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RESEARCH ARTICLE

Soil fertility response to land-use changes in agroforestry and silvopastoral systems of the Ecuadorian Amazon: A multivariate and stratification ratio approach

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Abstract

Conversion of Amazonian forests to pastures and crops threatens soil fertility, but whether tree-based land uses conserve it remains poorly quantified in the Ecuadorian Amazon. We compared a secondary forest (SF, reference) with a cacao agroforestry system (AFC), two silvopastoral systems (*Axonopus scoparius* and *Paspalum dilatatum* pastures with trees; GGWT, DGWT) and the same pastures without trees (GGWIT, DGWIT) in Napo and Pastaza provinces. Each land use comprised three plots (5 – 7 sampling points each) sampled at 0 – 10 and 10 – 30 cm (184 samples). Land-use effects were tested with linear mixed models with plot as a random effect. In the topsoil, land use affected aeration porosity (AP; 11.4% in AFC to 19.2% in SF), soil organic matter (SOM; 8.5% in GGWIT to 17.9% in GGWT) and exchangeable K^+ (0.09 $cmol_c$/kg in AFC vs. 0.22 – 0.28 $cmol_c$/kg in GGWT, DGWT and DGWIT), whereas bulk density, pH, total N, available P, Ca^{2+} and Mg^{2+} did not differ significantly. Relative to SF, AP decreased by 15% – 41% in all land uses, SOM by 47% in GGWIT and K^+ by 43% in AFC. Most nutrients were concentrated in the topsoil. Stocks in the 0 – 30 cm layer of exchangeable K^+ (53 – 102 kg/ha) and, except in DGWT, of available P (6.5 – 22.2 kg/ha) were below forest-maintenance thresholds, whereas NH_4^+ stocks were highest in treeless pastures and lowest in AFC. Multivariate analyses isolated AFC and grouped the silvopastoral systems with SF. Retaining trees in pastures and replenishing K and P in cacao agroforestry systems are recommended.

Keywords: Soil fertility; land-use change; silvopastoral systems; stratification ratio; multivariate analysis; Ecuadorian Amazon.

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1. Introduction

Land-use change is one of the main drivers of soil degradation in the humid tropics. The conversion of forests to pastures and cropland interrupts litter inputs, accelerates organic matter mineralisation and exposes soils to compaction and erosion, reducing soil organic carbon (SOC) stocks and the capacity of soils to supply nutrients (Lal et al., 2015; Guillaume et al., 2016). Because soil fertility cannot be measured directly, its response to land-use change is assessed with sets of physical and chemical indicators compared against an undisturbed reference, usually the native or secondary forest (Guillaume et al., 2016; Bravo-Medina et al., 2021). In highly weathered and leached Amazonian soils, where a large share of the nutrient capital is held in biomass and organic matter, these changes directly affect productivity and ecosystem services such as nutrient cycling and carbon sequestration (Quesada et al., 2011; Lal et al., 2015).

In the Ecuadorian Amazon, forest loss is driven mainly by the expansion of extensive cattle ranching and of cacao and other crops on smallholder farms (Torres et al., 2023). The soils of the region are predominantly acidic Inceptisols with high organic matter contents but low exchangeable bases, as a result of intense leaching under very high rainfall and the dominance of kaolinite and Fe and Al oxides (Custode & Sourdat, 1986; Espinosa et al., 2018). Forest clearing in the Napo River valley reduced surface C and N by 15% – 70% and exchangeable cations by 25% – 60% (Mainville et al., 2006), and

slash-and-burn conversion in southern Ecuador reduced SOC stocks by 14% – 19% and produced negative N, P and K balances (Bahr et al., 2014). Tree-based systems such as the Kichwa chakra, cacao agroforestry and silvopastoral systems have been proposed as land uses compatible with these conditions because they maintain litter inputs and nutrient recycling (Nieto & Caicedo, 2012; Coq-Huelva et al., 2017; Torres et al., 2024), and regional studies have shown that they store carbon and keep soil quality closer to that of the forest (Bravo-Medina et al., 2021, 2024; Torres et al., 2023; Huera-Lucero et al., 2024, 2025).

Recent evidence from the western Amazon indicates that the effect of trees on soil fertility is nutrient-specific. In the Colombian Amazon, silvopastoral adoption increased SOC stocks and improved soil chemical attributes relative to degraded pastures (Olaya-Montes et al., 2021), and scattered trees increased exchangeable K beneath their crowns (Álvarez et al., 2021). On farms of the southern Ecuadorian Amazon, silvopastoral systems stored more topsoil carbon than treeless pastures, cacao agroforestry systems stood out for exchangeable Ca and Mg, and pastures showed signs of acidification and base depletion (Jiménez et al., 2026). In grazing systems of the Colombian piedmont, silvopastures had higher available P and exchangeable bases than degraded pastures, although K was scarce in all systems (Trujillo-González et al., 2026). However, most studies have focused on carbon or on aggregated soil quality indices, and few have jointly assessed physical and chemical fertility indicators, the vertical stratification of nutrients and nutrient stocks in tree-based and treeless land uses under the same edaphoclimatic conditions of the central Ecuadorian Amazon. In particular, it is unknown whether the presence of trees in pastures and the management of cacao agroforestry systems differentially affect the nutrients that most limit production in these soils, namely P and K.

We hypothesised that land-use change from forest reduces soil fertility indicators, but that land uses that retain tree cover conserve physical and chemical fertility closer to the secondary forest than treeless pastures. The objectives were to (1) evaluate the effect of land-use change from secondary forest to cacao agroforestry, silvopastoral and pasture systems on soil physical and chemical fertility indicators and nutrient stocks in the Ecuadorian Amazon, and (2) group the land uses according to these indicators.

2. Methodology

2.1. Study area

The research was conducted in 2016 at agricultural production units located in the Ecuadorian Amazon provinces of Napo and Pastaza. The eighteen sampling sites are located between 1°04′ and 1°25′ S and between 77°36′ and 77°59′ W (Figure 1; Table 1).

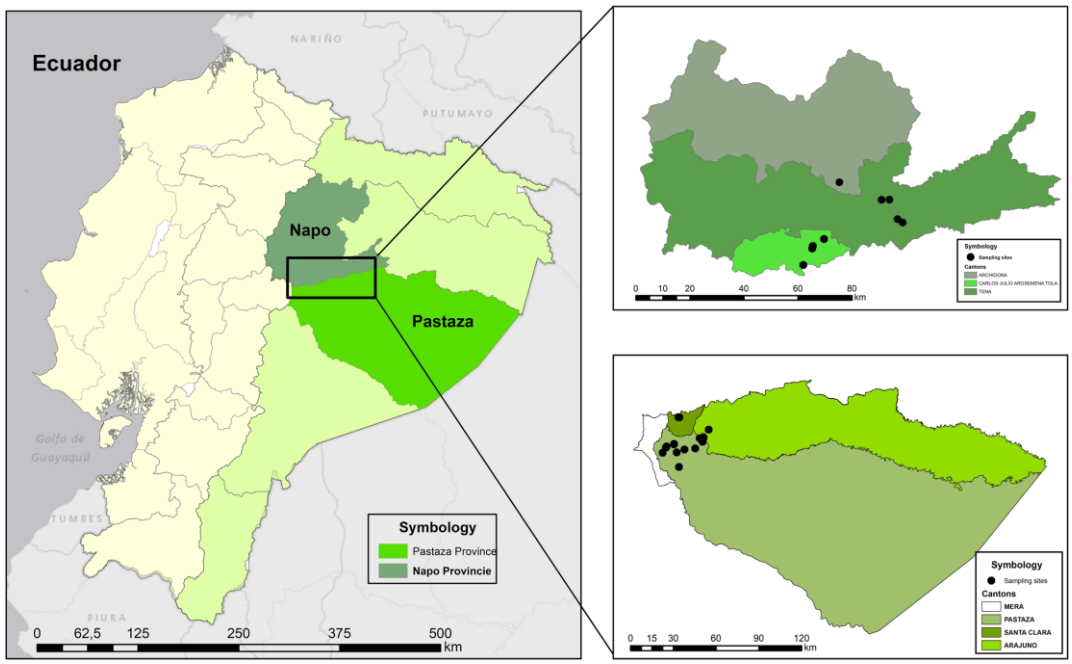


Figure 1. Location of the study area: (a) Ecuador in South America; (b) Napo and Pastaza provinces in the Ecuadorian Amazon region; (c) sampling sites of the six land uses with their geographic coordinates (WGS 84). AFC: cacao agroforestry system; GGWT and DGWT: Gramalote and Dallis grass with trees (silvopastoral systems); GGWIT and DGWIT: Gramalote and Dallis grass without trees; SF: secondary forest.

Table 1
Selected land uses in the study area (Napo and Pastaza provinces, Ecuadorian Amazon).

Land-Use Type	Description	Coordinates WGS 84/UTM, Zona 18 S	
		Coordenate X	Coordenate Y
1. Agroforestry cocoa system (AFC)	The production system of diversified cocoa is associated with tree species and crops such as cassava, plantain, bananas, and other crop species with short and perennial cycles, and animal components	210563	9881945
2. Gramalote Grass with tree (GGWT)	Gramalote grass (*Axonopus scoparius*) and trees	168378	9854606
3. Gramalote grass without trees (GGWIT)	Gramalote grass (*Axonopus scoparius*) without trees.	168488	9854268
4. Dallis grass with trees (DGWT)	Dallis grass *(Paspalum dilatatum*) with trees	177465	9862647
5. Dallis grass without trees (DGWIT	Dallis grass *(Paspalum dilatatum*) without trees	174448	9843560
6. Secondary forest (SF)	High biodiversity and predominance mainly of species of the families of the Fabaceae (*Inga vismifolia*), Sapotaceae (*Pouteria pastel*), and Arecaceae (*Iriartea deltoidea*)	168431	9855456

The climate is characteristic of a humid tropical forest, with an altitude of between 500 and 600 masl. The average annual rainfall is 4400 mm, evapotranspiration is 150 mm, temperatures range from 23.4 to 25 °C, and relative humidity is 87% (Uvidia et al., 2015). The soils belong to the Inceptisol order and are recent, shallow, and generally acidic soils without well-defined horizons but with high organic matter content, low natural fertility (low potassium, calcium, and phosphorus content), and high iron contents (Nieto & Caicedo, 2012).

2.2. Soil sampling

Six land uses representative of the Ecuadorian Amazon were evaluated (Table 1): one cacao agroforestry system (AFC), two silvopastoral systems (Gramalote grass, *Axonopus scoparius*, with trees, GGWT; and Dallis grass, *Paspalum dilatatum*, with trees, DGWT), the same two grasses without trees (GGWIT and DGWIT), and a secondary forest (SF) used as the reference. Each land use was represented by three plots, and the study followed a comparative (mensurative) design without blocks. In each plot, a transect covering the whole area was established and five equidistant sampling points were located along it. At each point, a 10 × 10 m subplot was delimited, and five soil subsamples were collected at each of two depths (0 – 10 and 10 – 30 cm) and homogenised into one composite sample per point and depth. The sampling point was therefore the observational unit and the plot the experimental unit (three plots per land use; 14 – 17 sampling points per land use and depth; 184 samples in total). In the centre of each subplot, undisturbed samples were collected with an Uhland-type sampler for the physical analyses. Because the sampling points of each plot are spatial subsamples rather than independent replicates, plot was included as a random effect in the statistical models (Section 2.6).

2.3 Soil physical analysis

To determine the physical attributes of the soil, undisturbed samples were taken with cylinders that were 5cm tall and 5cm in diameter. Then, the following variables were measured: a) bulk density (BD) using the cylinder method (Blake & Hartge, 1986); b) saturated hydraulic conductivity (K_{sat}) using the variable load method, following the pore size distribution method (Reynolds et al., 2009) (c) total porosity (TP); (d) aeration porosity (AP: pores of >15 µm radius); and (e) retention porosity (RP), using the saturation tension table method with -10 kPa a matric potential (Blake & Hartge, 1986).

2.4. Soil chemistry analysis

Determination of chemical soil properties was performed for mineral and organic samples after sieving through a 2 mm mesh size, as described in the following section. The soil pH in deionized water was measured by potentiometry (soil-water ratio 1:2.5), exchangeable acidity (Al^{3+} + H^{+}), and exchangeable aluminium (Al^{3+}) extracted with KCl 1N and titrated with NaCl and HCl, respectively (McLean, 1965). Soil organic carbon (SOC) was measured using the Walkley and Black wet digestion method (Nelson & Sommers, 1982). Soil organic matter (SOM) was calculated as SOC × 1.724. Total nitrogen (total N) was determined by the Kjeldahl method. Available P and extractable cations (K^{+}, $Ca^{2+,}$ and Mg^{2+}) micronutrients (Cu, Fe, Zn, Mn, and B) were removed using the Olsen extraction solution. P was measured colorimetrically

using the molybdenum blue method, while K^+, Ca^{2+}, and Mg^{2+}, and micronutrients (Cu, Fe, Zn, Mn, and B) were determined using an atomic absorption spectrophotometer (Okalebo et al., 2002).

2.5. Response of soil fertility indicators to land-use changes

A range of physical and chemical indicators related to soil fertility were used to assess the response to changes in land use. Because indices under land use may be either higher or lower compared to the forest, the response to land-use change was calculated with the following equation (Guillaume et al., 2016):

$$Ri = \frac{ILU - IF}{IF} x\ 100 \quad (1)$$

where Ri is the index response, ILU is the indicator value in the land use site, and IF is the mean index value under forest. Thus, the forest average is 0, and positive values indicate an increase in the index under land use, and vice versa.

The stratification ratio (SR) is another key metric used to evaluate the impact of Land use systems on soil fertility indicators. The stratification ratio is the ratio between soil fertility indicator fractions from two soil layers, usually the surface layer, with a strong influence of soil and management practices, and the adjacent subsurface soil layer, which is less affected by these practices (Melkani et al., 2024). The ratio was calculated using the following equation:

$$SR = \frac{\text{NF } 0-10 \text{ cm}}{\text{NF } 10-30 \text{ cm}} \quad (2)$$

where SR is the Stratification ratio, NF is the nutrient fraction in the land use.

The nutrient stock in the soil (NS) was calculated at the depth of 0 – 30 cm and derived mathematically from the bulk density (BD), nutrient, and depth using the following equation (Bond, 2010), computed separately for the 0 – 10 and 10 – 30 cm layers with their respective BD and then summed; exchangeable K^+, Ca^{2+} and Mg^{2+} (cmolc kg^{-1}) were converted to mg kg^{-1} by multiplying by 391, 200.4 and 121.5, respectively, and TN stocks (Mg ha^{-1}) were calculated as BD × TN (%) × layer thickness (cm):

$$\text{NS (kg ha}^{-1}\text{)} = \text{BD (kg m}^{-3}\text{) x nutrient [mg kg}^{-1}\text{] x layer thickness (m) x 0.01} \quad (3)$$

2.6. Statistical analysis

Statistical analyses were performed in R version 4.3.3 (R Core Team, 2024) with the lme4, lmerTest and emmeans packages (Bates et al., 2015; Kuznetsova et al., 2017; Lenth, 2024). Because the sampling points were nested within plots, the plot (three per land use) was treated as the experimental unit. For each depth, land-use effects were tested with linear mixed models with land use as a fixed effect and plot as a random effect; denominator degrees of freedom were estimated with the Satterthwaite method, and means were compared with Tukey's test ($p < 0.05$). A second model including land use, depth and their interaction, with plot and sampling point as random effects, was used to test depth effects. Right-skewed variables (K_{sat}, C:N, NH_4^+, P, K^+, Ca^{2+}, Mg^{2+}, SB, S, Zn, Fe, Mn and B) were log_{10}-transformed, and the normality and homogeneity of the residuals were checked with the Shapiro–Wilk and Levene tests. The same models were applied to the response to land-use change (Eq. 1; 0 – 10 cm), the stratification ratios (Eq. 2; log-transformed) and the nutrient stocks (Eq. 3; 0 – 30 cm), and each land use was compared with SF by Dunnett's test. Principal component analysis (PCA) was performed on the correlation matrix of 19 variables, using the depth-weighted 0 – 30 cm values of each sampling point (TP and SB were excluded because they are linear combinations of other variables); components with eigenvalues > 1 were retained, and loadings > |0.70| were considered relevant (Torres et al., 2008). Hierarchical cluster analysis was applied to the standardised land-use means using Euclidean distance and Ward's method, and the cophenetic correlation coefficient was used to assess the fit of the dendrogram.

3. Results and discussion

3.1. Soil properties associated with physical and chemical fertility as a function of land use.

Among the physical indicators, land use significantly affected only aeration porosity (AP) at both depths when plot-to-plot variability was considered (Table 2). In the 0 – 10 cm layer, AP ranged from 11.4% in AFC to 19.2% in SF, and AFC differed from SF, the two silvopastoral systems and DGWIT, whereas bulk density (BD; 0.41 – 0.79 Mg m^{-3}), saturated hydraulic conductivity (K_{sat}; 11.6 – 49.4 cm h^{-1}), total porosity (TP) and retention porosity (RP) did not differ significantly among land uses at either depth.At 10 – 30 cm, AFC had the lowest K_{sat} (0.44 cm h^{-1}) and AP (7.9%); its AP was below the 10% critical threshold for aeration (Pla, 2010a) and significantly lower than that of DGWIT (Table 2). Depth affected all physical indicators except RP: BD increased and K_{sat} and AP decreased from the 0 – 10 to the 10 – 30 cm layer, and the land use × depth interaction was significant for AP and K_{sat} ($p < 0.05$), indicating that land use modified mainly the macroporosity of the topsoil.

Table 2
Effect of land use on soil properties associated with physical fertility at two depths

Land use	BD (Mg m^{-3})	K_{sat} (cm h^{-1})	TP (%)	AP (%)	RP (%)
0–10 cm					
AFC	0.79 ± 0.07 a	11.55 ± 1.80 a	69.7 ± 3.4 a	11.4 ± 0.9 c	58.3 ± 2.8 a
GGWT	0.41 ± 0.03 a	21.56 ± 3.37 a	81.6 ± 2.6 a	15.5 ± 0.9 ab	66.1 ± 2.6 a
GGWIT	0.63 ± 0.04 a	30.14 ± 7.85 a	78.8 ± 1.5 a	13.9 ± 0.8 bc	64.9 ± 1.4 a
DGWT	0.53 ± 0.05 a	31.26 ± 5.39 a	77.2 ± 4.0 a	16.4 ± 0.9 ab	60.8 ± 4.1 a
DGWIT	0.57 ± 0.03 a	31.75 ± 7.47 a	79.8 ± 1.5 a	15.7 ± 0.8 ab	64.1 ± 1.3 a
SF	0.52 ± 0.05 a	49.42 ± 6.83 a	79.6 ± 2.0 a	19.2 ± 1.3 a	60.4 ± 2.1 a
p (land use)	0.214	0.180	0.652	< 0.001	0.815
10–30 cm					
AFC	0.98 ± 0.09 a	0.44 ± 0.09 a	65.8 ± 3.1 a	7.9 ± 0.5 b	57.8 ± 3.1 a
GGWT	0.61 ± 0.06 a	9.56 ± 3.38 a	84.4 ± 1.5 a	11.4 ± 0.6 ab	73.1 ± 1.7 a
GGWIT	0.70 ± 0.05 a	28.52 ± 5.93 a	74.0 ± 2.0 a	12.0 ± 0.6 ab	61.9 ± 1.8 a
DGWT	0.64 ± 0.07 a	29.68 ± 7.83 a	79.0 ± 2.0 a	12.6 ± 1.2 ab	66.3 ± 2.1 a
DGWIT	0.68 ± 0.04 a	35.16 ± 7.81 a	75.0 ± 1.7 a	13.4 ± 0.8 a	61.6 ± 1.7 a
SF	0.68 ± 0.09 a	23.03 ± 7.83 a	74.9 ± 2.7 a	12.2 ± 0.9 ab	62.7 ± 2.2 a
p (land use)	0.547	0.096	0.149	0.048	0.187

Values are means ± standard error (n = 14–17 sampling points from three plots per land use and depth). Different letters within a column and depth indicate significant differences among land uses (linear mixed model with plot as a random effect, Tukey test, $p < 0.05$). BD: bulk density; K_{sat}: saturated hydraulic conductivity; **TP**: total porosity; **AP**: aeration porosity; **RP**: retention porosity. AFC: cacao agroforestry system; **GGWT:** Gramalote grass with trees**; GGWIT:** Gramalote grass without trees; DGWT: Dallis grass with trees; DGWIT: Dallis grass without trees; SF: secondary forest.

BD ranged from 0.41 to 0.98 Mg m^{-3} across land uses and depths, well below the values considered limiting for root growth in clayey (> 1.40 Mg m^{-3}), medium-textured (> 1.60 Mg m^{-3}) and coarse-textured soils (> 1.80 Mg m^{-3}) (Blanco-Canqui & Ruis, 2018; Pla, 2010b). Total porosity was 75–80% on average, and retention pores accounted for 82% of it, suggesting an adequate air–water balance (Blanco-Canqui & Ruis, 2018; Rabot et al., 2018). BD was negatively correlated with TP ($r = -0.79$), AP ($r = -0.52$) and SOM ($r = -0.48$), which confirms that the low BD and high porosity of these soils are associated with their high organic matter contents (Reynolds et al., 2009; Bravo-Medina et al., 2021, 2023). Similar physical conditions have been reported for other land uses in the Ecuadorian Amazon (Espinosa et al., 2018; Huera-Lucero et al., 2025). The lower AP in AFC is consistent with its numerically higher topsoil BD (Section 3.2), whereas the continuous litter inputs and root activity of the silvopastoral systems and the forest favour aggregation and the stability of macropores (Murgueitio et al., 2011; Ewunetu et al., 2025). Overall, forest conversion did not reduce soil physical fertility to limiting levels in the topsoil, but it reduced aeration in all land uses, most strongly under cacao.

Among the chemical indicators, land use significantly affected SOM and exchangeable K^+ in the 0–10 cm layer, and NH_4^+, K^+ and Mg^{2+} in the 10–30 cm layer, although for Mg^{2+} the Tukey test did not separate the land-use means (Figure 2). pH, TN, the C:N ratio, available P, Ca^{2+} and the sum of bases (SB) did not differ among land uses at either depth; for most of these variables the land use × depth interaction was significant, because the decrease from the topsoil to the subsoil differed among land uses. All soils were strongly acidic (mean, pH 5.3) and had SOM contents above 5% in the topsoil (Figure 2A, B).

The strong acidic reaction of all soils is consistent with the leached, kaolinitic and oxidic nature of Amazonian soils, in which acidity is associated with low P, Ca, Mg and K availability and with Al, Fe and Mn toxicity (Espinosa et al., 2018; Bravo-Medina et al., 2023). Topsoil SOM was highest in GGWT (17.9%) and SF (16.0%) and lowest in the treeless pastures (GGWIT, 8.5%; DGWIT, 9.2%), which differed from GGWT (Figure 2B); the high SOM under trees is attributable to continuous litter and root inputs (Bravo-Medina et al., 2021, 2024; Ewunetu et al., 2025). TN was above the 0.2% critical level in all land uses (0.38 – 0.86% at 0 – 10 cm), and the higher C:N ratios in GGWT and SF (22–24; Figure 2D) indicate organic inputs of lower quality, slower mineralisation and transient N immobilisation (Unger et al., 2010; McGrath et al., 2014). Topsoil NH_4^+ tended to be higher in the grazed systems (56 – 85 mg kg^{-1}) than in SF (49 mg kg^{-1}) and AFC (26 mg kg^{-1}), and at 10 – 30 cm it was significantly lower in AFC (17 mg kg^{-1}) than in DGWIT (46 mg kg^{-1}) (Figure 2E).

Available P was below the sufficiency threshold of 10 mg kg^{-1} in SF, GGWT and GGWIT in the topsoil and in all land uses at 10–30 cm, confirming that P is a limiting nutrient in these soils (Espinosa et al., 2018). Because no fertilisers are applied to these pastures, the tendency towards higher NH_4^+ and P in grazed systems is best explained by nutrient recycling through cattle, which ingest organic N and P in forage and return them in labile forms in dung and urine patches (Garcia et al., 2021; Nascimento et al., 2024). In contrast, SF and AFC depend on

litter decomposition, in which the higher C:N ratio of the litter slows the release of mineral N, and the strong P fixation of these acidic, Fe- and Al-rich soils further limits the accumulation of available P (Espinosa et al., 2018). Exchangeable K^+ was the macronutrient that best separated AFC from the other land uses: AFC had the lowest K^+ at both depths (0.09 and 0.03 $cmol_c\ kg^{-1}$), below the 0.2 $cmol_c\ kg^{-1}$ critical level, and differed from GGWT, DGWT and DGWIT in the topsoil and from GGWIT, DGWT and DGWIT in the subsoil (Figure 2G). Conversely, exchangeable Ca^{2+} in AFC (7.3 $cmol_c\ kg^{-1}$) was similar to that in SF (10.2 $cmol_c\ kg^{-1}$) and DGWT (9.0 $cmol_c\ kg^{-1}$).

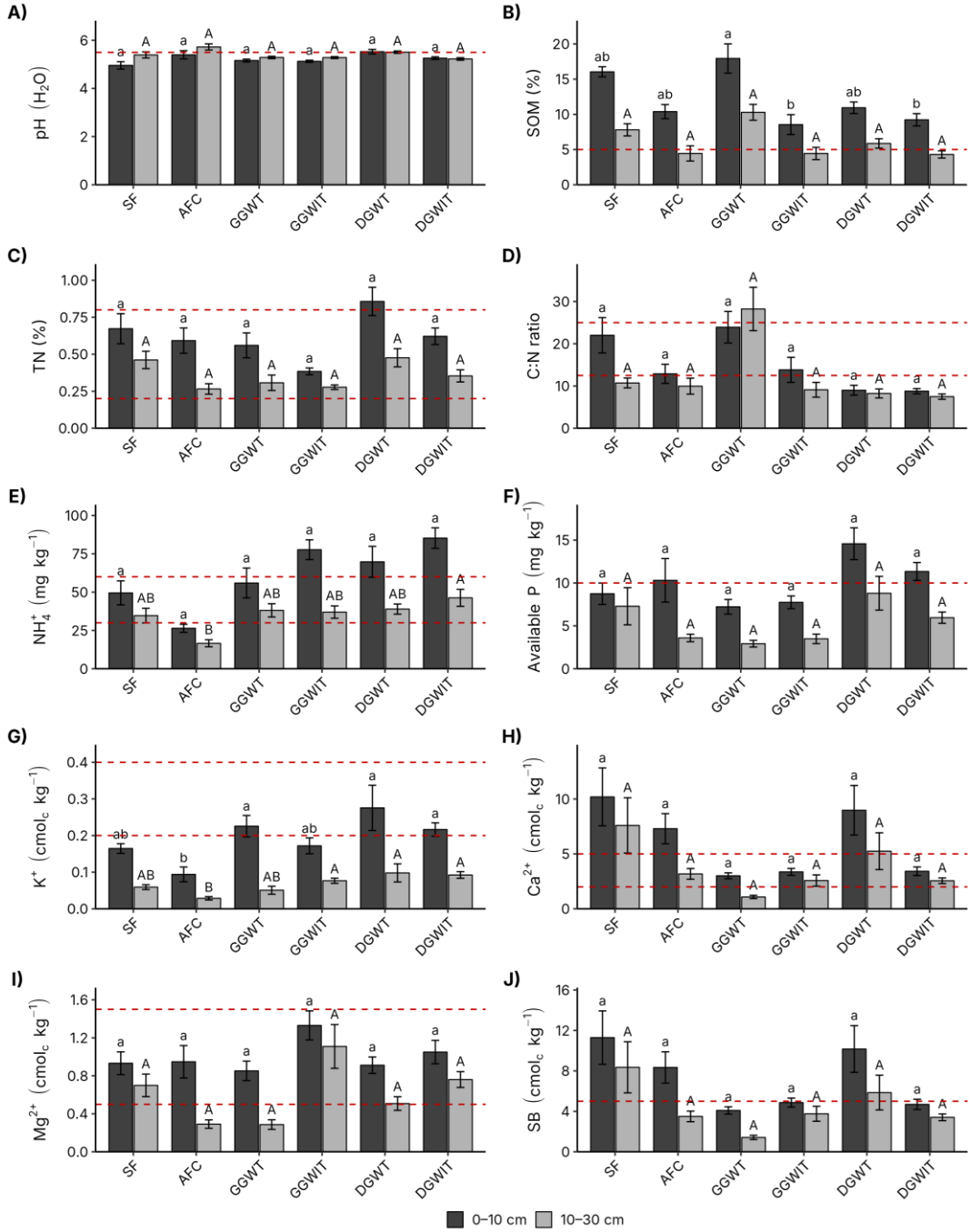


Figure 2. Effect of land use on soil properties associated with chemical fertility at 0 – 10 and 10 – 30 cm. Bars are means ± standard error (n = 14 – 17 sampling points from three plots per land use and depth). Different lowercase (0 – 10 cm) or uppercase (10 – 30 cm) letters indicate significant differences among land uses within each depth (linear mixed model with plot as a random effect, Tukey test, $p < 0.05$). Red dashed lines indicate critical thresholds (Okalebo et al., 2002). A) pH; B) SOM: soil organic matter; C) TN: total nitrogen; D) C:N ratio; E) NH_4^+; F) available P; G) exchangeable K^+; H) exchangeable Ca^{2+}; I) exchangeable Mg^{2+}; J) SB: sum of bases. Abbreviations of land uses as in Table 2.

Several management-related processes can explain this contrasting pattern. First, K is the nutrient most exported from cacao systems: pods are removed at harvest, husks are often heaped or discarded outside the plot, and partial nutrient balances of cacao systems without mineral fertilisation are consistently negative, especially for K (Hartemink, 2005). In the diversified AFC studied, plantain, banana and cassava, which are also highly K-demanding crops, are harvested and export additional K (Table 1). Second, unlike grazed systems, AFC receives no K return through cattle urine, which is the main K-recycling pathway in pastures (Garcia et al., 2021; Nascimento et al., 2024). Third, the monovalent K^+ is weakly retained by the kaolinitic exchange complex of these soils and is easily leached under high rainfall (Viana et al., 2014), whereas the divalent Ca^{2+} is retained more strongly. The relatively high Ca^{2+} in AFC is consistent with Ca inputs from cacao and shade-tree litter and, possibly, from liming or residue burning during the establishment and maintenance of the plantation. Similar patterns were recently reported in the southern Ecuadorian Amazon, where cacao agroforestry systems stood out for exchangeable Ca^{2+} and Mg^{2+} (Jiménez et al., 2026), while scattered trees in Amazonian pastures increased exchangeable K beneath their crowns (Álvarez et al., 2021). The resulting Ca^{2+}/K^+ imbalance may aggravate K deficiency in cacao through cation antagonism; therefore, returning pod husks and pruning residues to the plot and replenishing K should be management priorities in these systems. Exchangeable Mg^{2+} and SB did not differ among land uses in the topsoil; SB was below 5 $cmol_c$ kg^{-1} in GGWT, GGWIT and DGWIT at both depths and in AFC at 10 – 30 cm, confirming the low base status of these soils (Figure 2I, J). Among the micronutrients, land use affected available S, Fe, Mn and B in the topsoil and S, Fe and Mn in the subsoil (Table 3), where S was higher in GGWT (7.5 mg kg^{-1}) than in DGWIT (2.5 mg kg^{-1}). AFC had the lowest Fe (139 and 79 mg kg^{-1} at 0 – 10 and 10 – 30 cm) and Mn (8.3 and 4.0 mg kg^{-1}), with Mn below the critical threshold of 5 mg kg^{-1} in the subsoil, whereas B was lowest in the treeless pastures (0.29 – 0.33 mg kg^{-1} at 0 – 10 cm). Zn and Cu did not differ among land uses; Zn was below the critical threshold of 3 mg kg^{-1} in AFC in the topsoil and in most land uses at 10 – 30 cm. The levels of Cu, Fe and Mn in most land uses were well above their sufficiency thresholds, reflecting the pedogenic enrichment of these soils with Fe and Mn oxides (Custode & Sourdat, 1986; Horneck et al., 2011). Overall, the soils of the study area were acidic (mean pH 5.3), with high SOM, low available P, exchangeable K^+ and S, medium TN, Ca^{2+}, Mg^{2+}, Cu and Zn, and high Fe and Mn contents (Figure 2; Table 3). These characteristics agree with those described for other soils of the Amazon region, which are acidic, have low fertility and a low cation exchange capacity, and are dominated by low-activity minerals such as kaolinite and Fe and Al oxides (Quesada et al., 2011; Espinosa et al., 2018; Bravo-Medina et al., 2021). While the strong acidity, low base status and P and K limitation confirm patterns already reported for Amazonian soils, the reduction of topsoil aeration porosity after forest conversion and the low K^+ status of the cacao agroforestry system are specific contributions of this study.

Table 3
Effect of land use on available S and micronutrients at two depths

Land use	S (mg kg^{-1})	Zn (mg kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	B (mg kg^{-1})
			0–10 cm			
AFC	8.83 ± 0.67 a	2.29 ± 0.33 b	5.61 ± 0.23 a	138.6 ± 12.0 b	8.29 ± 0.86 b	0.77 ± 0.06 a
GGWT	9.14 ± 1.33 a	3.58 ± 0.63 ab	5.02 ± 0.52 a	354.0 ± 37.1 ab	13.62 ± 3.11 ab	0.52 ± 0.04 abc
GGWIT	4.60 ± 0.64 a	4.80 ± 0.70 ab	4.69 ± 0.45 a	509.3 ± 39.8 a	33.76 ± 5.89 a	0.29 ± 0.03 c
DGWT	9.88 ± 1.28 a	9.27 ± 1.95 a	4.88 ± 0.53 a	347.8 ± 36.8 ab	28.56 ± 5.86 ab	0.50 ± 0.05 abc
DGWIT	3.45 ± 0.37 a	4.43 ± 0.30 ab	4.33 ± 0.34 a	428.1 ± 24.9 a	31.14 ± 4.18 a	0.33 ± 0.03 bc
SF	13.61 ± 2.73 a	5.76 ± 0.70 ab	5.79 ± 1.22 a	255.0 ± 34.7 ab	22.60 ± 5.48 ab	0.85 ± 0.13 ab
p (land use)	0.049	0.056	0.959	0.007	0.022	0.009
			10–30 cm			
AFC	6.63 ± 1.03 ab	0.66 ± 0.05 a	4.79 ± 0.24 a	79.0 ± 7.6 b	3.95 ± 0.19 b	0.60 ± 0.04 a
GGWT	7.53 ± 1.00 a	2.05 ± 0.85 a	6.27 ± 0.61 a	203.2 ± 24.8 a	8.55 ± 1.88 ab	0.48 ± 0.08 a
GGWIT	3.22 ± 0.82 ab	1.74 ± 0.28 a	4.61 ± 0.37 a	348.4 ± 34.6 a	15.10 ± 2.93 ab	0.33 ± 0.03 a
DGWT	4.59 ± 0.55 ab	3.07 ± 0.70 a	4.90 ± 0.53 a	275.7 ± 29.2 a	17.76 ± 3.32 a	0.46 ± 0.06 a
DGWIT	2.45 ± 0.30 b	2.41 ± 0.17 a	4.10 ± 0.54 a	313.2 ± 15.3 a	18.95 ± 2.32 a	0.40 ± 0.03 a
SF	5.55 ± 0.48 ab	2.44 ± 0.39 a	5.74 ± 1.16 a	224.7 ± 21.9 a	10.65 ± 2.26 ab	0.54 ± 0.08 a
p (land use)	0.022	0.097	0.672	< 0.001	0.010	0.424

Values are means ± standard error (n = 14–17 sampling points from three plots per land use and depth). Different letters within a column and depth indicate significant differences among land uses (linear mixed model with plot as a random effect, Tukey test, $p < 0.05$). **S**: available sulphur; Zn: zinc; Cu: copper; Fe: iron; Mn: manganese; B: boron. Abbreviations of land uses as in Table 2.

3.2. Stratification ratio (SR), and response of land-use on soil fertility parameters

The stratification ratio (SR) is a useful metric to assess the effect of land use on the vertical distribution of soil organic carbon and nutrients (Melkani et al., 2024). SR values were greater than 1 for AP, SOM, TN, NH_4^+, available P, K^+, Ca^{2+} and Mg^{2+} in most land uses (Figure 3), indicating that these properties are concentrated in the 0 – 10 cm layer, whereas BD and pH had SR ≤ 1 because both increased with depth. K_{sat} showed the most variable SR, with a median of 33 in AFC, where K_{sat} dropped to 0.44 cm h^{-1} at 10 – 30 cm. Among land uses, SR differed significantly only for TN ($p = 0.019$), with the highest value in AFC (median 2.3) and the lowest in SF (1.5) and GGWIT (1.4); for the remaining indicators, the large within-land-use variability prevented the detection of differences. The concentration of SOM and nutrients in the surface layer reflects better structural conditions and greater aggregation in this layer, linked to its organic matter content (Blanco-Canqui & Ruis, 2018; Bravo-Medina et al., 2021), and is attributable to the continuous input of aboveground litter and root residues and to the absence of soil disturbance in the forest, silvopastoral and agroforestry systems (Zhang et al., 2019; Melkani et al., 2024).

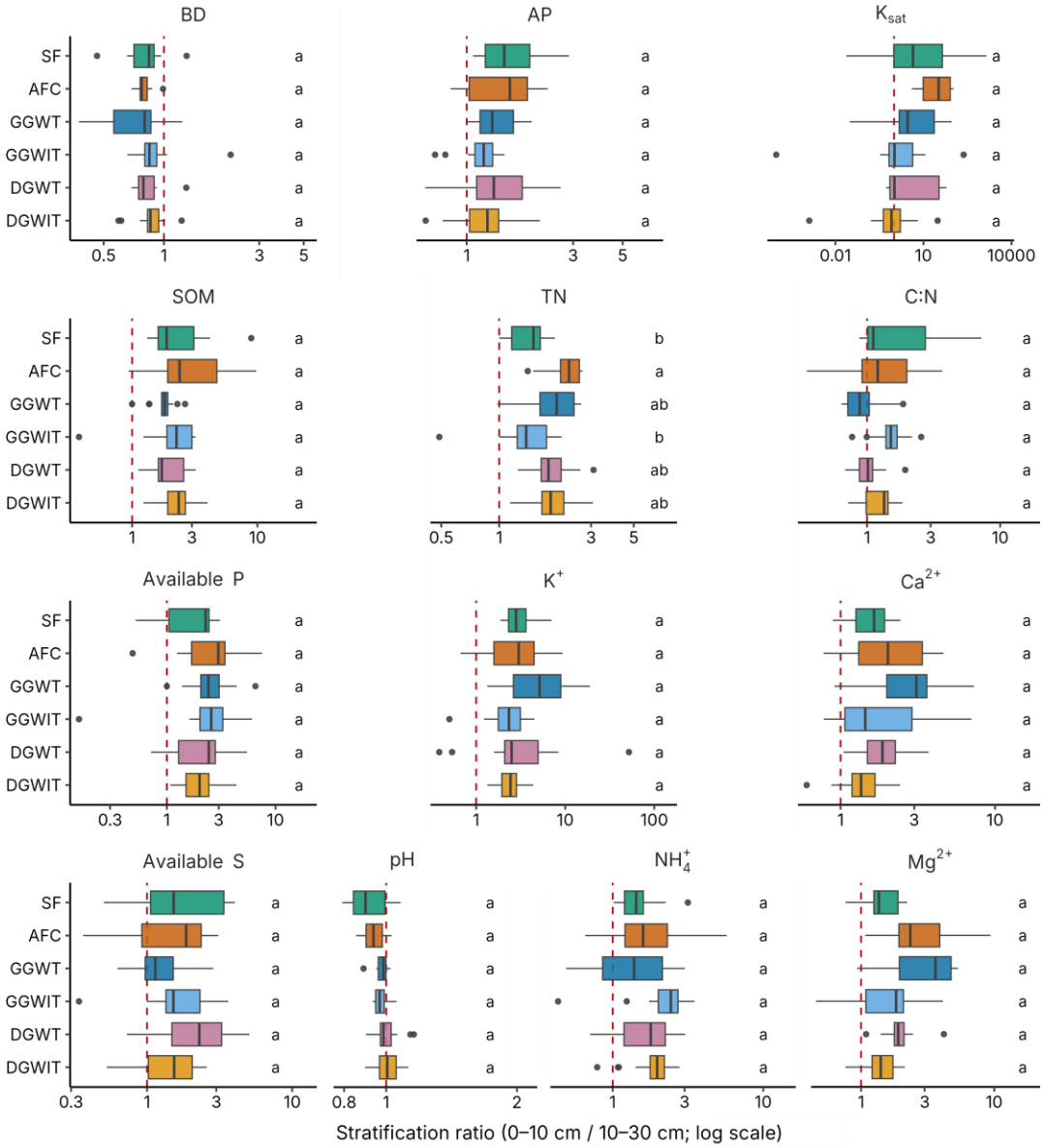


Figure 3. Stratification ratio (SR = value at 0 – 10 cm/value at 10 – 30 cm) of soil fertility indicators under the six land uses (logarithmic scale). Boxes show the median and interquartile range, whiskers extend to 1.5 times the interquartile range, and points are outliers (n = 14 – 17 sampling points per land use). The red dashed line indicates SR = 1. Different letters indicate significant differences among land uses (linear mixed model on log-transformed SR with plot as a random effect, Tukey test, $p < 0.05$). Abbreviations of land uses as in Table 2.

AP decreased in all land uses (−15% to −41%), and the decrease was significant in AFC, GGWT, GGWIT and DGWIT (Dunnett test, $p < 0.05$); among land uses, the response of AP was largest in AFC (−41%), which differed from GGWT, DGWT and DGWIT. BD increased by 52% in AFC and by 21% in GGWIT, and K_{sat} decreased by 36% – 77% in all land uses, but these responses were not significant because of their high within-land-use variability (Figure 4A). Among the chemical indicators (Figure 4B), SOM decreased by 32% – 47% in all land uses except GGWT (+12%); the decrease was significant only in GGWIT (−47%), whose response differed from that of GGWT. K^+ decreased significantly by 43% in AFC (Dunnett test, $p = 0.027$), whereas it increased by 31% – 67% in GGWT, DGWT and DGWIT; the response of K^+ in AFC differed from that in DGWT. The responses of TN (−43% to +27%) and available P (−17% to +67%) did not differ among land uses. Overall, AP, SOM and K^+ were the indicators most sensitive to forest conversion, whereas TN and available P were comparatively resistant, as also reported for the conversion of tropical rainforest to plantations (Guillaume et al., 2016). The tendency towards higher P and K^+ in grazed systems is consistent with the return of nutrients in cattle excreta (Nascimento et al., 2024). Together, the stratification ratio and the response to land-use change describe the vertical distribution of soil properties and their sensitivity to conversion, and both can help identify management practices to maintain or improve soil fertility.

The response of soil fertility indicators to land-use changes in the 0 – 10 cm layer, relative to SF, is shown in Figure 4.

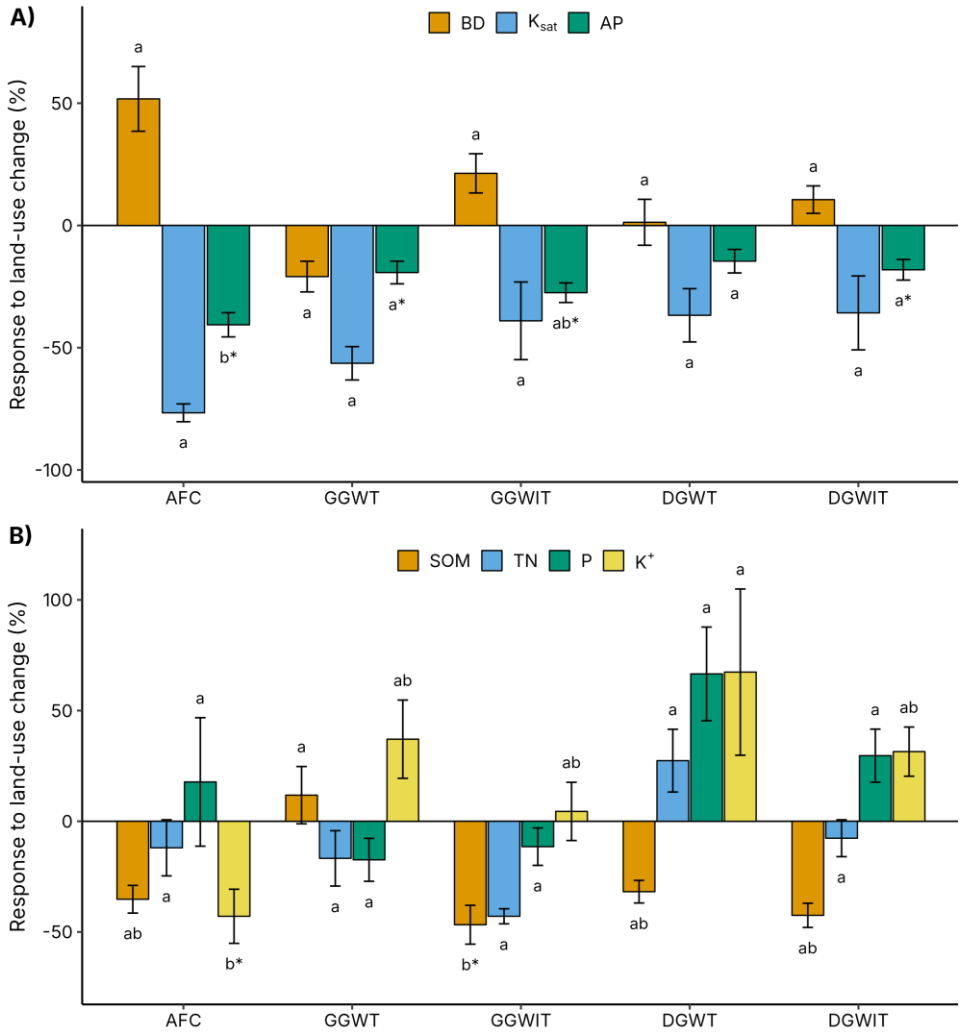


Figure 4. Response of soil fertility indicators (0 – 10 cm) to land-use change relative to the secondary forest (Eq. 1): A) physical indicators; B) chemical indicators. Bars are means ± standard error (n = 14 – 17). Positive values indicate an increase and negative values a decrease relative to SF. Different letters indicate significant differences among land uses for each indicator (linear mixed model with plot as a random effect, Tukey test, $p < 0.05$); * indicates a significant difference from SF (Dunnett test, $p < 0.05$). Abbreviations of land uses as in Table 2.

3.3. Multivariate analysis of soil fertility as a function of land use change

The PCA performed on the depth-weighted (0 – 30 cm) values of 19 physical and chemical variables retained five components with eigenvalues > 1, which together explained 80.1% of the total variance (PC1, 32.6%; PC2, 25.9%; PC3, 8.7%; PC4, 7.3%; PC5, 5.7%; Table 4). PC1 was positively associated with NH_4^+ (0.89) and Fe (0.80) and negatively with BD (−0.77) and B (−0.75), and therefore contrasted soils with low BD and higher N and Fe availability with denser soils. PC2 was positively associated with Mg^{2+} (0.84) and negatively with SOM (−0.77), with moderate positive loadings of Mn (0.69), P (0.68), Ca^{2+} (0.68) and Zn (0.65), representing a gradient from organic matter to exchangeable bases and micronutrients.

No variable had loadings > |0.70| on PC3 to PC5. In the biplot (Figure 5), AFC was separated from the other land uses along PC1, in the direction of higher BD and lower NH_4^+, K^+, Fe and K_{sat}, and GGWT was displaced towards higher SOM on PC2, whereas the remaining land uses overlapped widely. The land-use scores differed significantly on PC3 and PC4 but not on PC1 and PC2 (mixed models, $p < 0.05$), which indicates that most of the variation in soil fertility occurred within land uses, among plots and sampling points. The variables with the highest loadings (BD, NH_4^+, Fe, B, SOM and Mg^{2+}) can be used as a reduced set of indicators to monitor soil fertility in agroforestry and silvopastoral systems of the region (Bravo-Medina et al., 2023).

Also, all these factors contribute to the biomass input, leaf litter, and root remains, all of which increase the levels of organic matter and improve the C/N ratios. This, in turn, allows an adequate release of nitrogen in the soil for plants and microorganisms (Viana et al., 2014). For Amazonian conditions, regardless of the use, it has been pointed out that although high organic matter levels are maintained, this variable also decreases when the land use is changed from forest to another type of use (Bravo-Medina et al., 2021; Huera-Lucero et al., 2024).

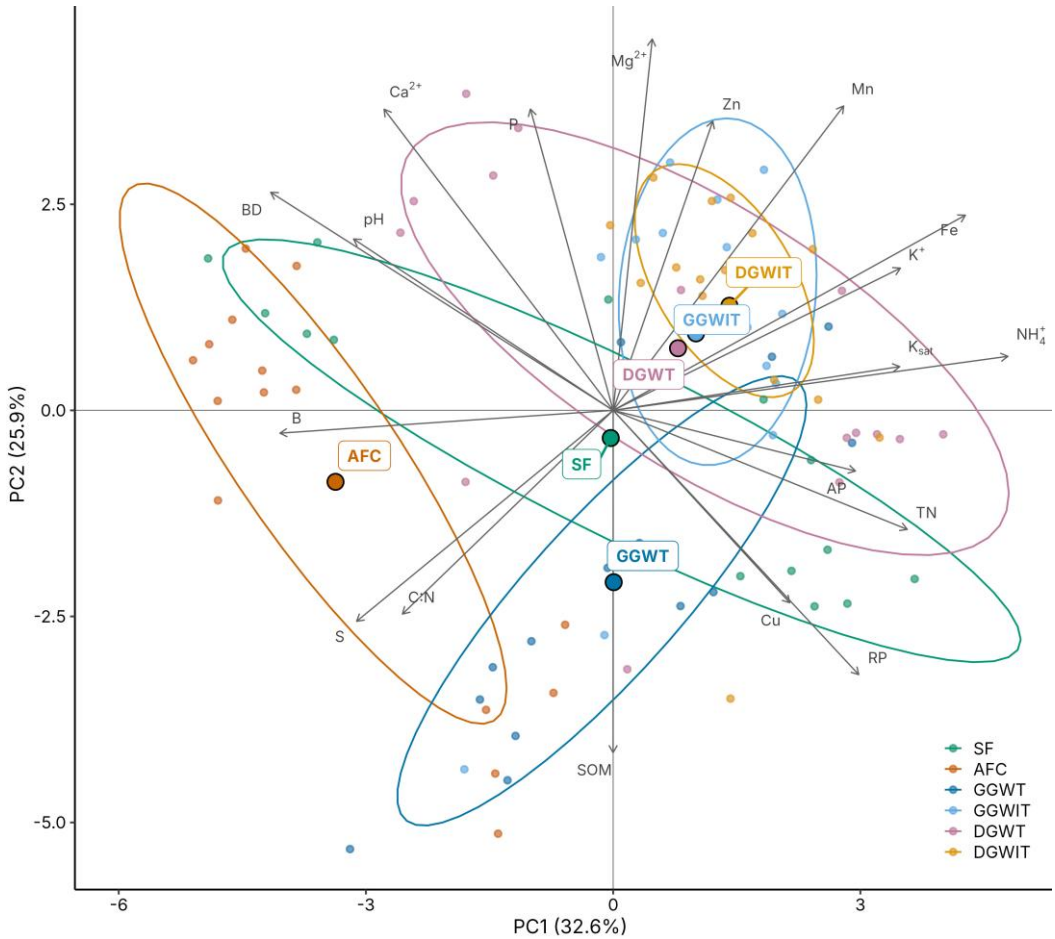


Figure 5. Biplot of the principal component analysis (PC1 vs. PC2) of 19 soil physical and chemical variables associated with fertility (depth-weighted 0–30 cm values of each sampling point). Small points are sampling points; large symbols are land-use centroids and ellipses enclose 68% of the points of each land use; arrows show variable loadings. Abbreviations of land uses as in Table 2.

Table 4
Loadings (correlation coefficients) of the soil physical and chemical variables on the principal components with eigenvalues > 1 (depth-weighted 0–30 cm values; n = 90 sampling points)

Variable	PC1	PC2	PC3	PC4	PC5
BD	**−0.77**	0.49	−0.27	−0.05	0.07
K_{sat}	0.65	0.10	−0.02	−0.17	−0.54
AP	0.55	−0.14	0.11	−0.30	−0.63
RP	0.56	−0.60	0.29	0.12	0.24
pH	−0.59	0.39	0.17	0.38	−0.20
SOM	0.00	**−0.77**	0.45	−0.31	0.11
TN	0.66	−0.27	0.18	0.52	−0.17
C:N	−0.48	−0.46	0.33	−0.60	0.17
NH_4^+	**0.89**	0.12	0.03	0.06	0.19
P	−0.19	0.68	0.47	0.25	−0.06
K^+	0.65	0.32	0.37	0.02	0.00
Ca^{2+}	−0.52	0.68	0.30	−0.01	−0.05
Mg^{2+}	0.09	**0.84**	−0.03	−0.29	0.14
S	−0.58	−0.48	0.48	0.02	−0.12
Zn	0.23	0.65	0.56	−0.04	0.09
Cu	0.40	−0.43	0.03	0.37	0.28
Fe	**0.80**	0.44	0.04	−0.18	0.15
Mn	0.52	0.69	0.10	−0.15	0.19
B	**−0.75**	−0.05	0.31	0.18	−0.05
Eigenvalue	6.19	4.92	1.65	1.39	1.07
Explained variance (%)	32.6	25.9	8.7	7.3	5.7
Cumulative variance (%)	32.6	58.5	67.2	74.5	80.1

Loadings > |0.70| are shown in bold. BD: bulk density; K_{sat}: saturated hydraulic conductivity; AP: aeration porosity; RP: retention porosity; TN: total nitrogen; SOM: soil organic matter; C:N: carbon-to-nitrogen ratio; P: available phosphorus; K^+, Ca^{2+}, Mg^{2+}: exchangeable cations; S: available Sulphur. TP and SB were excluded because they are linear combinations of other variables.

In deforested plots of the Napo River valley, decreases of 10% – 50% in surface soil C and of 25% – 60% in exchangeable cations have been reported (Mainville et al., 2006), and the low natural fertility of these soils reinforces the importance of recycling nutrients such as N, P, K^+, Ca^{2+}, Mg^{2+} and S (Mainville et al., 2006). Nutrient dynamics in Amazonian ecosystems are very intense because of the high precipitation and temperatures of the region, and exchangeable bases, especially K^+, are weakly adsorbed because of the predominance of kaolinite (Viana et al., 2014). The association of PC1 with BD and NH_4^+ and of PC2 with SOM and exchangeable Mg^{2+} indicates that the variation in soil fertility among the sampled sites was driven both by soil physical condition and organic matter and by the availability of exchangeable bases and micronutrients. Together with the deficiencies of available P and K^+ (Figure 2), these results suggest that the management of these nutrients is key to maintaining soil fertility when forests are converted to silvopastoral and agroforestry systems.

3.4. Grouping of land uses according to the physical and chemical parameters associated with soil fertility

The hierarchical cluster analysis (cophenetic correlation = 0.90) separated AFC from all other land uses at the largest linkage distance (Figure 6). A cut into three groups grouped SF with the two silvopastoral systems, DGWT and GGWT (Group I), grouped the two treeless pastures, DGWIT and GGWIT, which formed the most similar pair (Group II), and isolated AFC (Group III). Because the analysis is based on only six land-use means, this grouping should be interpreted with caution.

The isolation of AFC shows that this system, despite maintaining tree cover, was the land use whose soil fertility differed most from that of the forest, mainly because of its low K^+, NH_4^+ and AP and its higher BD. The presence of trees in pastures favours biodiversity and soil quality while enhancing carbon sequestration and other ecosystem services (Bravo-Medina et al., 2021; Torres et al., 2024), and traditional grazing systems with scattered trees have a high potential for carbon sequestration in the Ecuadorian Amazon (Torres et al., 2023). Consistently, the silvopastoral systems were grouped with the forest, whereas the two pastures without trees formed a separate group characterised by lower SOM and B and higher NH_4^+ and Fe (Figure 2; Table 3), which suggests that scattered trees help maintain a soil fertility profile closer to that of the forest, regardless of the grass species. Cacao agroforestry systems remain a sustainable option because of their contribution to carbon sequestration and soil protection (Bravo-Medina et al., 2021; Huera-Lucero et al., 2025), provided that K^+ and P are replenished.

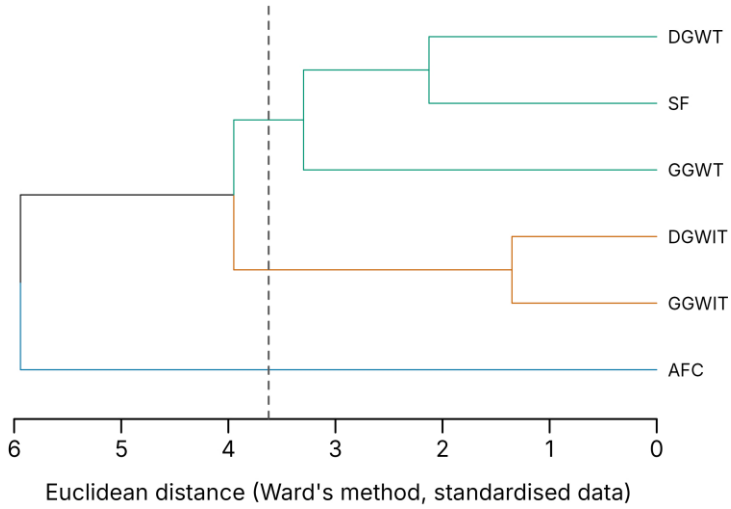


Figure 6. Dendrogram of the hierarchical cluster analysis of the six land uses based on the standardised means (0 – 30 cm) of 19 soil physical and chemical variables (Euclidean distance; Ward's method). The dashed line marks the cut that defines Group I (SF, DGWT and GGWT), Group II (DGWIT and GGWIT) and Group III (AFC). Abbreviations of land uses as in Table 2.

3.5. Nutrient stocks variation as a function of land use change

Among the nutrient stocks in the 0–30 cm layer, only those of TN and NH_4^+ differed significantly among land uses (Figure 7). TN stocks ranged from 5.5 Mg ha^{-1} in GGWT to 8.9 Mg ha^{-1} in DGWT, and NH_4^+ stocks were highest in the treeless pastures (DGWIT, 108 kg ha^{-1}; GGWIT, 100 kg ha^{-1}) and lowest in AFC (49 kg ha^{-1}) and SF (61 kg ha^{-1}). Available P (6.5 – 22.2 kg ha^{-1}), exchangeable K^+ (53 – 102 kg ha^{-1}), Ca^{2+} (496 – 4059 kg ha^{-1}) and Mg^{2+} (81 – 312 kg ha^{-1}) stocks did not differ among land uses because of their high within-land-use variability.

Compared with the stocks estimated to sustain tropical forest biomass (P: 20 – 30; K^+: 200 – 350; Ca^{2+}: 300 – 600; Mg^{2+}: 55 – 65 kg ha^{-1}; Bond, 2010), all land uses had sufficient Ca^{2+} and Mg^{2+} but insufficient exchangeable K^+, and available P stocks reached the lower threshold only in DGWT. Values for the 0 – 30 cm layer were used because the surface layers are the most influenced by vegetation and the least representative of the intrinsic nutrient status of the soil (Bond, 2010). The available nutrient reserve was calculated from the nutrient concentrations adjusted to the BD of each layer within the tree root zone (Bravo-Medina et al., 2023). Soil analysis extracts only part of the total amount of each element, and the amount extracted is proportional to the amount available for plant uptake. As in another study carried out in the area (Bravo-Medina et al., 2023), TN reserves were much larger than those of exchangeable bases and available P.

Regarding nitrogen, its practical implication in terms of management means that its large reserves do not represent any limitation for crops in any of the evaluated land uses. For TN and P were clear that these reserves are associated with soil organic matter; however, their importance in the productivity of these ecosystems is evident, not only with respect to those nutrients but also other nutrients like K^+, $Ca^{2+,}$ and Mg^{2+} (Unger et al., 2010; Wilcke et al., 2008). It should be noted that the reserves of P and NH_4^+ can be improved in livestock and silvopastoral systems through the continuous contribution of cattle feces (Nascimento et al., 2024). These results suggest that even in dystrophic environments, such as in the Ecuadorian Amazon region with medium to low levels of soil nutrients, there are nutrient reserve that plays an important role in the productivity of natural ecosystems through soil fertility and with potential input for plants, especially N and available P (Bravo-Medina et al., 2023). Most of the weathered soils in humid regions act as weak acidic systems, where the total acidity is much higher than the active acidity and, therefore, the potential acidity is high (Espinosa et al., 2018). In our study, available P and K are the most limiting nutrients, which is common in the tropical forests of the Amazon, and represents a forest that grows on nutrient-poor soils (Bravo-Medina et al., 2023; Espinosa et al., 2018). Organic P mineralization and dissolution (or weathering) of stable P minerals are natural processes that provide labile P to crops. However, in soils with low to medium available P, this means the supply for plants covers only 15% to 50% of the crop requirement (McGrath et al., 2014). Although soil nutrient concentration represents an important reserve for biomass production, it has been estimated that in some forests, 90% of the total

reserve of the Ca^{2+}, K^{+}, P, and N ecosystem may be trapped in aerial biomass reserves, whereby this proportion is lower if deeper soil layers are considered (Bond, 2010). It should be noted that the nutrient reserves in our study were obtained from available P and exchangeable fractions (K^{+}, Ca^{2+}, and Mg^{2+}). However, some studies recommend that the analysis should focus on the total nutrient stock rather than the fraction of the stock that is available to natural vegetation or the rate at which nutrients are available in decomposition processes. Therefore, when comparing the possible requirements of woody biomass with the nutrient reserves obtained in our study, we could indicate that the levels of exchangeable potassium in all land uses, and of available P in all land uses except DGWT, are below the indicated thresholds (Figure 7), which does not allow meeting these demands. Finally, the results obtained in practical terms mean that any land use change involving the intervention of the forest for crop sowing or cattle systems under a conventional scheme will require the application of fertilisers to obtain certain production levels. From an agroecological perspective, it is proposed that a change in land use must necessarily be oriented towards agroforestry systems that protect the soil, provide biomass, and encourage recycling (Bravo-Medina et al., 2017; Torres et al., 2024).

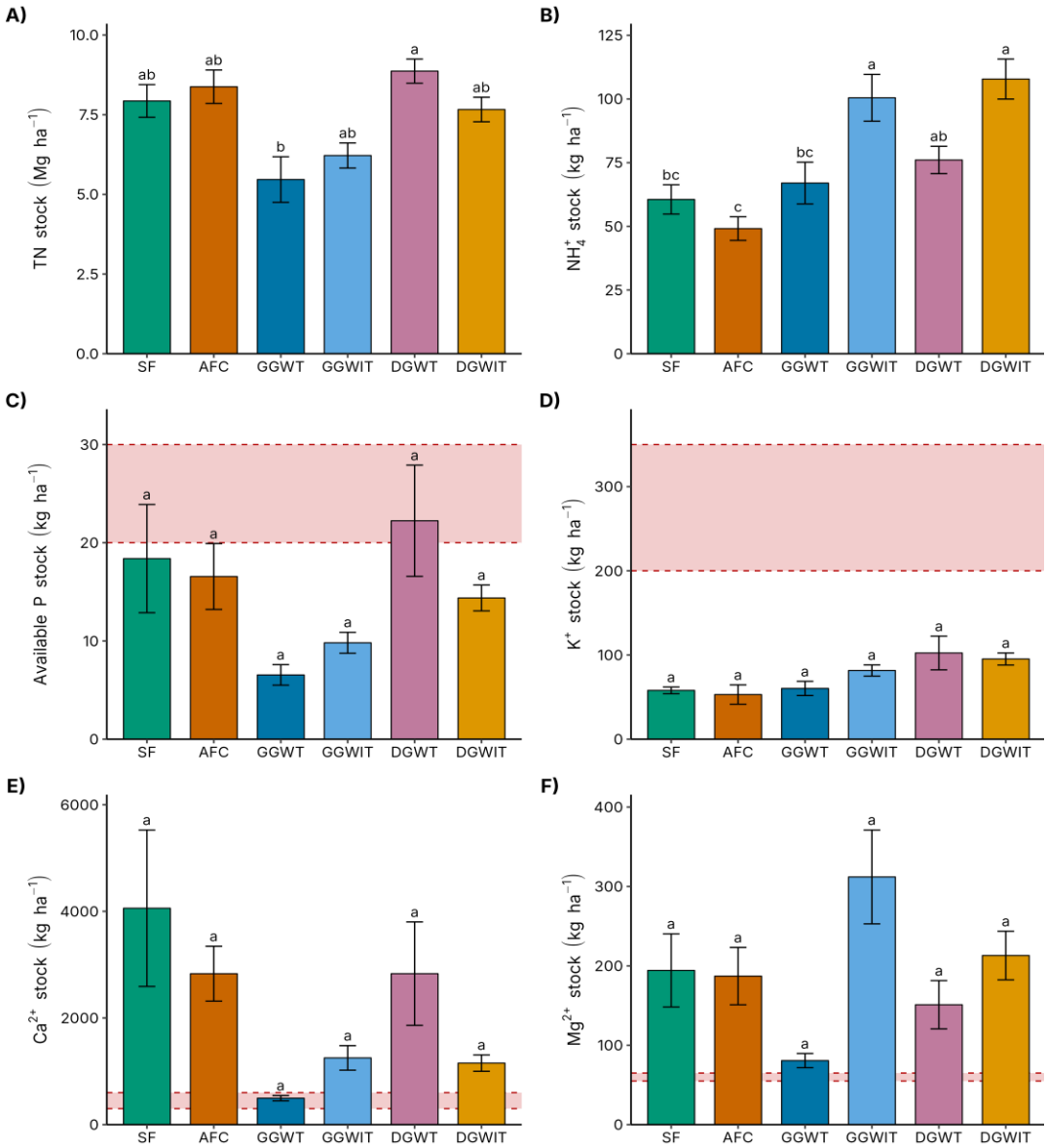


Figure 7. Soil nutrient stocks in the 0 – 30 cm layer as a function of land use: A) TN; B) NH_4^{+}; C) available P; D) exchangeable K^{+}; E) exchangeable Ca^{2+}; F) exchangeable Mg^{2+}. Bars are means ± standard error (n = 14 – 17 sampling points). Red bands indicate the stocks required to sustain tropical forest biomass (Bond, 2010). Different letters indicate significant differences among land uses (linear mixed model on log-transformed stocks with plot as a random effect, Tukey test, $p < 0.05$). Abbreviations of land uses as in Table 2.

5. Conclusions

Conversion of secondary forest to cacao agroforestry, silvopastoral and pasture systems in the central Ecuadorian Amazon modified soil fertility mainly through aeration porosity, exchangeable K^+ and, in the treeless Gramalote pasture, soil organic matter, whereas bulk density, K_{sat}, pH, total N, available P and exchangeable Ca^{2+} and Mg^{2+} did not differ consistently among land uses once plot-to-plot variability was considered. Aeration porosity decreased in all land uses relative to the forest, most strongly in the cacao agroforestry system (AFC), where it fell below the 10% critical threshold in the 10 – 30 cm layer. The cacao agroforestry system had the lowest exchangeable K^+ concentration and NH_4^+ stock and was the land used most distinct from the forest in the multivariate analyses, a pattern consistent with K export at harvest and the absence of nutrient return by livestock. Silvopastoral systems (GGWT, DGWT) kept K^+ and SOM at levels similar to those of the forest and showed the smallest reductions in aeration porosity, whereas the treeless Gramalote pasture (GGWIT) showed the largest SOM loss; in the cluster analysis, the silvopastoral systems were grouped with the forest and the treeless pastures formed a separate group. Exchangeable K^+ stocks in the 0 – 30 cm layer were below the levels required to sustain forest biomass in all land uses, and available P stocks in all except DGWT; these two nutrients are therefore the main fertility constraints after forest conversion. For farmers and extension services, we recommend retaining or reintroducing tree cover in pastures and, in cacao agroforestry systems, returning pod husks and pruning residues to the plot and replenishing K and P. Because each land use was represented by three plots, these results should be confirmed through temporal monitoring of a larger number of replicated plots, nutrient input–output balances (harvest export, excreta, litterfall and leaching) and deeper soil layers, to determine whether the differences observed here represent stable trends or site-specific conditions.

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Conflicts of interest

The authors declare no conflict of interest.

Authors' contributions

All authors contributed equally to all aspects that led to the development of this publication.

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