

Soil Quality Under Coca Cultivation: Evidence from Peru's Largest Coca-Growing Region Challenges Degradation Narratives and Maintains Alternative Crop Opportunities

Abstract

While drug control institutions and national governments have emphasized the impact of coca (*Erythroxylum* sp.) cultivation on soil degradation, empirical evidence on its effects on soil quality remains limited. We present a first analysis comparing the physicochemical properties of soils under coca cultivation for different time periods, compared to reference soils under rainforest. Using 125 soil samples from *Valle de los Ríos Apurímac, Ene y Mantaro* (VRAEM), we assessed key soil properties at the surface level (0-20 cm), including pH, electrical conductivity, total nitrogen, soil organic carbon, soil organic matter, available phosphorus, cation exchange capacity and exchangeable aluminum, in addition to bulk density and cumulative carbon stocks at 0-20, 20-40, 40-60 cm depth. Compared to reference rainforest soils, we found soil pH to be higher in recently (< 10 years) cultivated coca fields likely related to liming practices, while electrical conductivity was lower in all cultivated fields, and total nitrogen was only significantly lower in fields under cultivation for 11 to 20 years. Soil degradation could not be evidenced in terms of bulk density, cationic exchange capacity, soil organic carbon content and stock, phosphorous nor exchangeable aluminum. These findings suggest that coca's soil impacts are milder than presumed, challenging narratives on its environmental impact and indicating that crop substitution programs remain viable.

1. Introduction

Coca cultivation and cocaine production have expanded into the Amazon biome at unprecedented levels over the past decade (UNODC 2024). More than 2,700 Metric Tons (MT) of cocaine and over 350,000 hectares of the coca shrub (*Erythroxylum* sp.) are currently produced in tropical forests of Colombia, Peru and Bolivia (UNODC 2024). As a result, environmental impacts are an increasing concern (Dávalos et al. 2011, 2016; Rivadeneyra et al. 2023). Recently, the United Nations Office on Drugs and Crime (UNODC) and national governments are focusing not only on deforestation linked to coca cultivation but also on its implications for soil degradation (UNODC 2023a, 2023b). Nonetheless, in contrast with abundant evidence of the context-specific, spatially varying effects of coca cultivation on deforestation (Dávalos et al. 2011; Rivadeneyra et al. 2023), systematic evaluation of its impacts on soils is only recently starting (Manrique 2025).

Pushed by growing international demand for cocaine, coca leaf production relies on agricultural intensification. Large-scale use of chemical fertilizers (mainly NPK) has been documented in all major cocaine-producing countries (Acero et al 2023; Ortega 2015; Rhodes et al 2023). With an average price

of ~\$2 per dried kilo by May 2023, and a market where producers sell directly to intermediary merchants on the farm, coca outcompetes any legal crop (DEVIDA 2023b). Moreover, the coca shrub can remain productive for over 20 years, producing three to four leaf harvests annually. This high productivity raises concerns over impacts on soil quality and fertility, as continuous nutrient extraction coupled with heavy chemical input use may cause soil degradation, including acidification, compaction and loss of forest soil carbon.

Regardless of recent calls denouncing soil degradation from coca cultivation, only unpublished studies have explored the physical and chemical components of soils under coca cultivation (Camayo 2010; Oré et al 2022). Results suggest an enhanced compaction of the surface layer, higher penetration resistance and lower infiltration rates, as well as lower organic matter and lower soil pH in coca plantations than other management conditions (Celis et al 2020; Oré et al 2022). Nonetheless, due to their exploratory nature, these analyses present several limitations, including extremely small sample sizes, model misspecification and failing to account for the correlated nature of samples (e.g, Encarnación 2022; Sánchez 2021).

Therefore, the objective of this study was to assess the impact of coca cultivation on soil quality in Peru's largest coca-growing and cocaine-producing region, the *Valle de los Ríos Apurímac, Ene y Mantaro* (VRAEM). We aimed to i) quantitatively assess soil quality under high-intensity coca cultivation by analyzing key physical and chemical soil properties, ii) compare soil conditions across different coca cultivation periods (less than 5 years old, 6-10 years old, 11 to 20 years old and more than 20 years old) and with reference soils under rainforest to determine potential degradation patterns; and iii) inform development policies by assessing whether coca cultivation compromises the viability of alternative crop programs.

2. Materials & Methods

2.1. Study area

This study was conducted in the VRAEM, a Peruvian valley of approximately 30,000 km² located in the Andean-Amazonian transition zone (Fig. 1). With more than 35,000 hectares of coca cultivation, this valley is the main cluster of cocaine production in Peru. It has an altitude ranging from ~230 m.a.s.l. in the lowlands and it goes up more than 4,000 m.a.s.l. in the surrounding Andean mountain belt. Below 2,000 m.a.s.l., VRAEM has a tropical climate with a distinct wet (November to April) and dry (May to October) season with mean monthly temperatures ranging from around 16°C to 28°C and annual precipitation varying from 770 mm to 2,066 mm. The dominant soil types include Eutric Cambisols in valley floors, Dystric Leptosols in high slopes and Haplic Alisols in forested areas (ONERN 1981).

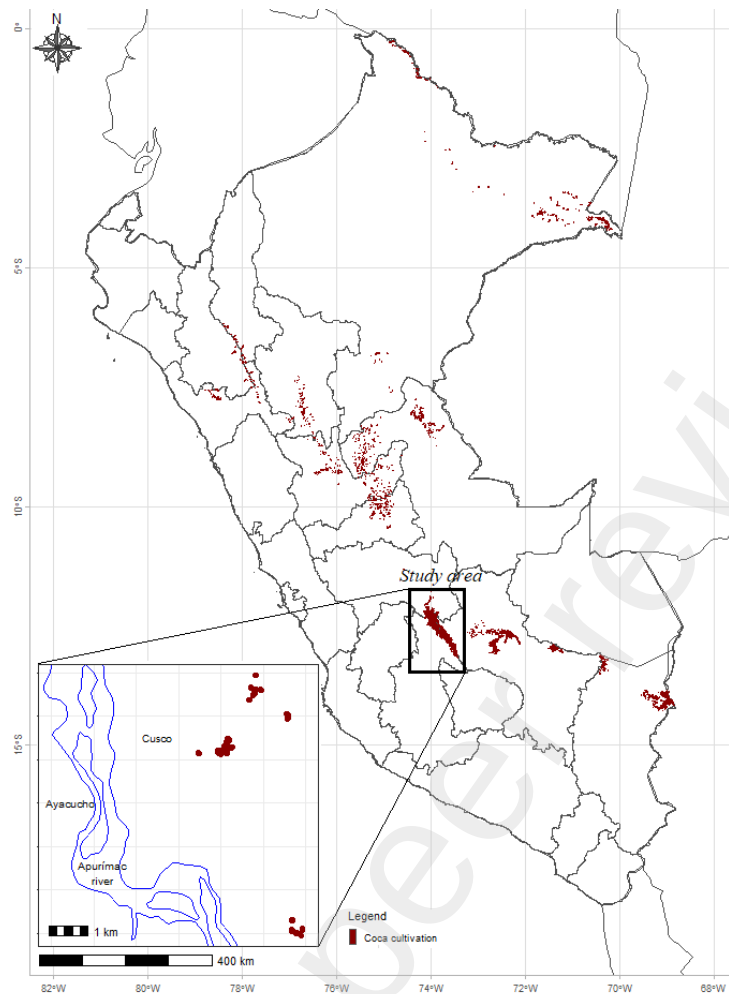


Figure 1. Coca cultivation sites in Peru. Location of sampling plots in Central *Valle de los Ríos Apurímac, Ene y Mantaro* (VRAEM).

Sampling was conducted near the Mantaro town in Central VRAEM, Cusco. At least since the last 25 years, *E. coca* is the predominant crop in Mantaro, covering most of its agricultural area. Most visited plantations with coca were organized in crop rows with a horizontal spacing of approximately 80-100 cm. Most of the plants were located in areas with a steep slope and had very little to no tree canopy cover. All coca shrubs of 5 years or older revealed signs of pruning, with older plants showing up to 3 or 4 prunes. Within or nearby most coca plots, many bags of chemical fertilizers, lime and pesticides were found (Fig. 2).



Figure 2. *E. coca* plantations in Mantaro in Central VRAEM. a. Crop rows in parcels. b. Disposed agrochemicals. c. Recently harvested coca leaves. d. Pruned coca plants.

2.2. Study design and sampling

Sampling locations were identified using spatial data from UNODC on coca cultivation sites. Farmers guided the research team to specific locations where *E. coca* was being grown. We adopted a stratified sampling design based on the planting date of *E. coca* to evaluate whether older coca fields had lower soil quality. We selected 5 coca fields in each of four categories: less than 5 years old, 6-10 years old, 11 to 20 years old and more than 20 years old. Five control sites consisting of primary rainforest were selected to provide a reference for undisturbed soil conditions.

At each of the 25 sites, we randomly established five 1×1 m plots and collected one pooled soil sample from the 0–20 cm layer. Additional samples for Soil Organic Carbon (SOC) and Bulk Density (BD) were taken using Kopecky rings at three depths (0–20 cm, 20–40 cm, 40–60 cm) in one plot per site, totaling 75 samples.

2.3. Soil analysis

Samples were stored, air-dried, and passed through a 2 mm sieve, whereafter we determined particle size distribution using the Bouyucos method. Soil texture was mainly clay loam, sandy clay loam or clay. Soil pH-H₂O and Electrical Conductivity (EC) were evaluated in water extracts (1:1 mL/g dry soil). SOC was obtained via the Walkley-Black Method, which was then multiplied by a conversion factor of 1.724 to obtain Soil organic matter (SOM). Subsequently, Cation Exchange Capacity (CEC) was obtained through saturation with ammonium acetate (NH₄OAc) at pH=7 replacing all exchangeable cations with ammonium. The adsorbed NH₄⁺ was then displaced and quantified via spectrometry to calculate the CEC. Exchangeable Aluminum levels (Al) were determined using the Yuan method, which involves extraction with 1 M KCl followed by quantification via titration with NaOH. Total nitrogen was quantified using atomic absorption, and soil available phosphorus using the Bray method. All analyses were carried out in two replicates per sample (as quality control) at the Soil and Plants Fertility Laboratory of the Instituto de Investigaciones de la Amazonía Peruana in Madre de Dios, Peru.

The BD and SOC was used to calculate the Carbon stock (Mg C/ha) at each depth. This carbon stock was expressed cumulatively over all depths (0-20 cm, 20-40 cm, 40-60 cm) to quantify the total soil carbon stock [Mg C/ha] in each site using the formula $C \text{ stock [Mg C/ha]} = C \text{ concentration [g C/kg soil]} \times BD \text{ [g soil/cm}^3\text{]} \times \text{Depth [m]} \times 10$.

2.4. Statistical analysis

We evaluated the physical and chemical properties of soils under coca cultivation across the age gradient and the rainforest reference. We fitted Linear Mixed-Effects Models (LMMs) with coca plantation age and rainforest (5 groups) as fixed effect and sites as random effects, using the *lme4* package in RStudio (Bates et al. 2024) using R version 4.2 (R Core Team 2022). LMMs were evaluated using Least Squares Means post-hoc pairwise comparison tests. Marginal and conditional R²-values were obtained for all models to evaluate the variance explained by the fixed factors and the variance explained by both fixed and random effects. We also conducted ANOVAs on the SOC, cumulative C stock and BD values across the three depth samples (0–20 cm, 20–40 cm and 40–60 cm) taken in each of the 25 sites. Finally, we further explored the patterns and relationships of the soil parameters by using a Principal Component Analysis (PCA) with varimax rotation to ease interpretability, using centered and scaled data to account for differences in measurement scales.

3. Results

LMMs showed overall significant differences between the five groups for pH ($F=0.58^{***}$), EC ($F=29.9^{***}$) and N ($F=12.4^{***}$) whereas there were no overall differences for P, SOC, CEC and Al. Pairwise comparisons of LMM means showed that the pH in the reference forest (pH=3.34) was significantly lower than in the fields cultivated for less than 5 years ($\text{coca}_{<5y} = 3.76^{**}$) and those cultivated for six to ten years ($\text{coca}_{6-10y} = 3.64^*$). EC was significantly higher in the rainforest (EC = 425 $\mu\text{S}/\text{cm}$) than in fields under coca cultivation for less than five years ($\text{coca}_{<5y} = 201^{***}$ $\mu\text{S}/\text{cm}$), for six to ten years ($\text{coca}_{6-10y} = 235^{***}$ $\mu\text{S}/\text{cm}$), eleven to twenty years ($\text{coca}_{11-20y} = 150.8^{***}$ $\mu\text{S}/\text{cm}$) and twenty years or more ($\text{coca}_{>20y} = 179^{***}$ $\mu\text{S}/\text{cm}$). Total N was significantly higher in the rainforest (N = 0.29%) than in fields under coca cultivation between 11 and 20 years ($\text{coca}_{11-20y} = 0.21\%^*$). Most marginal R^2 values were low when compared with conditional R^2 values, suggesting that a considerable part of the variation in the evaluated characteristics was explained at the random factor level, more specifically by study site ID. However, this pattern may be also due to sample size, which can influence the magnitude of random effects.

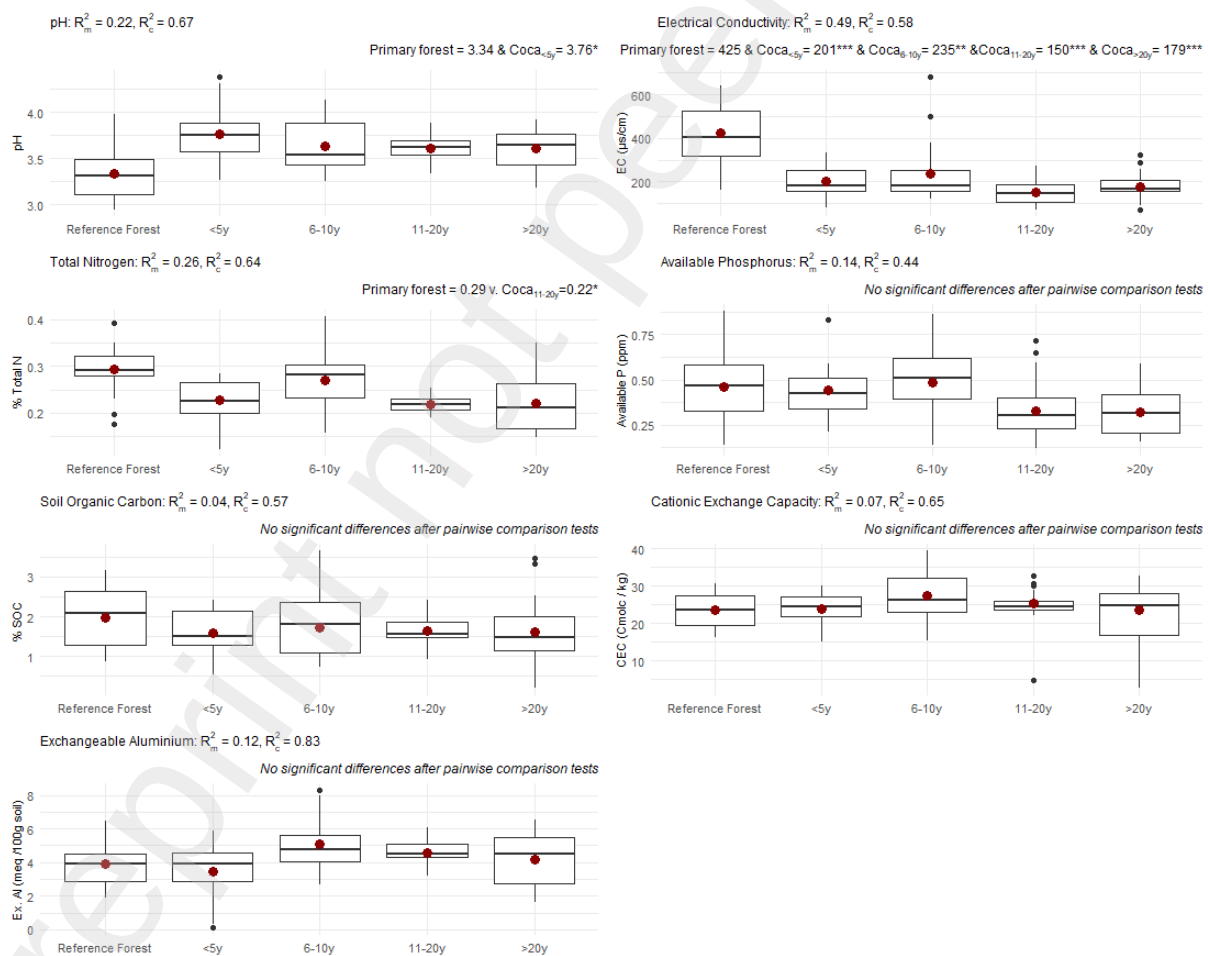


Figure 3. Boxplots of evaluated soil properties (pH, EC, P, SOC, CEC and exchangeable Al) from bivariate Linear Mixed Models, showing marginal (R^2_m) and conditional (R^2_c) R^2 values and the mean fitted values.

ANOVA tests suggested significant differences in BD across groups ($F=2.75^*$), with primary forest having the highest BD when aggregating all depths. The largest difference was found between primary forest ($BD = 1.39 \text{ g/cm}^3$) and soils with cultivated coca of between six to ten years ($BD = 1.24 \text{ g/cm}^3$). No significant differences in BD were found across 0-20cm depth ($F = 1.7$), 20-40cm ($F = 2.16$), nor 40-60cm ($F = 2.3$). There were no significant differences in C contents across groups when aggregating all depths ($F=1.13$) nor at any of the three examined depths. Similarly, no differences in C Stock (Mg C/ha) were found across groups, even when aggregating all depths ($F=0.56$) and when aggregating all coca plantations into one group ($t=0.65$) nor at any of the three examined depths (Fig. 4).

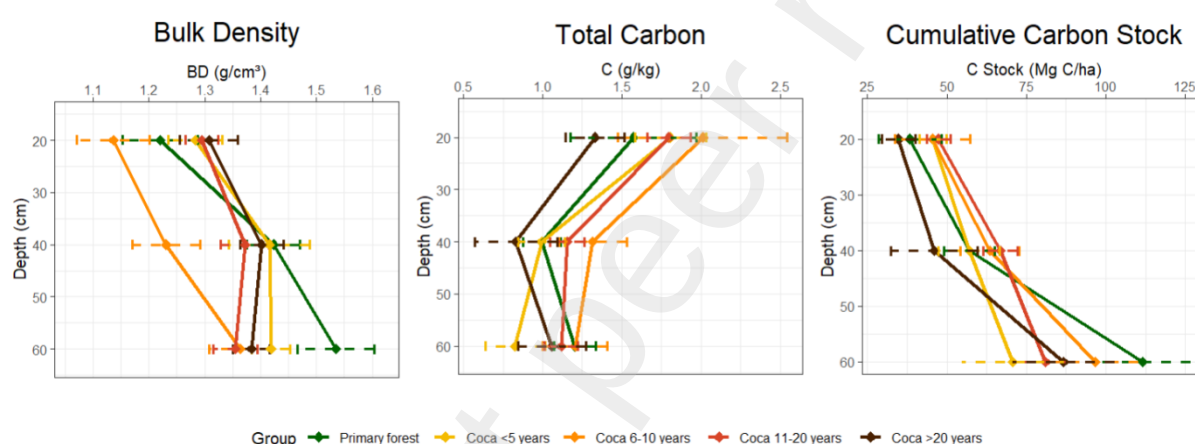


Figure 4. Profiles (means $\pm$ SE) of Bulk Density, Total Organic Carbon Content and Cumulative Carbon Stock varying with depth for the reference rainforest and soils with cultivated coca.

We conducted a PCA excluding BD due to its smaller sample size. Two PCs were retained, explaining ~61% of variance. PC1 (31.4%) was linked to Al ($\lambda=0.83$), CEC ($\lambda=0.81$) and C ($\lambda=0.64$). PC2 (29.2%) had high loadings for EC ($\lambda=0.87$), N ($\lambda=0.60$) and a strong negative loading for pH ($\lambda=-0.60$). Reference rainforest soils differed from coca soils mainly along PC2 (EC and pH), while soils under coca showed no clustering by plantation age.

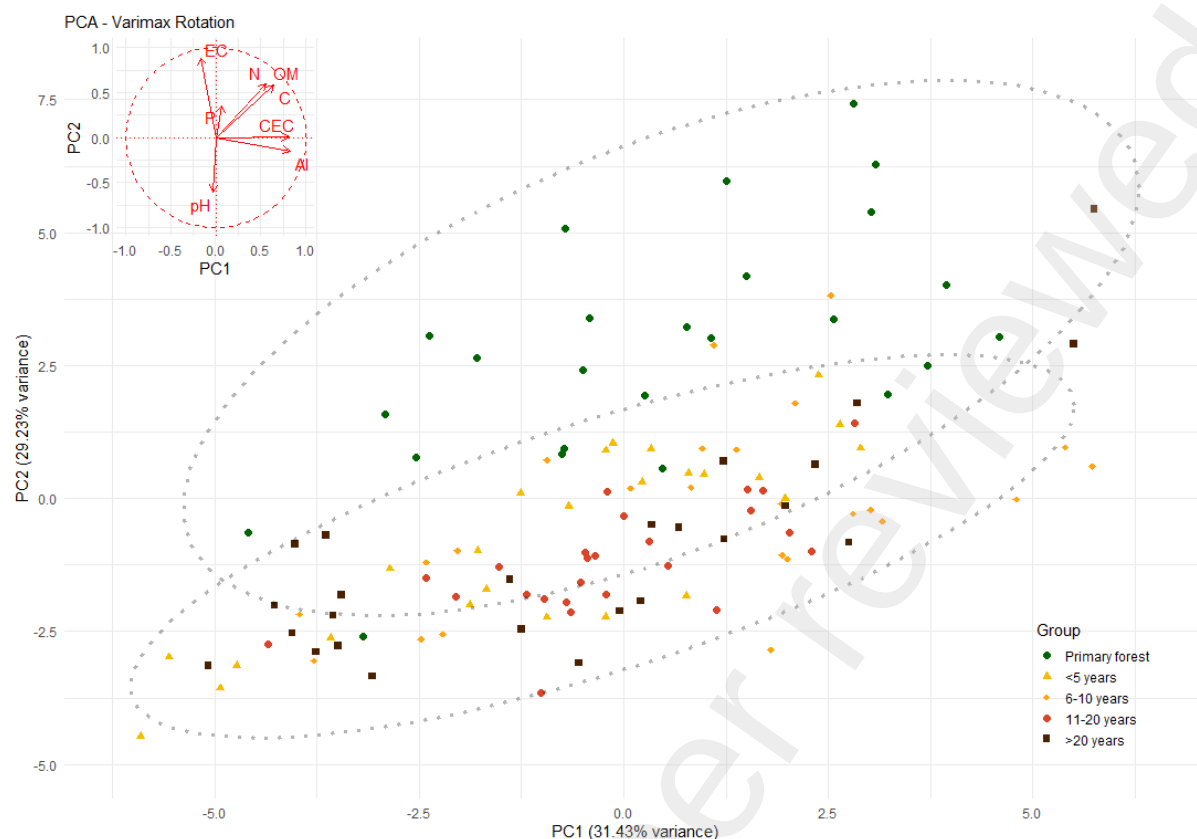


Figure 4. PCA Biplot of soils' chemical and physical properties shows that the conversion of primary forest towards coca plantation has properties towards smaller PC1, i.e., lower CEC and lower soil carbon, and towards a smaller PC2, i.e., higher pH, lower EC, lower N.

4. Discussion

This is the first systematic study to evaluate soil quality responses to coca cultivation. While coca cultivation has raised concerns about its impact on soil properties (UNODC 2023a), to the best of our knowledge, there are no published studies so far evaluating how this practice affects soil quality. Given that several alternative development programs seek to replace coca with commercial crops such as cacao and coffee, assessing the physical and chemical properties of the soil is crucial to determining the viability of these initiatives.

Contrary to recent claims suggesting a process of large-scale soil degradation under cultivation of *E. coca* (UNODC 2023a), which could jeopardize the success of alternative development programs, this study did not find alarming levels of soil degradation in the largest coca cultivation site in Peru, VRAEM. With the exception of EC, most indicators of soil fertility and structure (BD, CEC, SOC, and SOC stocks) remained stable across coca plantation ages and did not show significant differences with the reference rainforest (Fig. 3). What is more, pH proved to be significantly higher across all plantation ages with respect to the reference forest. This can be attributed to lime application, a common practice which was observed during fieldwork and discussed with farmers. Lime amendments not only optimize

soil conditions for crop growth by neutralizing soil acidity, but also prevents increases in Al^{3+} availability, which can be toxic to plants (Enesi et al 2023; Goulding 2016). This is in stark contrast with the typical claim from governmental institutions blaming coca cultivation for soil acidification (UNODC 2010; PNDA 2014). The higher pH in cultivated coca soils reflects the lime management practices also adopted by Peruvian farmers to alleviate soil acidity. The lime can be both broadcasted as amended in the planting pits to stimulate plant foliar nutrition and production (Van Der Bauwhede et al., 2024, 2025). Other evaluated metrics which remained unchanged, such as SOM and P indicate that the capacity of soils to sustain productivity has been largely preserved despite coca cultivation. Similarly, the lower BD in mid-aged coca plots indicates that these soils are not highly compacted (Fig. 4), likely due to an increase in earthworm activity stimulated by liming, which enhances soil porosity (Hartmann et al 2024).

The perennial nature of *E. coca* can play a crucial role in preserving suitable soil conditions. Perennial plants typically develop deeper root systems and sustain SOM inputs over time, which mitigates soil erosion, compaction and degradation compared to annual crops (Crews & Rumsey 2017). Unlike conventional row crops that require frequent tillage and replanting, the coca plant can be cultivated for several decades, reducing the mechanical disturbances that often contribute to soil degradation in intensive agriculture (Estevam et al 2021).

Nonetheless, we found some indications of nutrient depletion, specifically in terms of lower EC, and to a much lesser degree, lowered N contents. Lower EC might be linked to nutrient leaching. High rainfall without sufficient canopy cover can lead to leaching of soluble nutrients deeper into the soil profile or completely out of the soil system. Over time, this can significantly reduce the EC of the surface soil. Furthermore, the high frequency of coca leaf harvesting, together with the lack of sufficient replenishment (fertilizers, crop residues or organic amendments) in high slope coca fields might have contributed to the N loss.

That said, nutrient leaching can be managed through targeted fertilization and agroecological practices, such as integrating nitrogen-fixing agroforestry trees to enhance soil fertility. Local species such as *Inga edulis* (guaba) have already shown promising results in abandoned coca fields by contributing essential macronutrients like N, P, K, supporting both soil fertility and crop productivity (Lu et al 2022). Providing technical support and financial incentives to farmers can encourage the implementation of such sustainable soil management practices, ultimately strengthening the viability of alternative development programs.

Nonetheless, without proper training for farmers, improved infrastructure and market access, a successful transition to alternative development remains unlikely, particularly given the lower price of alternative crops with regards to coca. During more than thirty years of implementation, research on Alternative Development schemes seeking to replace coca with coffee and cacao highlight limited

success (Grillo et al 2021). Constraints not only include alternative crops not being as profitable as coca, but also the conditionality of alternative development programs on previous crop eradication and limited farmer participation during the planning of Alternative Development schemes (Farthing & Kohl 2005). Agricultural diversification requires not only suitable soil conditions but also sustained institutional support, economic incentives and the necessary technical knowledge to ensure long-term viability.

While offering a broader assessment than prior work, this study remains observational. As a first step in evaluating soil quality under intensive coca cultivation, it highlights the need for further research. Future studies should assess long-term impacts on biological soil parameters, such as mycorrhizal associations and compare coca cultivation with alternative land uses like agroforestry or traditional crops.

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