https://doi.org/10.17221/47/2025-JFS

Tree growth and soil recovery in Amazonian lands degraded by coca cultivation and grazing

*Luis Walther Espinoza-Ambicho[1], Luis Alberto Valdivia-Espinoza[2], Warren Ríos-García[2], Martin Valtera[3], Luis Alberto Valdivia-Ruiz[4], Tito Felipe González-Manrique de Lara[5], Lenka Ehrenbergerová[3]**

[1]Department of Forest Sciences, Professional School of Forest Engineering, Faculty of Renewable Natural Resources, National Agrarian University of the Jungle, Huánuco, Peru
[2]Department of Renewable Natural Resources Sciences, Faculty of Renewable Natural Resources, National Agrarian University of the Jungle, Huánuco, Peru
[3]Department of Forest Botany, Dendrology and Geobiocoenology, Faculty of Forestry and Wood Technology, Mendel University in Brno, Brno, Czech Republic
[4]Civil Engineering Program, Faculty of Science and Engineering, Pontifical Catholic University of Peru, Lima, Peru
[5]Department of Humanities, Faculty of Economic and Administrative Sciences, National Agrarian University of the Jungle, Huánuco, Peru

**Corresponding author: lenka.ehrenbergerova@mendelu.cz*

Citation: Espinoza-Ambicho L.W., Valdivia-Espinoza L.A., Ríos-García W., Valtera M., Valdivia-Ruiz L.A., González-Manrique de Lara T.F., Ehrenbergerová L. (2025): Tree growth and soil recovery in Amazonian lands degraded by coca cultivation and grazing. J. For. Sci., 71: 393–405.

Abstract: Soil degradation resulting from illicit coca cultivation and unsustainable grazing practices poses a major challenge to ecosystem restoration in the Peruvian Amazon. This study evaluates the potential of fast-growing tree species to rehabilitate degraded soils while producing economically valuable timber. Monoculture plantations of *Corymbia torelliana* (eucalyptus), *Calycophyllum spruceanum* (capirona), *Colubrina glandulosa* (shaina), and *Cedrelinga cateniformis* (tornillo) were established on former coca and pasture lands in the Alto Huallaga Valley. We assessed tree growth and key soil physicochemical properties – including soil organic matter (*SOM*), bulk density (*BD*), pH, extractable phosphorus (P), and cation exchange capacity (*CEC*) – in topsoil (0–10 cm) and subsoil (10–40 cm) layers. Eucalyptus and tornillo showed the highest diameter growth, while tornillo plots had significantly higher *SOM* levels. Soil pH was strongly acidic across all plots, and subsoil P was lowest under tornillo. *CEC* was highest in eucalyptus and capirona plots. Our findings suggest that tree plantations, particularly with eucalyptus, capirona, and tornillo, represent a viable strategy for the sustainable use and rehabilitation of soils formerly used for coca cultivation and grazing.

Keywords: Amazon; degraded soils; fast-growing trees; Peru; reforestation; soil quality

Supported by the National Agrarian University of the Jungle (Universidad Nacional Agraria de la Selva), Tingo María, Peru, and by the Specific University Research Fund MENDELU.

https://doi.org/10.17221/47/2025-JFS

The Peruvian Amazon, which contains the second-largest portion of the Amazon rainforest after Brazil, is experiencing significant anthropogenic pressures, leading to increased deforestation (Rojas et al. 2021). The clearance of Amazonian forests and their conversion to agricultural land removes plant biomass, disrupts soils, and results in the loss of soil organic carbon (C) and mineral nutrients, thereby altering both soil properties and biodiversity (Cerri et al. 2004; Smith et al. 2016). Primary drivers of deforestation in the Peruvian Amazon include the cultivation of coca (*Erythroxylum coca* Lam.) (Salisbury, Fagan 2013) and cattle ranching (Vijay et al. 2018; Anzualdo et al. 2022).

In various coca-producing regions of Peru, including the Ene, Marañón, Monzón, Huallaga, and Aguaytía valleys, more than 90% of the harvested coca leaves are processed into cocaine base paste and cocaine hydrochloride (Bernex 2009; Celis et al. 2020). The cultivation of coca plants involves the heavy application of nitrogen-based fertilisers and pesticides, which contribute to soil acidification and freshwater ecotoxicity (Barrera-Ramírez et al. 2019; Puri et al. 2023). According to a study from Colombia, total fertiliser use ranges from 1.76×10^6 kg to 2.94×10^6 kg annually, while pesticide use varies from 6.70×10^4 kg to 1.12×10^5 kg per year (Barrera-Ramírez et al. 2019). Cellis-Tarazona et al. (2020) reported that conventional coca management significantly affects physical indicators such as bulk density and increases resistance to surface penetrability, exchangeable aluminium, and exchangeable acidity when compared to forested soils. These negative impacts clearly represent soil degradation and contribute to the overall decline of ecosystem services and the destruction of vital forest ecosystems (Bernex 2009).

In the Amazon basin, tropical rainforests are being slashed and burned at an accelerated rate to make way for annual crops, followed by the establishment of forage grasses (Martínez, Zinck 2004). Due to inadequate pasture management, the productivity of established pastures declines within a few years. As a result, grazing plots are abandoned, and new forested areas are cleared for pasture expansion (Martínez, Zinck 2004). Pasture degradation is a significant issue in the Amazon region, prompting farmers to clear more forest land (Müller et al. 2004). Despite the relatively low cattle density (typically one cow per hectare) on Peruvian pastures, studies in the region indicate that soils under pastures, particularly degraded ones, exhibit higher bulk density than soils under forests (Martínez, Zinck 2004; Müller et al. 2004). However, Müller et al. (2004) did not observe decreases in organic C and total nitrogen (N) levels after forest areas were converted into pasture. They studied both degraded and non-degraded pastures, finding that soil pH, the sum of bases, and the saturation degree were higher compared to forest soils, while extractable phosphorus remained stable in pasture soils, although it was lower than in forest soils.

One potential solution for managing land degraded by coca cultivation and pasture use is the establishment of fast-growing tree plantations. Both introduced and native fast-growing tree species are used in reforestation efforts (Boivin-Chabot et al. 2004). Common species used for reforestation in the region include eucalyptus (*Corymbia torelliana, Myrtaceae*), capirona (*Calycophyllum spruceanum, Rubiaceae*), shaina (*Colubrina glandulosa, Rhamnaceae*), and tornillo (*Cedrelinga cateniformis, Fabaceae*). Eucalyptus, native to Australia, is widely used in Brazil for firewood, wood chips, and charcoal production (Massuque et al. 2023). Capirona, a native pioneer species in the Amazon Basin, is crucial for timber, charcoal, and firewood production (Sotelo-Montes et al. 2003, 2006). Shaina, also native to the Amazon Basin, produces valuable poles and promotes favourable microclimatic conditions for advanced forest species (Silva et al. 2015). Additionally, shaina has demonstrated satisfactory growth in reforestation projects aimed at restoring degraded pastures (Gama et al. 2013; Silva et al. 2020). Tornillo (*Cedrelinga cateniformis*), a native species valued for its economic importance, is among the most commercially utilised timber species in the region (Campos-Zumaeta, Tomazello-Filho 2009). Notably, it is also the only species among those studied that demonstrates the ability to fix atmospheric N (Magalhães, Blum 1984). However, while fast-growing species offer multiple benefits for reforestation, they may also pose risks, such as the potential for soil nutrient depletion – particularly in already degraded tropical soils (Zech, Drechsel 1998) – which must be carefully considered in restoration planning.

The challenge of restoring degraded Amazonian soils, particularly those impacted by coca cultivation and pasture, represents a frontier in ecological and agricultural research. Despite the urgent need,

https://doi.org/10.17221/47/2025-JFS

studies exploring effective recovery strategies for these soils are still scarce. This gap underscores the critical importance of understanding and innovating sustainable practices in tropical soil management. Fast-growing tree species have emerged as a promising tool, offering economic potential through sustainable timber and biomass production. Our study, conducted in the Alto Huallaga region of the Peruvian Amazon highlands, explores the potential of this approach. We investigated reforested soils formerly used for coca cultivation and pasture. By examining both soil properties and the growth rates of four tree species (eucalyptus, capirona, shaina, and tornillo), we provide critical insights into how these species contribute to sustainable land use. The main hypotheses of this study were: (*i*) Fast-growing tree plantations of eucalyptus, capirona, shaina, and tornillo are suitable for wood production on former coca and pastureland, and (*ii*) fast-growing trees may seriously deplete soil phosphorus (P).

To date, few studies have focused on forest plantations in Amazonian soils degraded by coca cultivation and pasture use. The implications of this work extend well beyond Peru, offering a model for similar efforts across the Amazon basin and other tropical regions facing deforestation. As the global demand for sustainable solutions grows, this research encourages further exploration into the synergy between ecological restoration and economic productivity.

MATERIAL AND METHODS

Study location

This study was conducted on forest plantations located in the Valle Alto Huallaga, spanning the San Martín and Huánuco departments in Peru. By the late 1970s, this area had become known as one of the world's major illegal coca production hubs (Paredes, Manrique 2021). However, in recent years, coca cultivation has largely been replaced by legal crops.

We selected four plantations of fast-growing tree species: eucalyptus (*Corymbia torelliana)* (Figure 1), capirona (*Calycophyllum spruceanum)* (Figure 2), shaina (*Colubrina glandulosa*), and tornillo (*Cedrelinga cateniformis*) (Figure 3). These tree species were chosen due to their rapid growth and frequent use in reforestation efforts, particularly on land previously used for agriculture in this region.

Figure 1. Plantation of eucalyptus *Corymbia torelliana* (October 2024)

https://doi.org/10.17221/47/2025-JFS

Figure 2. Plantation of capirona *Calycophyllum spruceanum* (October 2024)

Figure 3. Plantation of tornillo *Cedrelinga cateniformis* (October 2024)

https://doi.org/10.17221/47/2025-JFS

The Nuevo Progreso site was reforested with eucalyptus, capirona, and shaina monocultures, while the Uchiza site was exclusively planted with capirona. Both sites were formerly used for coca cultivation and were established in 2018. Additionally, two sites that had previously served as pastureland (with a low stocking density of approximately one cow per ha) were selected: the Morada site, reforested with tornillo in 2017, and the Cholón site, reforested with eucalyptus in 2018. The geographic locations of each site and plot are provided in Table 1 and Figure 4. In all plantations, trees were spaced 3 meters apart. The altitudes across sites were comparable (508–526 m a.s.l.), and the topography was generally flat. The average annual rainfall at the sites is 3 170 mm, with 169 wet days per year (FAO 2025). Based on the WRB soil classification (IUSS Working Group WRB 2015), the most likely reference soil group for all plantations was Ferralsols, with surrounding areas classified as Acrisols or Cambisols (SoilGrids250m; Hengl et al. 2017). Seedlings were planted manually, without the use of machinery.

Table 1. Location of the studied plots

Plot	Tree species (local name)	Site name (municipality)	GPS
CA1	capirona	Nuevo Progreso	8°29'19"S, 76°25'9"W
CA2		Uchiza	8°23'36"S, 76°25'8"W
SH1	shaina	Nuevo Progreso	8°29'19"S, 76°25'9"W
SH2		Nuevo Progreso	8°29'19"S, 76°25'9"W
EU1	eucalyptus	Cholón	8°29'19"S, 76°25'9"W
EU2		Nuevo Progreso	8°29'19"S, 76°25'9"W
TO1	tornillo	Morada	8°46'40"S, 76°16'0"W
TO2		Morada	8°46'40"S, 76°16'0"W

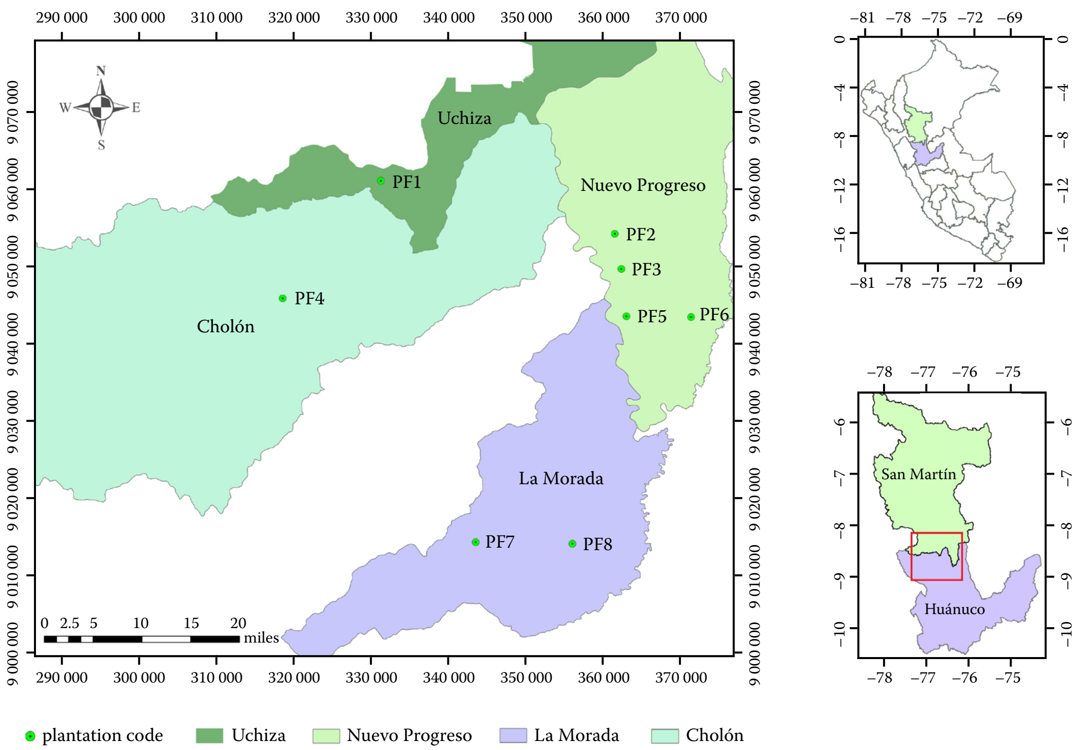

Figure 4. Location of the studied plantations

https://doi.org/10.17221/47/2025-JFS

Data collection

Tree inventory. In 2024, a forest inventory was conducted. Four inventory plots were established in Nuevo Progreso (one in an eucalyptus plantation, one in a capirona plantation, and two in shaina plantations) and two in Morada (both in tornillo plantations), with six inventory subplots in each plot, 36 subplots in total. Thirty-six tree inventory subplots were established in Nuevo Progreso (one on a eucalyptus plantation, one on a capirona plantation, and two on a shaina plantation) and 12 subplots in Morada (two on tornillo plantations). The diameter at breast height (DBH > 10 cm) and height of nine trees from the dominant species were measured at each plot. At the time of measurement, the eucalyptus, capirona, and shaina trees were 6 years old, while the tornillo trees were 7 years old. The annual increment was calculated as the DBH of the trees divided by the number of years since planting.

Soil sampling and analysis. Soil sampling was conducted in 2022, four years after the establishment of plantations with capirona, eucalyptus, and shaina, and five years after the establishment of tornillo plantations. Sampling was conducted on eight plots across four plantations – two plots per species, each measuring one ha. Seven sampling points were established per plot, with two subsamples (0–10 cm and 10–40 cm) collected from each point, resulting in 14 samples per plot and a total of 112 samples. Sampling points were systematically distributed across each plantation using a zigzag pattern. The zigzag pattern refers to the trajectory followed by the researchers across each 100 × 100 m plot during soil sampling. The sampling points were systematically distributed along a zigzag line that ensures representative coverage of the whole area. At each point along this zigzag line, one soil sample was taken.

To assess the soil characteristics, each sampled layer was analysed in the laboratory of the National Agrarian University of the Jungle (Universidad Nacional Agraria de la Selva) in Tingo María, Peru. Soil cation-exchange capacity (CEC) and exchangeable bases (Ca^{2+}, Mg^{2+}, and Na^{+}) were determined using ammonium acetate extraction at pH 7. Soil pH was measured in a 1 : 1 soil-to-water suspension. Soil organic matter content was analysed using the Walkley & Black method (Baldock, Broos 2000). Extractable phosphorus was analysed using the Olsen method (Olsen et al. 1954). Bulk density was determined using the Core method (USDA 1999).

Statistical analysis. Linear regression models and the Tukey's HSD (post-hoc) test on multiple comparisons were used to estimate the means and test the differences in evaluated soil properties and tree growth between individual plantations, using the 'multcomp' package (Hothorn et al. 2008) in R (Version 4.4.2; R Core Team 2024). If not specified elsewhere, estimated means ± standard error (SE) are provided throughout the paper. Linear model assumptions were tested using the 'gvlma' package (Pena, Slate 2019). Boxplots were produced using the 'ggplot2' package (Wickham 2016).

RESULTS AND DISCUSSION

Tree increment. Eucalyptus (*Corymbia torelliana*) on studied sites exhibited higher annual diameter increment at breast height (DBH) compared to shaina and capirona. There was no difference in growth between eucalyptus and tornillo, nor between tornillo and capirona species (Figure 5). The absolute DBH and height values for each species are presented in Table 2. These findings highlight the varying growth potential of fast-growing tree species, with eucalyptus demonstrating the highest performance under the studied conditions.

To assess whether the tree growth observed on former coca and pasture lands falls within a typical range, we compared our results with findings from previous studies. De Morais et al. (2019) reported a DBH increment of 2.7 cm per year for shaina on degraded land in Brazil, which is higher than in our study, although their research was conducted in a colder and drier climate, limiting direct comparability. Tornillo is considered a promising, fast-growing native species in the Amazon. For example, Angulo-Ruíz et al. (2016) observed annual DBH increments ranging from 2.0 cm to 2.4 cm in the Peruvian Amazon regions of Loreto, El Dorado, and Ucayali – slightly lower than the values recorded in our study. Similarly, Barglini de Melo et al. (2024) reported annual increments of 2.4 cm and 1.87 cm for eucalyptus (*Corymbia torelliana)* under conditions of low and high soil water deficit, respectively – both lower than our findings. Sotelo-Montes et al. (2006) documented a breast height increment of 2.09 cm for capirona in the Peruvian Amazon, which is also below the values observed in our research. Based on a comparison of our findings with the literature, forest plantations – particularly with tornillo (*Cedrelinga cateniformis*),

https://doi.org/10.17221/47/2025-JFS

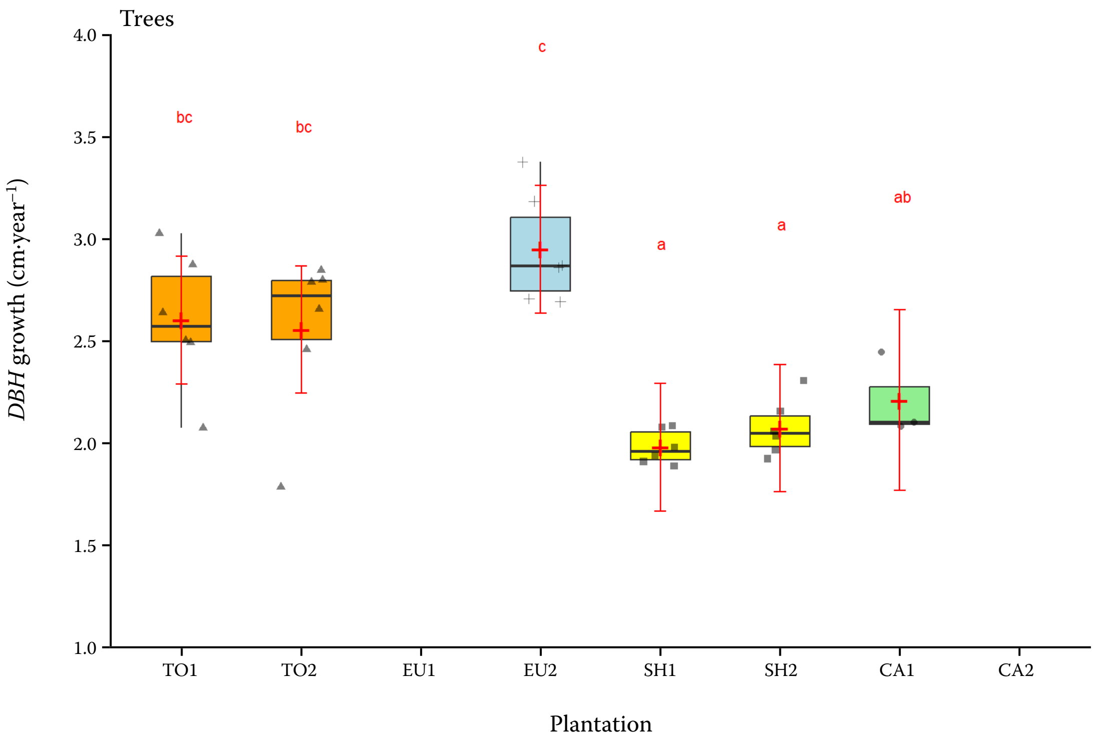

Figure 5. Average annual increment of *DBH* (cm·year^{-1}) for the studied tree species

DBH – diameter at breast height; TO – tornillo plots; EU – eucalyptus plots; SH – shaina plots; CA – capirona plots; dots – raw data; boxplots with whiskers – median and quartiles; red cross and error bar – mean (± 95%) confidence interval based on a linear regression model; means not sharing any letter are significantly different by the Tukey-test ($P < 0.05$)

Table 2. *DBH* (cm) and height (m) of the studied tree species

Species	Site	*DBH*			Height			Age (years)
		mean	SD	max.	mean	SD	max.	
Capirona	CA1	13.3	2.3	20	16	3.3	23	6
Eucalyptus	EU2	17.7	3.8	25	18	2.6	23	6
Shaina	SH1, 2	12.2	1.5	16	18	2.8	25	6
Tornillo	TO1, 2	18.1	4.4	28	17	3.3	26	7

DBH – diameter at breast height; SD – standard deviation

eucalyptus (*Corymbia torelliana*), and capirona (*Calycophyllum spruceanum*) – appear to be a productively viable strategy for utilising soils previously used for coca cultivation and pastures.

Soil properties. Extractable phosphorus (P) levels exhibited considerable heterogeneity, ranging between 1.73 mg·kg^{-1} and 14.83 mg·kg^{-1} in the topsoil layer, with no significant differences among plots planted with different tree species. In the subsoil layer, however, P concentrations ranged between 0.65 mg·kg^{-1} and 9.39 mg·kg^{-1} and were significantly lower in the tornillo plots compared to those with eucalyptus and capirona (Figure 6).

Additionally, cation exchange capacity (*CEC*) was approximately two-fold higher in both topsoil and subsoil layers in plots with capirona and eucalyptus, relative to those with shaina and tornillo (Table 3). In contrast, the contents of exchangeable cations (Ca, Mg, and Na) did not display a consistent pattern associated with tree species identity.

Mean topsoil bulk density (*BD*; g·dm^{-3}) ranged between 1.11 ± 0.2 and 1.29 ± 0.2 at the studied plots (Figure 7) but did not differ among the study species; however, it was significantly lower in the subsoil of eucalyptus plots (1.07 ± 0.02) compared to those with tornillo (Figure 8; Table 3). *BD* is a fundamen-

https://doi.org/10.17221/47/2025-JFS

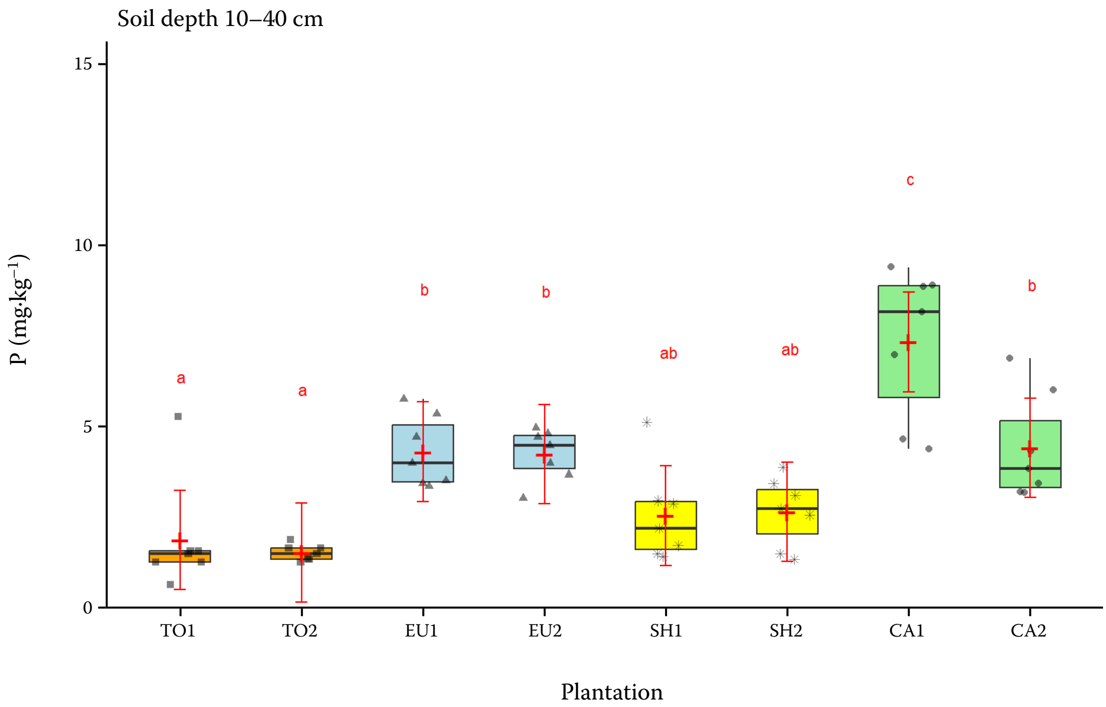

Figure 6. Subsoil (10–40 cm depth) extractable phosphorus (P) contents

TO – tornillo plots; EU – eucalyptus plots; SH – shaina plots; CA – capirona plots; dots – raw data; boxplots with whiskers – median and quartiles; red cross and error bar – mean (± 95%) confidence interval based on a linear regression model; means not sharing any letter are significantly different by the Tukey-test ($P < 0.05$)

tal indicator of soil structure and quality (Håkansson, Lipiec 2000). Elevated *BD* values in the topsoil suggest notable surface compaction in some plots, likely resulting from anthropogenic activities that predominantly impact the upper soil layers.

The high topsoil *BD* observed at the study sites may be linked to specific land-use practices, such as frequent foot traffic during coca leaf harvesting, or to the widely recognised effects of compaction in pasture systems. Greenwood and McKenzie (2001) reported that most grazed pastures, even when managed to minimise physical degradation, exhibit some degree of compaction, typically restricted to the upper 5–15 cm of the soil profile. Similarly, research from the Brazilian Amazon by Melo et al. (2017) showed that soil *BD* in pastures was significantly higher than in primary or secondary forests and coffee plantations, underscoring the more intense compaction pressure associated with pasture use.

Soil pH across the study plots was acidic, with high heterogeneity observed in the topsoil layer (mean values from 4.5 ± 0.1 to 5.2 ± 0.1), which did not correspond to differences among tree species (Figure 9). In contrast, subsoil pH was more homogeneous, with mean values ranging from 4.5 ± 0.1 to 4.9 ± 0.1 (Table 3). These values indicate strongly acidic conditions (Schoeneberger et al. 2012), consistent with the chemical characteristics typical of Ferralsols (IUSS Working Group WRB 2015).

According to SAGARPA (2012), in regions with high rainfall, leaching of base cations commonly leads to soil acidification, resulting in pH values between 4.0 and 6.5. This pattern was also observed in a study by Aquino et al. (2020) in the Huánuco region, where soils under agroforestry systems, secondary forest, and coca plantations all exhibited acidic pH values of 4.77, 4.39, and 4.23, respectively. Similarly, Cellis-Tarazona et al. (2020) reported acidic pH levels in soils under secondary forest (4.04), coca plantations (3.8), and cocoa cultivation (3.9).

Soil organic matter (*SOM*) content was quite heterogeneous across species in both soil layers, with significantly higher *SOM* contents in tornillo plots, reaching 180% to 250% compared to those with capirona and shaina (Table 3). This difference can be due to the N input from root-symbiotic associations that supply tree growth at tornillo plots

https://doi.org/10.17221/47/2025-JFS

Table 3. Comparison of soil characteristics for capirona, eucalyptus, shaina, and tornillo study plots based on a linear regression model

Variable	Layer	Plot	Capirona		Eucalyptus		Shaina		Tornillo		ANOVA		
			mean	± SE	mean	± SE	mean	± SE	mean	± SE	adj. R^2	$F_{7, 48}$	P
SOM (%)	0–10	1	1.47^{a}	0.18	2.72^{bcd}	0.28	1.66^{ab}	0.22	2.88^{cd}	0.29	0.483	8.195	0.000
		2	1.75^{ab}	0.21	2.11^{abc}	0.23	1.78^{abc}	0.21	3.66^{d}	0.35			
	10–40	1	1.19^{ab}	0.16	1.53^{bc}	0.18	0.82^{a}	0.13	2.22^{cd}	0.23	0.635	14.639	0.000
		2	1.25^{ab}	0.16	0.97^{ab}	0.14	0.99^{ab}	0.14	3.04^{d}	0.29			
P (mg·kg^{-1})	0–10	1	9.35^{d}	0.75	7.12^{cd}	0.75	4.28^{abc}	0.75	2.60^{a}	0.75	0.513	9.267	0.000
		2	6.31^{bcd}	0.75	6.67^{bcd}	0.75	7.47^{cd}	0.75	3.38^{ab}	0.75			
	10–40	1	7.33^{c}	0.48	4.31^{b}	0.48	2.55^{ab}	0.48	1.88^{a}	0.48	0.647	15.380	0.000
		2	4.42^{b}	0.48	4.24^{b}	0.48	2.66^{ab}	0.48	1.53^{a}	0.48			
CEC (cmol^{+}·kg^{-1})	0–10	1	8.95^{c}	0.59	7.39^{c}	0.45	4.08^{ab}	0.19	4.17^{b}	0.20	0.855	47.332	0.000
		2	6.95^{c}	0.41	7.25^{c}	0.44	3.39^{a}	0.15	4.21^{b}	0.20			
	10–40	1	7.16^{c}	0.46	6.15^{c}	0.37	2.98^{ab}	0.13	3.32^{b}	0.15	0.890	64.382	0.000
		2	6.00^{c}	0.35	6.51^{c}	0.40	2.68^{a}	0.11	3.29^{b}	0.15			
Ca (cmol^{+}·kg^{-1})	0–10	1	6.73^{e}	0.68	4.78^{de}	0.40	2.80^{ab}	0.18	3.16^{bc}	0.21	0.734	22.637	0.000
		2	4.35^{cd}	0.35	3.84^{cd}	0.29	2.18^{a}	0.12	3.21^{bc}	0.22			
	10–40	1	5.16^{e}	0.52	3.93^{de}	0.34	1.99^{ab}	0.12	2.51^{bc}	0.17	0.752	24.766	0.000
		2	3.59^{de}	0.30	3.16^{cd}	0.25	1.69^{a}	0.10	2.50^{bc}	0.17			
Mg (cmol^{+}·kg^{-1})	0–10	1	1.10^{c}	0.07	1.00^{c}	0.06	0.43^{ab}	0.04	0.46^{ab}	0.04	0.792	30.969	0.000
		2	0.60^{b}	0.05	0.47^{ab}	0.04	0.39^{a}	0.03	0.44^{ab}	0.04			
	10–40	1	0.78^{d}	0.08	0.65^{d}	0.06	0.30^{ab}	0.01	0.38^{bc}	0.02	0.788	30.189	0.000
		2	0.39^{c}	0.02	0.36^{bc}	0.02	0.26^{a}	0.01	0.38^{bc}	0.02			
Na (cmol^{+}·kg^{-1})	0–10	1	0.15^{c}	0.01	0.15^{c}	0.01	0.06^{a}	0.01	0.09^{ab}	0.01	0.530	9.869	0.000
		2	0.11^{bc}	0.01	0.12^{bc}	0.01	0.08^{ab}	0.01	0.08^{ab}	0.01			
	10–40	1	0.08^{bcd}	0.01	0.08^{cd}	0.01	0.04^{a}	0.01	0.05^{abc}	0.01	0.456	7.574	0.000
		2	0.09^{d}	0.01	0.08^{bcd}	0.01	0.05^{abc}	0.01	0.05^{ab}	0.01			
pH	0–10	1	5.18^{d}	0.07	4.93^{cd}	0.07	4.72^{abc}	0.07	4.49^{ab}	0.07	0.649	15.275	0.000
		2	4.59^{ab}	0.07	4.47^{a}	0.07	4.77^{bc}	0.07	4.45^{a}	0.07			
	10–40	1	4.92^{b}	0.08	4.77^{ab}	0.07	4.74^{ab}	0.07	4.84^{b}	0.07	0.202	2.947	0.012
		2	4.65^{ab}	0.07	4.52^{a}	0.07	4.76^{ab}	0.07	4.68^{ab}	0.07			

$^{a-d}$means not sharing any letter are significantly different by the Tukey-test at the 5% level of significance; *SOM* – soil organic matter content; P – extractable phosphorus; *CEC* – cation exchange capacity; Ca, Mg, Na – exchangeable base cations; pH – soil pH in water; SE – standard error; ANOVA – analysis of variance; adj. R^2 – adjusted R^2

https://doi.org/10.17221/47/2025-JFS

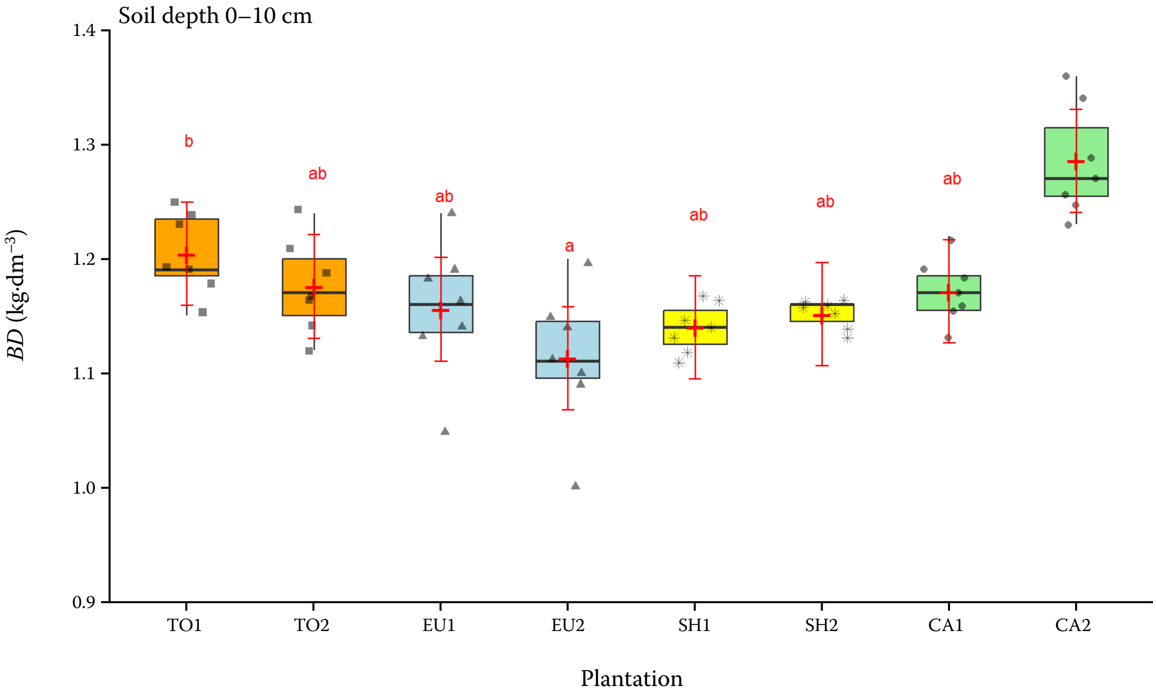

Figure 7. Topsoil (0–10 cm depth) bulk density (*BD*)

TO – tornillo plots; EU – eucalyptus plots; SH – shaina plots; CA – capirona plots; dots – raw data; boxplots with whiskers – median and quartiles; red cross and error bar – mean (± 95%) confidence interval based on a linear regression model; means not sharing any letter are significantly different by the Tukey-test ($P < 0.05$)

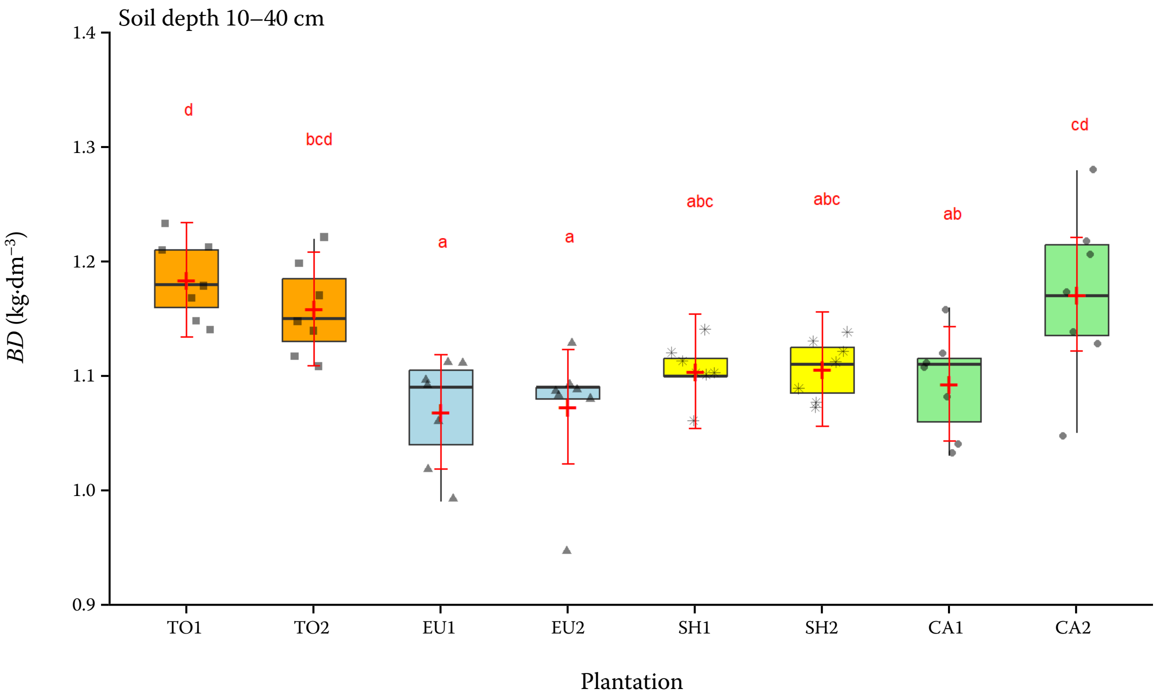

Figure 8. Subsoil (10–40 cm depth) bulk density (*BD*)

TO – tornillo plots; EU – eucalyptus plots; SH – shaina plots; CA – capirona plots; dots – raw data; boxplots with whiskers – median and quartiles; red cross and error bar – mean (± 95%) confidence interval based on a linear regression model; means not sharing any letter are significantly different by the Tukey-test ($P < 0.05$)

https://doi.org/10.17221/47/2025-JFS

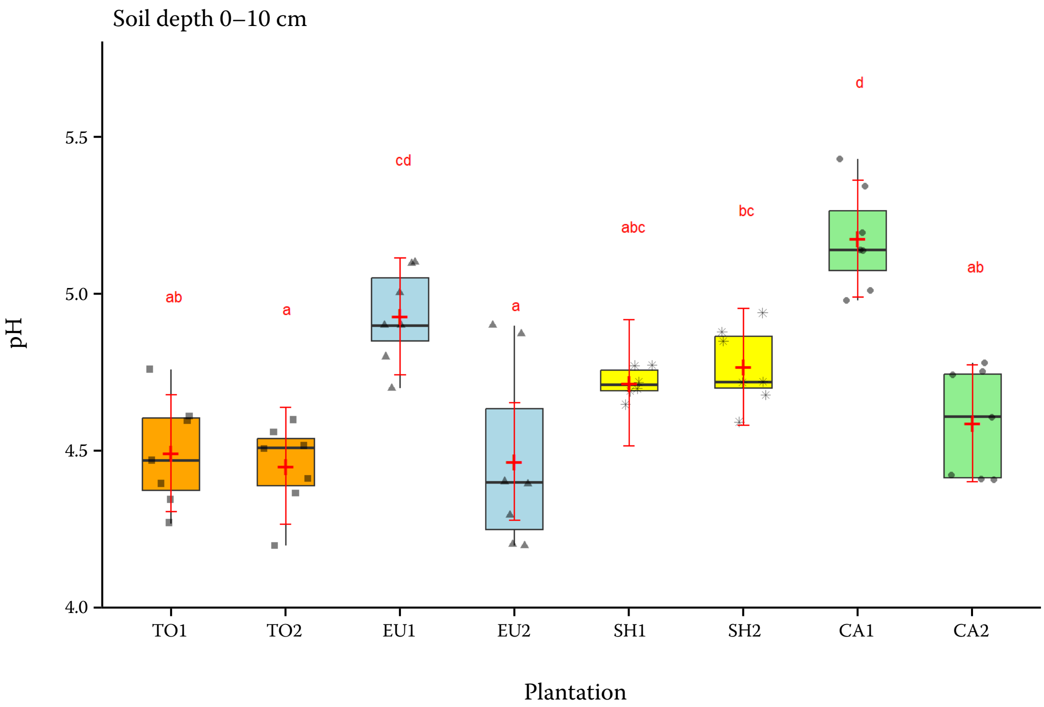

Figure 9. Soil pH (0–10 cm depth)

TO – tornillo plots; EU – eucalyptus plots; SH – shaina plots; CA – capirona plots; dots – raw data; boxplots with whiskers – median and quartiles; red cross and error bar – mean (± 95%) confidence interval based on a linear regression model; means not sharing any letter are significantly different by the Tukey-test ($P < 0.05$)

(Magalhães, Blum 1984), while the N uptake of the other tree species may rely more on the mineralisation of *SOM*. The relative deficits in *SOM* or P levels can be attributed to the management practices associated with intense pruning for timber production, leaving little organic matter as a litter input to replenish the soil.

CONCLUSION

Comparing our findings with existing literature suggests that forest plantations, especially with tornillo (*Cedrelinga cateniformis*), eucalyptus (*Corymbia torelliana*), and capirona (*Calycophyllum spruceanum*), may offer a productively viable approach for the rehabilitation of soils formerly used for coca cultivation and grazing.

Our hypothesis that fast-growing trees may seriously deplete soil phosphorus (P) was approved only partially. The lowest P values were recorded in the 10–40 cm layer in the plantation of fast-growing and N-fixing tornillo species, with only slightly higher levels observed in shaina plantations (the difference between them was not statistically significant). Significantly higher P levels compared to the tornillo plantations were found in the capirona and eucalyptus plantations.

Future research should focus on long-term monitoring of soil changes and the identification of appropriate management practices for degraded soils. Due to the short interval between the planting of fast-growing trees and the initial pedological measurements, we plan to repeat these measurements after five years to assess changes in the studied soil properties.

REFERENCES

Angulo-Ruíz W.E., Fasabi Pashanasi H., Ruíz Castro G. (2016): Crecimiento y productividad de plantación de tornillo Cedrelinga cateniformis Ducke, establecida en la Amazonía peruana. In: XII Congreso Nacional Forestal CONAFOR, Lima, Oct. 26–28, 2016: 1–7. (in Spanish).

Anzualdo V.I.T., Esenarro D., Guillen R., Reyna S. (2022): Deforestation in Peru and strategic plan for its reduction in Amazonian forests. 3C Tecnología: Glosas de Innovación Aplicadas a la Pyme, 11: 97–111.

Aquino L.A., Alvarez M.Ñ., Rofner N.F. (2020): Calidad del suelo en diferentes sistemas de uso en selva alta de Huánuco, Perú. Tayacaja, 3: 112–125. (in Spanish)

https://doi.org/10.17221/47/2025-JFS

Baldock J., Broos K. (2000): Soil organic matter. In: Huang P.M., Li Y., Summer M.E. (eds): Handbook of Soil Sciences: Resource Management and Environmental Impacts. Boca Raton, CRC Press: B25–B84.

Barrera-Ramírez J., Prado V., Solheim H. (2019): Life cycle assessment and socioeconomic evaluation of the illicit crop substitution policy in Colombia. Journal of Industrial Ecology, 23: 1237–1252.

Barglini de Melo A., Muller da Silva P.H., de Lima Araujo S., da Silva J.G.M., de Vicente Ferraz A., Rocha S.M.G., Almeida M.N.F., Araújo M., Godinho T., Neto T.C.C., Moulin J.C. (2024): Productivity and wood quality traits of Corymbia and Eucalyptus species in two soil water deficit sites. Industrial Crops and Products, 219: 119141.

Bernex N. (2009): El impacto del narcotráfico en el medio ambiente; Los cultivos ilícitos de coca, un crimen contra los ecosistemas y la sociedad. In: Mapa del narcotráfico en el Perú, Parte I. Lima, Instituto de Estudios Internacionales, Pontificia Universidad Católica del Perú: 83–98. Available at: https://repositorio.pucp.edu.pe/server/api/core/bitstreams/a1c329ff-44c6-4070-ab51-c44ac8b087b8/content (in Spanish)

Boivin-Chabot S., Margolis H.A., Weber J.C. (2004): Variation in coppice-shoot growth among provenances of *Calycophyllum spruceanum* Benth. in the Peruvian Amazon Basin. Forest Ecology and Management, 198: 249–260.

Campos-Zumaeta L.E., Tomazello-Filho M. (2009): Dendrocronología en árboles de tornillo, *Cedrelinga cateniformis* Ducke (*Fabaceae*), del Centro de Investigaciones Jenaro Herrera en el noreste de la Amazonia, Región Loreto – Perú. Lima, Universidad Nacional Agraria La Molina: 129. (in Spanish)

Cellis-Tarazona R., Florida N., Rojas A.R. (2020): Impacto sobre indicadores físicos y químicos del suelo con manejo convencional de coca y cacao. Revista Ciencia UNEMI, 13: 1–9. (in Spanish)

Cerri C.E.P., Paustian K., Bernoux M., Victoria R.L., Melillo J.M., Cerri C.C. (2004): Modeling changes in soil organic matter in Amazon forest to pasture conversion with the Century model. Global Change Biology, 10: 815–832.

De Morais Jr. V.T.M., Jacovine L.A.G., Torres C.M.M.E., Alves E.B.B.M., de Paiva H.N., Alcantara-de la Cruz R., Zanuncio J.C. (2019): Early assessment of tree species with potential for carbon offset plantations in degraded areas from southeastern Brazil. Ecological Indicators, 98: 854–860.

FAO (2025): AQUASTAT Climate Information Tool [Dataset]. Climate data derived from the CRU CL 2.0 dataset (Climatic Research Unit, University of East Anglia). Rome, Food and Agriculture Organization of the United Nations. Available at: https://aquastat.fao.org/climate-information-tool/climate-data?lat=-8.788701446299791&lon=-76.24835839547356 (accessed July 29, 2025).

Gama M.M.B., Rocha R.B., Salman A.K.D., Mendes A.M., Figueiró M.R. (2013): Reforestation feasibility in area formerly used for cattle raising in the state of Rondônia, northwest Brazilian Amazon. Revista Árvore, 37: 1001–1010.

Håkansson I., Lipiec J. (2000): A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil and Tillage Research, 53: 71–85.

Hengl T., Mendes de Jesus J., Heuvelink G.B.M., Ruiperez Gonzalez M., Kilibarda M., Blagotić A., Shangguan W., Wright M.N., Geng X., Bauer-Marschallinger B., Guevara M.A., Vargas R., MacMillan R.A., Batjes N.H., Leenaars J.G.B., Ribeiro E., Wheeler I., Mantel S., Kempen B. (2017): SoilGrids250m: Global gridded soil information based on machine learning. PLoS ONE, 12: e0169748.

Hothorn T., Bretz F., Westfall P. (2008): Simultaneous inference in general parametric models. Biometrical Journal, 50: 346–363.

IUSS Working Group WRB (2015): World Reference Base for Soil Resources 2014, Update 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106. Rome, FAO: 193. Available at: https://www.fao.org/3/i3794en/I3794en.pdf

Magalhães L., Blum W.E. (1984): Nodulation and growth of *Cedrelinga catenaeformis* Ducke in experimental stands in the Manaus region – Amazonas. Pesquisa Agropecuaria Brasileira, 19: 159–164.

Martínez L.J., Zinck J.A. (2004): Temporal variation of soil compaction and deterioration of soil quality in pasture areas of Colombian Amazonia. Soil and Tillage Research, 75: 3–18.

Massuque J., Sanchez J.Y.S.C., Loureiro B.A., Setter C., Lima M.D.R., da Silva P.H.M., de Paula Protásio T., Hein P.R.G., Trugilho P.F. (2023): Evaluating the potential of non-commercial *Eucalyptus* spp. and *Corymbia* spp. for bioenergy in Brazil. BioEnergy Research, 16: 1592–1603.

Melo V.F., Orrutéa A.G., Motta A.C.V., Testoni S.A. (2017): Land use and changes in soil morphology and physical-chemical properties in southern Amazon. Revista Brasileira de Ciência do Solo, 41: p.e0170034.

Müller M.M., Guimaraes M.F., Desjardins T., Mitja D. (2004): The relationship between pasture degradation and soil properties in the Brazilian Amazon: A case study. Agriculture, Ecosystems, Environment, 103: 279–288.

Olsen S.R., Cole C.V., Watanabe F.S. (1954): Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. USDA Circular No. 939. Washington, D.C., U.S. Government Printing Office: 19.

Paredes M., Manrique H. (2021): The state's developmentalist illusion and the origins of illegal coca cultivation in Peru's Alto Huallaga Valley (1960–80). Journal of Latin American Studies, 53: 245–267.

https://doi.org/10.17221/47/2025-JFS

Pena E.A., Slate E.H. (2019): gvlma: Global Validation of Linear Models Assumptions_. R Package Version 1.0.0.3. Available at: https://CRAN.R-project.org/package=gvlma

Puri E.E., Rofner N.F., Vásquez L.N. (2023): Impact of *Erythroxylum coca* cultivation on soil quality in the Aguaytia valley, Peru. Soil & Environment, 42: 65–76.

R Core Team (2024): R: A Language and Environment for Statistical Computing. Vienna, R Foundation for Statistical Computing. Available at: https://www.R-project.org/

Rojas E., Zutta B.R., Velazco Y.K., Montoya-Zumaeta J.G., Salvà-Catarineu M. (2021): Deforestation risk in the Peruvian Amazon basin. Environmental Conservation, 48: 310–319.

SAGARPA (2012): Subíndice de Uso Sustentable del Suelo – Metodología de Cálculo. Mexico City, Secretaría de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación: 53. Available at: https://portal.edirepository.org/nis/mapbrowse?packageid=edi.1965.1 (in Spanish)

Salisbury D.S., Fagan C. (2013): Coca and conservation: cultivation, eradication, and trafficking in the Amazon borderlands. GeoJournal, 78: 41–60.

Schoeneberger P.J., Wysocki D.A., Benham E.C., Soil Survey Staff (2012): Field book for describing and sampling soils, Version 3.0. Lincoln, Natural Resources Conservation Service, National Soil Survey Center: 312.

Silva K.A., Martins S.V., Neto A.M., Campos W.H. (2015): Semeadura direta com transposição de serapilheira como metodologia de restauração ecológica. Revista Árvore, 39: 811–820. (in Spanish)

Silva A.C.R., Camara R., Pereira M.G., Oliveira J.Q., Santana J.E.D.S., Silva E.V. (2020): Production of *Colubrina glandulosa* seedlings with different mycorrhizal inocula. Floresta, 50: 1731–1740.

Smith P., House J.I., Bustamante M., Sobocká J., Harper R., Pan G., West P.C., Clark J.M., Adhya T., Rumpel C., Paustian K., Kuikman P., Cotrufo M.F., Elliott J.A., McDowell R., Griffiths R.I., Asakawa S., Bondeau A., Jain A.K., Meersmans J., Pugh T.A.M. (2016): Global change pressures on soils from land use and management. Global Change Biology, 22: 1008–1028.

Sotelo-Montes C., Vidaurre H., Weber J. (2003): Variation in stem-growth and branch-wood traits among provenances of *Calycophyllum spruceanum* Benth. from the Peruvian Amazon. New Forests, 26: 1–16.

Sotelo-Montes, Hernandez R.E., Beaulieu J., Weber J.C. (2006): Genetic variation and correlations between growth and wood density of *Calycophyllum spruceanum* at an early age in the Peruvian Amazon. Silvae Genetica, 55: 217–228.

USDA (1999): Soil Quality Test Kit Guide. Washington, D.C., United States Department of Agriculture, Agricultural Research Services, Natural Resources Conservation Service, Soil Quality Institute: 82.

Vijay V., Reid C.D., Finer M., Jenkins C.N., Pimm S.L. (2018): Deforestation risks posed by oil palm expansion in the Peruvian Amazon. Environmental Research Letters, 13: 114010.

Wickham H. (2016): ggplot2: Elegant Graphics for Data Analysis. New York, Springer: 260.

Zech W., Drechsel P. (1998): Nutrient disorders and nutrient management in fast growing plantations. In: Schulte A., Ruhiyat D. (eds): Soils of Tropical Forest Ecosystems: Characteristics, Ecology and Management. Berlin, Springer: 99–106.

Received: June 11, 2025
Accepted: August 4, 2025
Published online: August 27, 2025