use types. The range of TOC values for the PALs was 12.98 to 21.34 g kg^{-1}, while for the BHLs it was 14.19 to 19.72 g kg^{-1}. It is important to note that higher TOC levels are generally associated with improved soil fertility, as organic matter contributes to nutrient retention, water-holding capacity, and overall soil health. Therefore, the higher TOCs values observed in both the PALs and BHLs indicate the potential for good soil quality and fertility in the studied area.

Overall, the PMFs exhibited higher TOCs values compared to PALs and BHLs. This difference can be attributed to the presence of plant residues and animal materials, which serve as raw materials for TOCs production in the PMFs compared to other land types. Additionally, TOCs decreased with increasing soil depth (Table 4). The TN, TP, and TC showed significant differences among the different SSS, with the following order: PMFs > PALs > BHLs (Figures 6A, B and C).

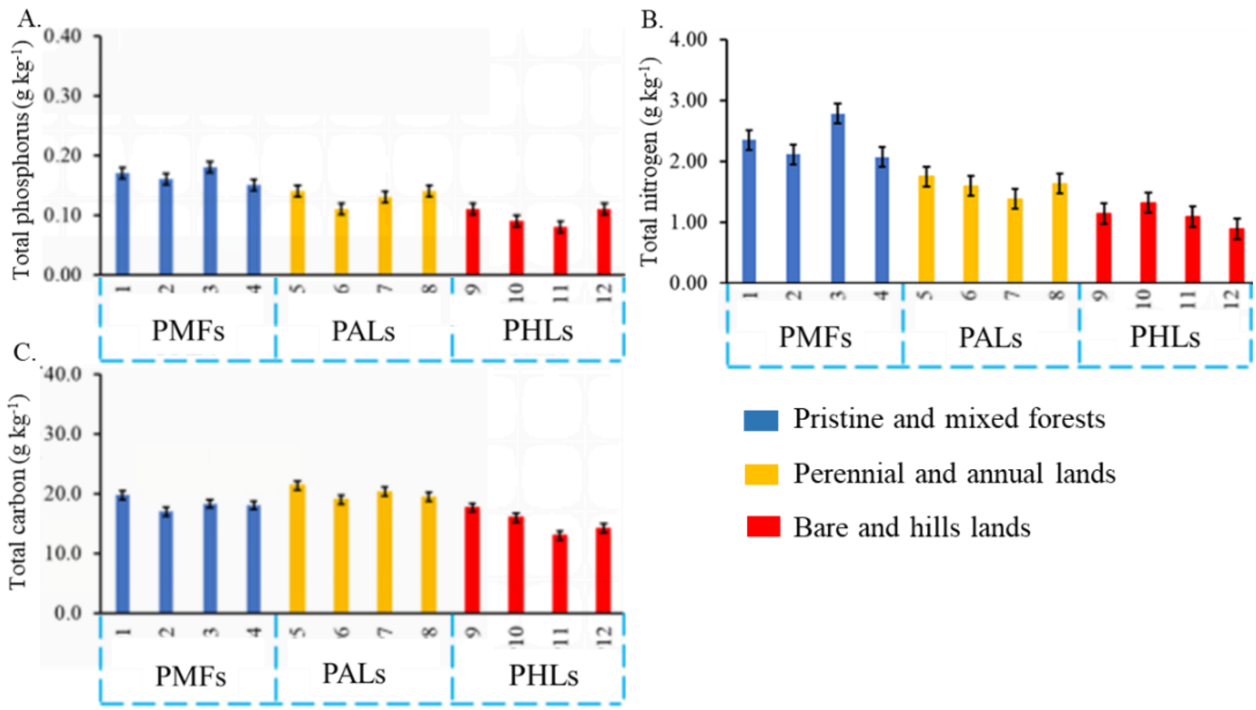

Figure 6. Analysis results of total phosphorus (A), total nitrogen (B), and total carbon (C) contents in the different sample spatial sites across the study area

The PMFs exhibit higher soil fertility compared to the PALs and BHLs. The low values of CEC may be attributed to soil nutrient decline resulting from anthropogenic activities such as slash and burn farming, logging, and infrastructure construction. Thomaz et al. (2014) conducted a study on the effects of anthropogenic activities on soil properties in Prudentópolis municipality, Brazil, which revealed that soil chemical properties were more sensitive than physical properties.

Conclusions

1. Significant variations in soil properties were observed among different soil sampling positions and soil profiles. There were distinct differences in soil properties and functions between the primeval and mixed forests, perennial and annual lands, and bare and hills land areas, particularly in the surface soil layer.

2. High soil bulk density, sand, and clay contents were observed in bare hills and lands, and perennial and annual lands in the surface soil layer, when compared to pristine and mixed forests.

3. The cation exchange capacity and total carbon content were found to be higher in perennial and annual lands, as well as in bare hills and lands, compared to pristine and mixed forest areas. However, there was little difference in total organic content between different land types.

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