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Original Article

Effect of land use change on soil chemical properties in Gede-Pangrango volcanic soil, West Java, Indonesia

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Abstract

Land use change from forest to agricultural land affects soil chemical properties. This study aims to determine the impact of land use change on the chemical properties of volcanic soils. Soil samples were collected at Mt. Gede and Mt. Pangrango, West Java, from different land uses including natural forest, pine forest, tea plantation, and horticultural land. The soil samples were analyzed in the laboratory to determine the soil chemical properties. Then, laboratory analysis results were compared between forest and other uses. The results indicated differences in chemical characteristics among different land uses, including in pH, organic carbon, and exchangeable bases, especially in the topsoil. The levels of Al_o and Si_o, which are indicative of non-crystalline minerals, were observed to be highest in agricultural areas. Conversely, the presence of organo-metallic complexes identified by Al_p, Fe_p, and C_p was more pronounced in the forest compared to the agricultural land.

Keywords: land use change, metal-humus complexes, organic matter stability, soil chemical properties, volcanic soil

1. Introduction

Indonesia boasts a multitude of volcanoes due to the seismic ring of fire, especially on the island of Java (Pambudi, 2018). The soils created by these volcanic eruptions are exceptionally rich in nutrients and have distinct qualities that set them apart from other soil types (Fiantis, Ginting, Gusnidar, Nelson, & Minasny, 2019). The abundance of organic matter, high water retention, low density, and presence of various non-crystalline substances (allophane, imogolite, and ferrihydrite), and mineral humus complexes (Al/Fe-humus complexes) contribute to the richness of volcanic soil (Dahlgren, Saigusa, & Ugolini, 2004; Takahashi, 2020). In addition to enhancing agricultural productivity, volcanic soils play a significant role in global carbon sequestration owing to their abundant organic carbon content (Anda & Dahlgren, 2020a; Basile-Doelsch, Balesdent, & Pellerin, 2020). The occurrence of non-crystalline minerals, as indicated by the extraction of Al and Fe oxalates (Al_o and Fe_o), is a key factor in the stabilization of carbon in volcanic soils (Lyu, Watanabe, Kilasara, Hartono, & Funakawa, 2021). The stability of carbon is also influenced by the interaction between aluminium/iron and organic matter, which can be detected through the pyrophosphate extract (Al_p/Fe_p). A study by Parada, Neaman, Zamorano, Najera & Matus (2024) showed a remarkable correlation between Al_p+Fe_p and organic carbon in Andisol. Nevertheless, fertile volcanic soils are vulnerable to changes in land use due to their favourable chemical properties (Anindita *et al.*, 2022).

Land use change from forest to agricultural land has the potential to impact the chemical properties of the soil (Bejar-Pulido *et al.*, 2020). Soil characteristics like pH, organic carbon, and nitrogen are particularly susceptible to changes resulting from land use conversion (Ordonez, Galicia, & Olaya, 2022). Additionally, studies have demonstrated that the transformation of forested areas into agricultural land can

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significantly influence the chemical properties of volcanic soils, including P retention, exchangeable cations, and soil pH (Anda & Dahlgren, 2020a). According to a study conducted on East Java volcanic soils by Kurniawan, Agustina, Wiwaha, Wijaya, & Fitria (2021), it was observed that agricultural land experienced a significant decline in N and C stocks, up to 50%, in comparison to forest soils.

The interaction of organic Al-Fe metals, crucial for maintaining the stability of organic matter in volcanic soils, also can be influenced by alterations in soil pH and organic matter content resulting from land conversion (Neculman *et al.*, 2013; Shoji & Fujiwara, 1984). Anda & Dahlgren (2020b) conducted a study that also demonstrated the impact of land utilization on non-crystalline minerals found in volcanic soils. The research revealed that tea plantations had lower levels of allophane in their soils compared to other land uses. This difference is probably due to soil acidification caused by the application of N fertilizers. In addition, agricultural use of volcanic soils often occurs on sloping terrain, making them vulnerable to degradation. Therefore, it is imperative to collect data on the chemical characteristics of soils under different land uses and management practices to assess the resilience of volcanic soils in sustaining agricultural endeavours. The objective of this research is to evaluate the influence of land use alteration on the chemical properties of volcanic soils in the Gede-Pangrango Area, located in West Java, Indonesia.

2. Materials and Methods

2.1 Study area and soil sampling

The Gede-Pangrango Area is located in West Java and covers three regencies: Bogor, Cianjur, and Sukabumi. Soil samples were collected on the slope of Gede-Pangrango Mount in Cianjur Regency at about 6°46′0″ S and 6°43′0″ S and 106°59′0″ E and 107°2′0″ E with the altitude ranging from 1,300 and 1,400 m above sea level (asl). The mean annual precipitation and air temperature in the study site are 3,185 mm and 21.3 °C, respectively (Central Agency of Statistics [BPS] Cianjur Regency, 2023). The research site map is shown in Figure 1.

To study how land use change affects the soil chemical properties, samples were taken from different land uses, namely natural forest, pine forest as secondary forest, tea plantation, and horticultural land. Soils were sampled using a profile of 2m length, 1m width, 1.5m depth, or shallower if the C-level was encountered. Soils from each land use were sampled across all layers/horizons, depending on the soil profile. The total number of samples collected was 18, consisting of tea plantation (5), horticultural land (4), natural forest (4), and pine forest (5)**.**

2.2 Soil chemical analysis

The chemical analysis of the soil included soil pH, organic C, total N, cation exchange capacity (CEC), base saturation (BS), P retention, and the determination of Al, Fe, and Si in oxalate extracts and Al, Fe, and C in pyrophosphate extracts. The chemical analysis performed was based on the guidelines for chemical analysis of soil, plants, water, and fertilizers issued by the Soil Research Institute (Eviati *et al.*, 2022). Before analysis, the soil was air-dried and sieved using a 2 mm and 0.5 mm sieve. Soil pH analysis was performed using a pH meter with a soil/extractor ratio of 1:5 with an ion-free water extractor to determine the pH of H_2O. The organic carbon content of the soil was analyzed by the Walkley and Black method, while the total nitrogen content was measured by the Kjeldahl method. The cation exchange capacity (CEC) was determined using 1 M ammonium acetate at pH 7. The ammonium adsorbed in the soil was released with NaOH and distilled. Distilled ammonium was scavenged using 0.1 N H_2SO_4. The excess of 0.1 N H_2SO_4 was titrated with 0.2 N NaOH and the CEC was calculated. Exchangeable cations were measured from the extracted 1 M ammonium acetate at pH 7. A flame photometer and AAS were used. Determination of phosphate retention was done by calculating the phosphate retained by the soil after reaching equilibrium between phosphate absorbed and phosphate in solution after adding 1,000 ppm phosphate solution.

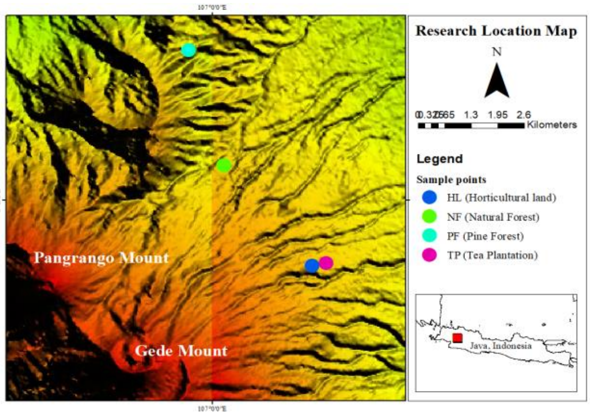


Figure 1. Map of sampled site locations

Determination of Al, Fe, and Si with oxalic acid solution extract (Al_o, Fe_o, Si_o) was based on dissolving the active elements in the form of amorphous compounds. 1.00 g of fine soil measuring <0.5 mm was added, then 50 ml of ammonium oxalic acid was added and shaken for four hours. The solution was then centrifuged to obtain the supernatant. The supernatant was then diluted 20 -fold with deionized water. The Fe, Si, and Al elements in the diluted solution were measured by AAS using a standard series of mixtures of Fe, Al, and Si for comparison. The sodium pyrophosphate solution can dissolve Al and Fe compounds (Al_p, Fe_p) that form complexes with organic compounds. However, the determination steps are almost the same as for the oxalate extract. 1.00 g of fine soil measuring <0.5 mm was added, then 100 ml of sodium pyrophosphate extract was added and shaken for 16 hours. The solution was then centrifuged to obtain the supernatant. The supernatant was then diluted fivefold with deionized water. The elements of Fe and Al in the solution were then measured by AAS using a standard series of mixtures of Fe and Al for comparison. In addition to Fe and Al, C analysis was also performed with pyrophosphate extracts (C_p) to provide an overview of the carbon associated with Al and Fe in forming complexes with soil organic matter (Burt, 2004; Eviati *et al.*, 2022; Neculman *et al.*, 2013). The data were analyzed descriptively by comparing the characteristics of natural forest soils with those of other land uses to determine the impact of land use change on soil chemical properties.

3. Results and Discussion

Based on the data presented in Table 1, the conversion of forest to agricultural land leads to changes in soil characteristics, including pH, organic carbon content, total nitrogen levels, cation exchange capacity (CEC), and base saturation (BS). These alterations were due to differences in land management of each land use. Specifically, horticultural land exhibited more intensive land management practices than tea plantations. Additionally, secondary pine forests experienced greater human interference than natural forests. Thus, land use ranking based on intensive land management is horticultural land > tea plantations > pine forest > natural forest.

3.1 Soil acidity and exchangeable cations

The pH (Table 1) represents the acidity of soil, and it varies by land use due to land management practices. Generally, soil pH-H_2O is classified as acidic when the pH is less than 6.5 for any land use. This condition is inextricably linked to climate conditions. High precipitation at a study site causes strong soil cation leaching. The study site experiences an annual rainfall of 3,185 mm, as reported in the Statistics of Cianjur Regency (2023). Cations, such as Ca and Mg, are dissolved by high-intensity rainfall, leading to their loss through surface and subsurface flow. Ma *et al.* (2018) found a direct relationship between rainfall intensity and the loss of Ca and Mg ions. The depletion of cations results in the soil sorption complex being primarily composed of H^+ ions, leading to soil acidity.

Horticultural land had a moderately acidic soil reaction with a pH from 5.87 to 6.03. In contrast, the natural forest, pine forest, and tea plantation areas displayed a strongly acidic soil reaction, with a pH below 5.5. The elevated pH level observed in the horticultural land was attributed to the land management techniques employed by the farmers, specifically the addition of lime into the soil. Conversely, other land uses did not receive this liming treatment. The lowest pH (4.52-4.59) was found in the topsoil of the tea plantation. This is further connected to the preference of tea plants for acidic conditions. Soils with a pH of 4.5 - 5.5 are most suitable for tea (Ritung, Nugroho, Mulyani, & Suryani, 2011). According to the findings, the pH-H_2O of the soil, particularly in the uppermost layer, exhibited a decline as the land transitioned from a natural forest (5.36) to a pine forest (4.65) and further to tea plantations (4.52 - 4.59). This indicates that the conversion of land from forest to agricultural use, without any additional inputs, can lead to a reduction in soil pH.

The exchangeable cations in all land uses are shown in Figure 2. According to the figure, Ca and Mg were highest in the natural forest land use (Figure 2a, 2b), especially in the top layer. This was followed by horticultural land, pine forest, and tea plantation. The high levels of Ca and Mg in the top layer of forest soil were related to the accumulation of organic matter in this layer, which released bases into the soil. High levels of Ca and Mg were found in horticultural soils (Figures 2a, 2b) because farmers routinely applied dolomite ($(CaMg)(CO_3)_2$) before planting.

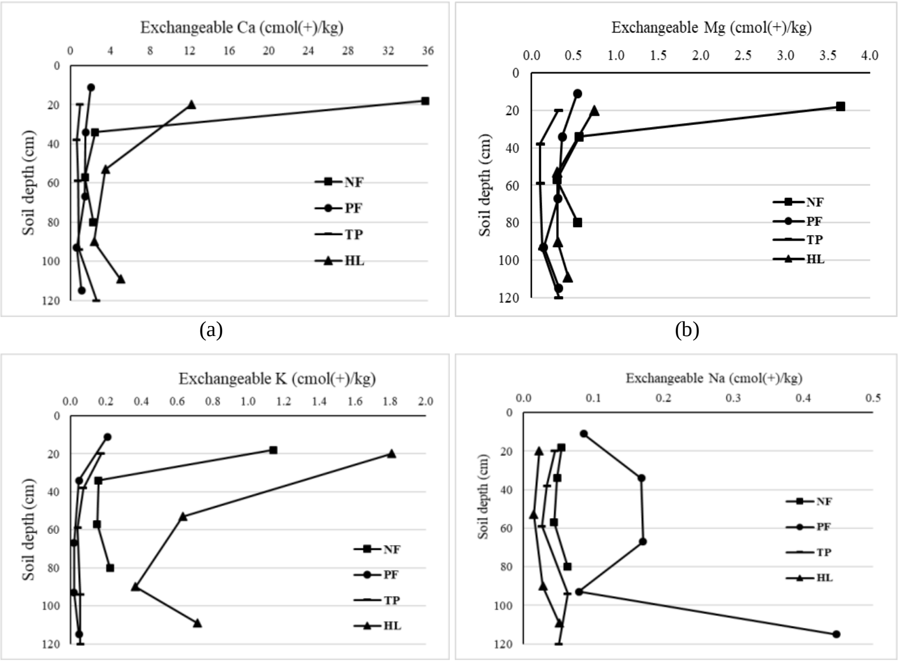
Furthermore, NPK fertilizer was utilized by farmers as an additional measure, leading to the attainment of the most elevated levels of K on horticultural land in comparison to other land uses. The application of NPK fertilizer also resulted in the potassium content of tea plantation surpassing that of pine forest (Figure 2c). The highest Na cation level (Figure 2d) was found in the pine forest. This may be due to weathering of soil minerals containing higher levels of Na.

Based on these data, land-use change from forest to agricultural land also increases soil macronutrients such as Ca, Mg, and K due to farmers' inputs into the soil. Several studies have shown similar results. Adugna & Abegaz's research (2016) found that exchangeable Ca and Mg were higher in cultivated land than in forest land. Similarly, Anindita *et al.* (2022) found that exchangeable bases were higher in arable soil than in forest soil. However, in this study, regardless of lime and fertilizer effects, natural forest had the highest bases (except Na). In contrast, croplands without additional Ca and Mg inputs, such as tea plantation, had the lowest Ca and Mg.

Table 1. Soil chemical properties of volcanic soil samples representing various land uses

Soil profile	Horizon	Soil depth (cm)	pH H_2O	Organic C (%)	N total (%)	CEC (cmol(+)/kg)	BS (%)	P retention (%)
Natural forest	A	0 - 18	5.36	11.98	1.08	42.43	95.62	58.1
	Bw1	18 - 34	5.31	4.05	0.32	12.08	26.90	71.6
	Bw2	34 - 57	5.03	0.86	0.08	5.76	33.28	54.7
	BC	57 - 80	5.23	0.66	0.08	7.50	41.50	59.9
Pine forest	A	0 - 11	4.65	9.26	0.57	22.06	12.99	74.4
	Bw1	11 - 34	5.26	2.74	0.19	7.69	26.86	82.8
	Bw2	34 - 67	5.35	1.21	0.12	7.23	26.65	76.7
	Bw3	67 - 93	5.18	1.40	0.08	8.23	10.41	97.7
	BC	93 - 115	5.06	0.56	0.04	7.24	26.71	96.0
Tea plantation	Ap1	0 - 20	4.52	8.38	0.80	20.17	7.36	75.1
	Ap2	20 - 38	4.59	6.40	0.58	15.39	5.31	83.7
	Bw1	38 - 59	4.54	3.74	0.31	10.48	8.72	97.7
	Bw2	59 - 94	4.80	2.58	0.26	7.84	14.00	83.0
	BC	94 - 120	5.54	1.66	0.19	8.85	34.16	77.7
Horticultural land	Ap1	0 - 20	5.87	4.40	0.33	19.76	74.45	78.5
	Bw1	20 - 53	5.69	1.50	0.16	12.59	35.20	92.8
	Bw2	53 - 90	6.07	1.57	0.21	10.88	28.25	97.0
	BC	90 - 109	6.03	1.61	0.25	13.44	46.45	85.2

Notes: CEC: cation exchange capacity, BS: base saturation



(a) (b)

(c) (d)

Figure 2. Exchangeable cations Ca (a), Mg (b), K (c), and (d) Na in samples representing different land uses
Notes. NF: Natural forest; PF: Pine forest; TP: Tea plantation; HL: Horticultural land

This implies that the transformation of forest land into cropland, without any soil replenishment, leads to a swift depletion of essential nutrients through crop absorption or heightened leaching. Markewitz, Davidson, Moutinho, & Nepstad (2004) discovered that over decades, soils are capable of losing essential elements like K, Ca, and Mg due to soil leaching and plant uptake.

3.2 Organic carbon, nitrogen total, and CEC

The organic carbon content of the topsoil is higher than the subsoil for all land uses due to the supply of organic matter from the overlying vegetation. The organic C content decreases with depth in the soil. The highest organic C in the top layer was found in natural forest soils (11.98%) followed in rank order by pine forest (9.26%), tea plantation (8.38%), and horticultural land (4.4%) (Table 1). This shows that land use change from forest to agricultural land decreases soil organic C due to heterogeneous vegetation change from forest to agricultural land with homogeneous vegetation. Changing the amount and type of vegetation affects soil organic C content in the soil. Research conducted by Wang *et al.* (2020) showed that soil organic carbon sequestration was influenced by the type of vegetation in each land use. The findings of Wan *et al.* (2019) also suggest that the presence of different vegetation types can affect soil organic C levels through their contribution to soil moisture. Forests are characterized by tall canopy plants that contribute to increased soil moisture and enhanced water-holding capacity. This environment promotes the proliferation of soil organisms involved in the decomposition of organic matter. In addition, the greater diversity and abundance of plant species in forests leads to greater accumulation of litter. As a result, forest soils have higher levels of soil organic carbon than agricultural lands or forests dominated by uniform plant species such as pine.

The vegetation of each land use also influences total nitrogen because most soil N (over 95% of total N) is in the form of organic N (Food and Agriculture Organization of the United Nations [FAO], 2021). Total N followed a similar pattern to organic C, with deeper soils having lower total N levels. Natural forest (1.08%) was the land use with the highest total N content in the top layer, followed by tea plantation (0.88%), pine forest (0.57%), and horticultural land (0.33%) (Table 1). Contrary to organic C, the total N content of the tea plantation soils was higher than that of the pine forest soils. This may be because N fertilization in tea plantations provides more nitrogen than pine litter. Tea plantation farmers apply N fertilizer at a rate of 161 kg/year, leading to tea leaf litter contributing more nitrogen to the soil compared to pine forests. Previous studies support this finding, indicating that while the topsoil in tea plantations and pine forests has similar total nitrogen levels, the deeper soil layers in tea plantations contain higher total nitrogen levels (Anda & Dahlgren 2020a).

Cation exchange capacity (CEC) is influenced by the organic C content of the soil. Organic matter has a negative charge that can increase soil CEC (Bi *et al.*, 2023). Table 1 shows that soil CEC is higher in the top layer than in the bottom layer for all land uses. This is due to the higher organic C content in the top layer, as discussed above. Natural forest soil had the highest CEC value (42.43 cmol(+)/kg) in the top layer compared to other land uses, followed by pine forest soil (22.06 cmol/(+)kg), tea plantation (20.17 cmol(+)/kg) and horticultural land (19.76 cmol/(+)kg). In contrast, the lower layers in all land uses have values that tend to be the same (7 - 8 cmol(+)/kg), except for horticultural land. The CEC values are almost the same in all land uses, presumably due to the same type of minerals, since they come from the same parent material. However, on horticultural land, deep tillage causes slightly higher CEC values (10.88 - 13.44 cmol(+)/kg). This finding is similar to that of a previous study conducted by Anda & Dahlgren (2020a), where the Cation Exchange Capacity (CEC) of agricultural soils in the lower layer was slightly higher than that of forest soils. This disparity could be attributed to the effect of organic matter leaching into the subsoil as a result of tillage practices, thereby increasing the CEC in this particular layer.

3.3 P retention

One of the characteristics of volcanic ash-originated soils is high P retention. In this study, the three profiles of tea plantation, horticultural land, and pine forest had a high range of P retention (74.4% - 97.7%) (Table 1). However, the natural forest had a lower range of P retention (54.7% - 59.9%) (Table 1). The low percentage of P retention in forest soils was related to allophane content. Forest had the lowest allophane content compared to other land uses (Table 2). Volcanic soils often have limited phosphorus (P) availability due to the fixation of P by active aluminum (Al) and iron (Fe) components such as allophane, imogolite, and Al-humus complexes. Conversely, P retention can be low when the concentration of active Al and Fe is also low (Dahlgren *et al.*, 2004).

3.4 Al, Fe, and Si abundances

The amounts of Al, Fe, and Si extracted with ammonium oxalate (Al_o, Fe_o, Si_o) represent the amounts of these elements derived from short-range order (SRO) minerals (incompletely crystallized Al and Fe oxides and aluminosilicates) and forming complexes with organic matter. Meanwhile, pyrophosphate-extracted Al and Fe (Al_p, Fe_p) are the levels of these elements bound to or complexed with organic matter (Ashida *et al.*, 2021). Both formations play an important role in chemical processes in volcanic soils. Based on Table 2, Fe_o levels were the highest in pine forest soils (1.17 – 3.18%) and the lowest in horticultural land (0.75 – 1.07%). In contrast, the highest levels of Al_o and Si_o were found in horticultural land, followed by tea plantation, pine forest, and natural forest, in decreasing order. These results were similar to the research of Anindita *et al.* (2022) in the Tangkuban Perahu mountain area, West Java, where the Al_o and Si_o levels of natural forest soils were lower than those of agricultural land. Cultivated soils are believed to undergo more extensive weathering of primary minerals due to intensive tillage practices, resulting in elevated levels of Fe, Al, and Si.

Contrary to Al_o and Fe_o, Al_p and Fe_p levels were the highest in forests (pine forests and natural forests) superior to agricultural land (tea plantation and horticultural land) (Table 2). The absence of tillage in forest soils ensures that the formation of metal-humus complexes remains undisturbed, thereby explaining this phenomenon. High levels of organic matter also promote the association of Al and Fe with organic matter. The evidence indicates that organic matter serves as the primary binding agent for Al and Fe elements in forest soils, rather than their precipitation as allophane and ferric hydrate minerals. According to Tan (2009), the presence of humic acids in organic-rich soils poses a challenge for the formation of allophane due to their ability to chelate free Al.

The percentages of ferrihydrite and allophane are shown in Table 2. The highest levels of allophane were found in horticultural land (26.93 – 30.90%), while the lowest levels were found in natural forests (3.11 – 6.09%). Meanwhile, ferrihydrite was highest in pine forests (1.99 – 5.41%) and lowest in horticultural land (1.28 – 1.82%). In non-acidic soils, Al precipitates with Si to form allophane, while Fe precipitates as ferrihydrite (Mizota & Van Reeuwijk, 1989). Allophane is a mineral commonly found in soil derived from

Table 2. Selected soil chemical properties of volcanic soil representing various land uses

Soil profile	Layer	Soil depth (cm)	Oxalic acid (%)			Pyrophosphate (%)		Ferrihydrite (%)	Allophane (%)
			Fe_o	Al_o	Si_o	Fe_p	Al_p		
Natural forest	A	0 - 18	0.93	1.19	0.13	0.46	0.70	1.58	3.11
	Bw1	18 - 34	1.07	2.33	0.45	0.43	1.01	1.82	5.33
	Bw2	34 - 57	0.94	1.62	0.29	0.17	0.56	1.60	6.09
	BC	57 - 80	1.21	1.32	0.25	0.09	0.40	2.06	5.40
Pine forest	A	0 - 11	1.17	3.70	0.79	0.20	0.84	1.99	16.00
	Bw1	11 - 34	3.18	3.63	0.97	0.46	1.35	5.41	8.50
	Bw2	34 - 67	2.55	3.93	1.06	0.29	0.95	4.34	11.70
	Bw3	67 - 93	1.63	7.20	2.70	0.06	0.54	2.77	24.95
	BC	93 - 115	1.27	4.29	1.81	0.12	0.57	2.16	14.01
Tea plantation	Ap1	0 - 20	1.56	4.54	1.10	0.11	0.77	2.65	18.58
	Ap2	20 - 38	1.48	5.05	1.34	0.08	0.66	2.52	20.02
	Bw1	38 - 59	1.32	5.96	2.06	0.04	0.55	2.24	20.59
	Bw2	59 - 94	1.00	6.90	2.02	0.01	0.36	1.70	29.33
	BC	94 - 120	1.38	7.58	2.36	0.02	0.32	2.35	30.61
Horticultural land	Ap1	0 - 20	1.07	7.00	2.26	0.03	0.35	1.82	26.93
	Bw1	20 - 53	0.75	8.14	2.80	0.02	0.47	1.28	29.69
	Bw2	53 - 90	0.85	8.09	2.89	0.02	0.41	1.45	29.35
	BC	90 - 109	0.99	8.34	2.88	0.02	0.39	1.68	30.90

Notes: Ferrihydrite % = 1.7*Fe_o% (Parfitt & Childs, 1988). Allophane = Si_o (100/y), y = 23.4 – 5.1x, where x = (Al_o-Al_p)/Si_o (Parfitt & Wilson, 1985) modified by Mizota & van Reeuwijk (1989).

loose volcanic material or tephra, either as ash, pumice, or otherwise. It is formed by the dissolution of Al from volcanic glass (Churchman & Lowe, 2012). The presence of even small amounts of allophane can significantly affect soil chemical processes due to its large specific surface area (Harsh, Chorover, & Nizeyimana, 2002).

Figure 3 shows the sum of (Al_p+Fe_p) divided by (Al_o+Fe_o), which represents the amount of Al and Fe bound to organic matter compared to the total free Al and Fe in the soil. According to Ashida *et al.* (2021), the value of (Al_p+Fe_p)/(Al_o+Fe_o) describes the tendency of Al and Fe in the soil to form complex compounds with organic matter. The stability of the organic matter increases with the (Al_p+Fe_p)/(Al_o+Fe_o) ratio. Binding Al and Fe in metal-humus complexes keeps organic matter relatively stable and protected from microbial decomposition (Aran, Gury, & Jeanroy, 2000; Dahlgren *et al.*, 2004; Mizota & Van Reeuwijk, 1989). Metal-humus complex formation is primarily driven by the interaction of metals with carbonaceous functional groups (Takahashi & Dahlgren, 2015). As a result, volcanic soils are black and have high levels of organic matter. This supports the function of volcanic soil as a carbon sink in terrestrial ecosystems.

The C_p values in Figure 4 represent organic matter chemically associated with metals as it dissolves organic molecules and removes associated Al and Fe. However, it should be noted that C_p may include C not associated with Al and Fe but soluble in weak bases (Ashida *et al.*, 2021). The C_p content follows the same pattern as the (Al_p+Fe_p)/(Al_o+Fe_o) ratio. The percentage of C_p is highest in the topsoil of natural forest, followed by pine forest, tea plantation and horticultural land (Figure 4). The percentage of C_p decreased as the opportunity for metal-humus complex formation was reduced with lower organic matter in the deep soil layers.

4. Conclusions

Studies have shown that land use conversion from forest to other types of land use, especially agricultural land affects soil chemistry by altering soil pH, decreasing soil organic carbon and total nitrogen, and influencing cation exchange capacity, base saturation, P retention, and abundances of Al, Fe, and Si. However, changes in chemical properties indicate that volcanic soils remain well preserved despite conversion to other uses. Thus, volcanic soil with its unique characteristics has high resilience in supporting agricultural activities and can store carbon in terrestrial ecosystems.

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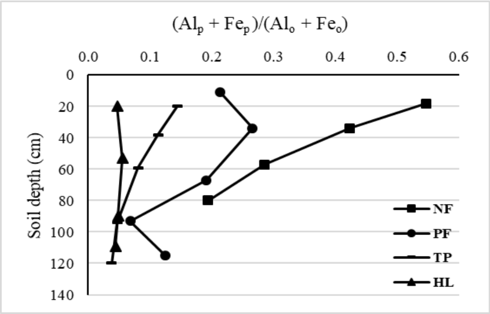

Figure 3. Al and Fe of pyrophosphate extraction (Al_p, Fe_p) divided by Al and Fe of oxalate extraction (Al_o, Fe_o) in samples representing different land uses.
Notes. NF: Natural forest; PF: Pine forest; TP: Tea plantation; HL: Horticultural land

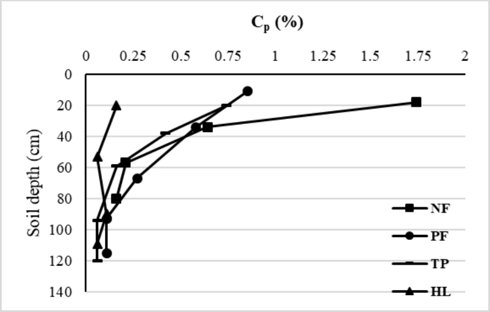

Figure 4. C_p level by land use. Notes. NF: Natural forest; PF: Pine forest; TP: Tea plantation; HL: Horticultural land

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