



Soil quality under coca cultivation: Evidence from Peru's largest coca-growing region challenges degradation narratives and maintains alternative crop opportunities

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ABSTRACT

While drug control institutions and national governments are increasingly denouncing the negative impacts of coca (*Erythroxylum* sp.) cultivation on soil degradation, empirical evidence on its effects on soil quality remains limited. Here, we present a first analysis comparing the physicochemical properties of soils that have been under coca cultivation for different time periods, compared to reference soils under rainforest. Using 125 soil samples collected in 2023 in *Valle de los Ríos Apurímac, Ene y Mantaro* (VRAEM), we assessed key soil properties at the surface level (0–20 cm). Compared to reference rainforest soils, soil pH was slightly higher (+0.3–0.5 pH units) in recently (< 10 years) cultivated coca fields likely related to liming practices and increased base cation cycling. Electrical conductivity was lower in all cultivated fields, and total nitrogen was only slightly lower in fields under cultivation for 11–20 years. Promisingly, soil degradation under coca cultivation could not be evidenced in terms of bulk density, cation exchange capacity, soil organic carbon concentration and cumulative carbon stock (0–60 cm depth), phosphorus nor exchangeable aluminum. In conclusion, the findings suggest that the effects of coca cultivation on soil degradation are not as severe as presumed, challenging prevailing narratives on its environmental impact and indicating that crop substitution programs could also mitigate these issues using agro-ecological approaches.

1. Introduction

Coca cultivation and cocaine production have reached unprecedented levels in the last decade (United Nations Office on Drugs and Crime, 2024). More than 2700 Metric Tons (MT) of cocaine and over 350,000 ha of the coca shrub (*Erythroxylum* sp.) are currently being produced in tropical forests of Colombia, Peru and Bolivia (United Nations Office on Drugs and Crime, 2024). As a result, the environmental impacts of drug trafficking have become an increasing concern (Dávalos et al., 2011, 2016; Rivadeneyra et al., 2023). In recent years, the United Nations Office on Drugs and Crime (UNODC) and national governments have not only focused on coca-related deforestation, but also on its implications for soil degradation (United Nations Office on Drugs and

Crime, 2023a, United Nations Office on Drugs and Crime, 2023b). Such concerns are mainly related to potential physicochemical impacts from intensive coca cultivation such as increased soil acidity, depletion of the nutrient status (nitrogen, calcium, magnesium), soil carbon loss through compaction/contamination (United Nations Office on Drugs and Crime, 2023a). Nonetheless, in contrast with the abundant evidence of the context-specific and spatially-varying effects of coca cultivation on deforestation (Dávalos et al., 2011; Rivadeneyra et al., 2023), the empirical evaluation of the impacts of coca cultivation on soils remained underexplored.

Pushed by an ever-growing international demand for cocaine (United Nations Office on Drugs and Crime, 2023a), the production of coca leaves relies increasingly on agricultural intensification. The

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large-scale use of chemical fertilizers (mainly NPK fertilizers) has been documented in all major cocaine producing countries (Acero et al., 2023; Encarnación, 2022; Ortega, 2015; Rhodes et al., 2023). With an average price of ~\$2 for one dried kilo of coca leaves by May 2023 and with a market dynamic in which producers sell coca leaves directly to intermediary merchants on the farm, the coca shrub outcompetes any legal crop (Zevallos, 2014). Moreover, the coca shrub can remain productive for over 20 years, producing three to four leaf harvests per year. This high productivity raises concerns over its impacts on soil quality and fertility, as the continuous extraction of nutrients coupled with heavy reliance on chemical inputs may lead to soil degradation, e.g., acidification, compaction and a loss of forest soil carbon.

Soil degradation has important consequences for the success of drug control policies, in particular for alternative development programs seeking to replace the coca shrub with alternative crops such as cacao or coffee. As degraded soils with depleted nutrients compromise the viability of alternative crops (Grillo et al., 2021), this not only might reduce the effectiveness of crop substitution efforts but also increases the likelihood of farmers reverting to coca cultivation (Vargas, 2004).

Regardless of recent calls denouncing soil degradation from coca cultivation, only unpublished studies in Peru have explored the physical

and chemical properties 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 (Camayo 2010; Celis et al., 2020; Encarnación, 2022; Oré et al. 2022). Nonetheless, due to their exploratory nature, these analyses present several limitations, including small sample size, unclear time component, model misspecification, as well as failing to account for the correlated nature of samples within the same agricultural plots (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). Specifically, 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, 11–20 years old and more than 20 years old) 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.

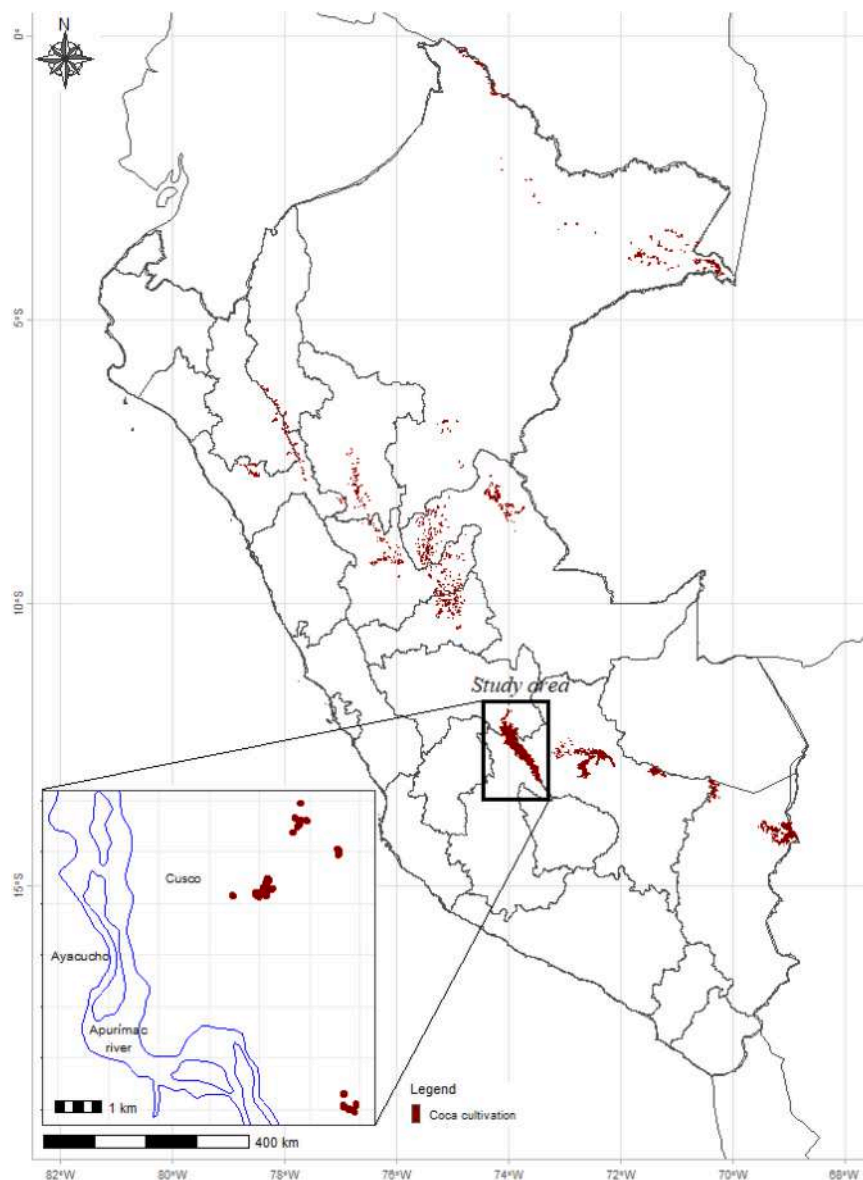


Fig. 1. Coca cultivation sites in Peru. Inset map shows the location of sampling points in Central VRAEM.

2. Materials & methods

2.1. Study area

We conducted the study in the VRAEM, a Peruvian valley of approximately 30,000 km² located in the Andean-Amazonian transition zone (Fig. 1). This valley accounts for more than 35,000 ha of coca cultivation and it represents the main cluster of cocaine production in Peru. It has an altitude ranging from ~230 masl. in the lowlands and it goes up more than 4000 masl in the surrounding Andean mountain belt. Below 2000 masl, 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 2066 mm. The dominant soil types include Eutric Cambisols in valley floors, Dystric Leptosols in high slopes and Haplic Alisols in forested areas (ONERN, 1981).

We conducted the sampling near the Mantaro town in Central VRAEM on July 2023, during the dry season. 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 coca plants were located in areas with a steep slope and had 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, we found discarded bottles and bags of chemical fertilizers, lime, bio-stimulants, insecticides and pesticides (Fig. 2).

2.2. Study design and sampling

We identified sampling locations 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* with the explicit goal of evaluating whether older coca fields had lower soil quality. We selected coca fields across four time periods: less than 5 years old, 6–10 years old, 11–20 years old and more than 20 years old. In addition, we selected control sites consisting of primary rainforest to provide a reference for undisturbed soil conditions.

We selected 25 sampling sites for each of the five categories. On each sampling site, we randomly established five 1 × 1 m plots and collected one sample per plot from the uppermost 0–20 cm depth layer, after removing the litter. This resulted in 125 individuals samples across the 25 sampling sites. In no case were samples pooled. To measure Soil Organic Carbon (SOC) and Bulk Density (BD) throughout the soil profile, we used Kopecky rings in the first plot of each of the 25 sites, sampling at two additional depth intervals (20–40 cm and 40–60 cm). This resulted in 75 samples for SOC and BD across, all taken on the first plot from each of the 25 sampling sites. As a result, the SOC and BD results do not capture within-site variability. This limitation, alongside the small sample size, may reduce the representativeness of SOC and BD estimates.

2.3. Soil analysis

Samples were stored, air-dried, and passed through a 2 mm sieve, whereafter we determined physical and chemical characterization by following ISRIC, (2002) procedures. Particle size and texture were determined using the Bouyucos method (Bouyoucos, 1962). 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) (Walkley, Black, 1934). Subsequently, Cation Exchange Capacity (CEC) was obtained through saturation with ammonium acetate (NH₄OAc) at pH= 7 replacing all exchangeable cations with ammonium (Thomas, 1982). 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 (Yuan, 1959). Total nitrogen was quantified using Kjeldahl method (Bremner, 1960), and soil available phosphorus using the Bray method (Bray and Kurtz, 1945). 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 (IIAP) in Madre de Dios, Peru.

The Carbon Stock – CS for each depth layer (0–20 cm, 20–40 cm, 40–60 cm) and plot (for the 20–40 and 40–60 cm layer) or subplots (for



Fig. 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.

the 0–20 cm layer) was calculated using Eq. 1.

$$CS_{ij} = CC_{ij} \times BD_{ij} \times Depth_i \times 10 \quad (1)$$

In which CS is the carbon stock at plot *i* and depth *j*, CC is the carbon concentration [kg C/kg soil] measured for (sub)plot *i* at depth *j*, BD the bulk density [kg soil/m³] for plot *i* at depth *j*, Depth was the thickness of that soil layer, in this case always 0.2 m, and 10 the conversion factor from kg C/m² to Mg C/ha.

Subsequently, cumulative Carbon Stock – CCS (Mg C/ha) were then calculated for further analyses for each depth interval (0–20 cm *n* = 125). Because the 20–40 cm and 40–60 cm intervals had no replicates within each plot, a mean value of the five subplots was used of the CS of 0–20 cm to calculate the CCS at 0–40 cm (*n* = 25) and 0–60 cm (*n* = 25).

2.4. Statistical analysis

We evaluated the physical and chemical properties of soils under coca cultivation across an age gradient with rainforest as control. We fitted Linear Mixed-Effects Models (LMMs) with coca plantation age and rainforest as fixed effect and the 25 sites as random intercept effects, using the *lme4* package in RStudio (Bates et al., 2015) using R version 4.2 (R Core Team, 2022). We evaluated results from LMMs using ANOVAs and Least Squares Means post-hoc pairwise comparison tests. Marginal and conditional *R*²-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 conducted ANOVAs on BD, SOC, and

CCS 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

ANOVA tests on fitted LMMs revealed significant differences among the five groups for EC ($F(4, \sim 20) = 17.4, p < 0.001$), N ($F(4, \sim 20) = 3.68, p = 0.02$) and marginally significant differences for pH ($F(4, \sim 20) = 2.7, p = 0.06$). No significant group differences were found for P, SOC, CEC and Al. Pairwise comparisons of LMM means suggested that pH in the reference forest (pH=3.3) was significantly lower than in fields cultivated for less than 5 years (pH coca<5y = 3.8, $p = 0.03$). EC was significantly higher in the rainforest (EC = 425 μ S/cm) than in fields under coca cultivation for less than five years (EC coca<5y = 201 μ S/cm, $p < 0.0001$), between six and ten years (EC coca6–10y = 235 μ S/cm, $p < 0.0004$), between eleven and twenty years (EC coca11–20y = 151 μ S/cm, $p < 0.0001$) and twenty years or more (EC coca>20y = 179 μ S/cm, $p < 0.0001$). Total N was significantly higher in the rainforest ($N = 0.29\%$) than in fields under coca cultivation between 11 and 20 years (N coca11–20y = 0.22%, $p < 0.05$) and twenty years or more (N coca>20y = 0.22%, $p = 0.056$). 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

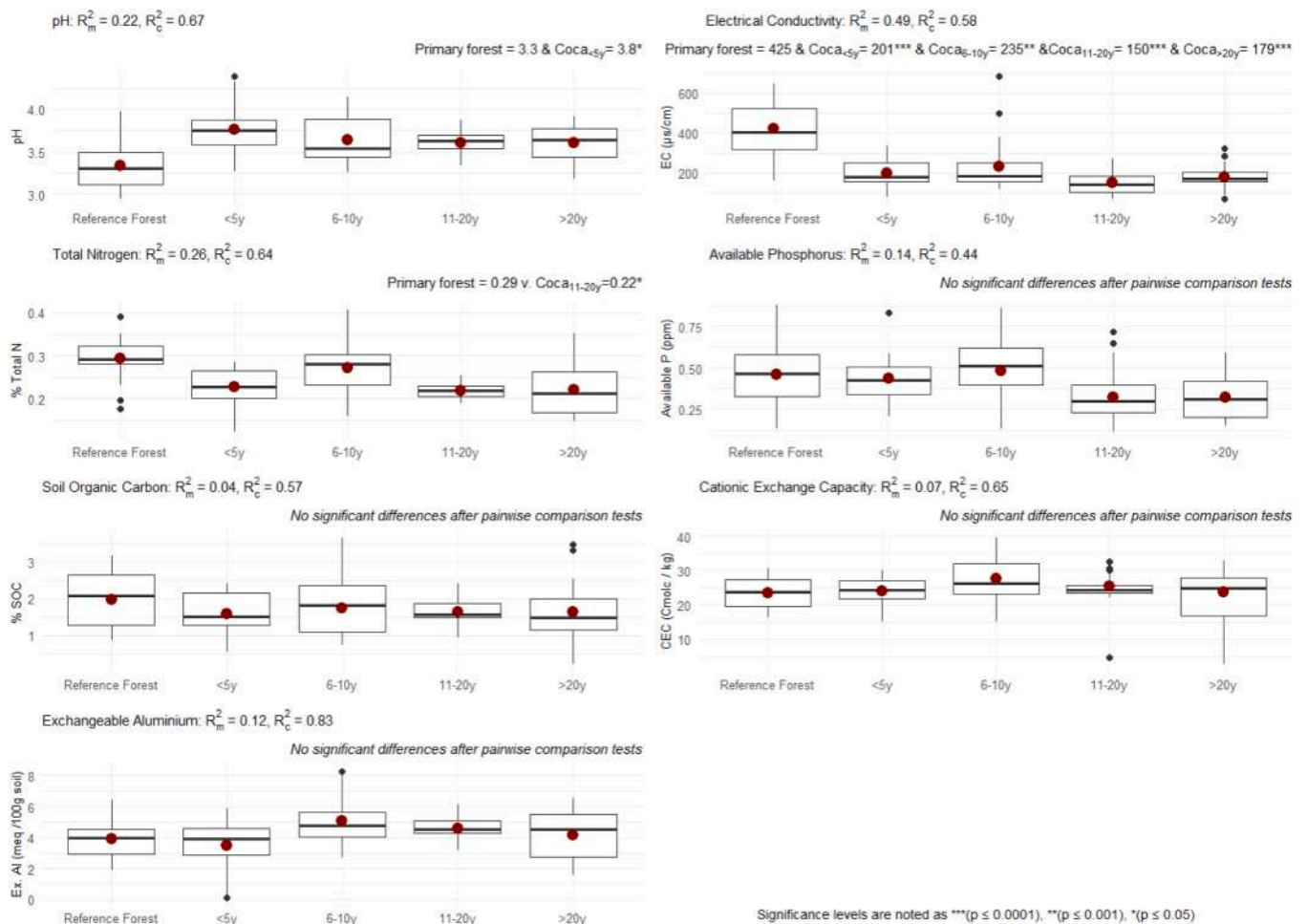


Fig. 3. Boxplots of evaluated soil properties (pH, EC, N, P, SOC, CEC and exchangeable Al) based on bivariate Linear Mixed Models, showing marginal (*R*_m²) and conditional (*R*_c²) *R*² values with mean fitted values (colored in red). Annotations denote the presence or absence of significant differences for each soil property.

random factor level, more specifically by study site ID (Fig. 3). However, this pattern may be also due to sample size, which can influence the magnitude of random effects.

ANOVA tests on fitted LMMs for BD found no significant differences across groups ($F(4, \sim 20) = 1.61, p = 0.21$). The largest difference was found between primary forest (BD = 1.39 g/cm^3) and soils with cultivated coca of between six to ten years (BD = 1.24 g/cm^3). No significant differences in BD were found across 0–20 cm depth ($F = 1.7$), 20–40 cm ($F = 2.16$), nor 40–60 cm ($F = 2.3$). 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 CCS (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).

We conducted a PCA based on all soil variables except BD due to its lower sample size (Fig. 5). Two Principal Components (PCs) were retained, accounting for $\sim 61\%$ of the variance. PC1 explained 31.4 % of the variance and was mainly associated with variables such as Al ($\lambda=0.83$), CEC ($\lambda=0.81$) and C ($\lambda=0.64$). PC2 explained 29.2 % of the variance and had highest loadings for EC ($\lambda=0.87$) and N ($\lambda=0.60$), and having strong negative loadings for pH ($\lambda=-0.60$). Overall, reference rainforest soils were only differentiated from soils under coca plantations along PC2, mainly showing differences among them in EC and pH, whereas soils under coca cultivation did not show any clustering based on plantation age.

4. Discussion

This is the first systematic study to evaluate soil quality responses to coca cultivation. Contrary to recent claims suggesting a process of large-scale soil degradation under cultivation of *E. coca* (United Nations Office on Drugs and Crime, 2023a; United Nations Office on Drugs and Crime, 2024), which could jeopardize the success of alternative development programs seeking to replace coca with commercial crops, this study did not find alarming levels of soil degradation. With the exception of EC, most indicators of soil fertility and structure (BD, CEC, SOC) remained stable across coca plantation ages and did not show significant differences with the reference rainforest even up to 20 years after the conversion. Contrary to claims by drug control institutions regarding soil acidification (Policía Nacional Dirección de Antinarcóticos, 2014; United Nations Office on Drugs and Crime, 2024), our results indicate that soil pH levels of the coca plantations were about 0.3–0.5 pH units higher -though marginally significant- across all plantation age groups compared to the reference forest. The higher pH in cultivated coca soils could partly reflect the lime management practices adopted by Peruvian farmers to alleviate soil acidity. Lime amendments not only optimize soil

conditions for crop growth by neutralizing soil acidity, but also prevent increases in Al^{3+} availability, which can be toxic to plants (Enesi et al., 2023; Goulding, 2016). The observed pH increases in the coca plantations are consistent with doses of 2–4 Mg dolomite/ha, and the lime can be both broadcasted as amended locally in the planting pits to stimulate the base cation nutrient cycling and crop production (Van Der Bauwhede et al., 2024, Van Der Bauwhede et al., 2025). Moreover, the coca plantations had lower stand density than the reference forest, which is also known to accelerate the nutrient cycle and thereby increase topsoil pH to some extent.

Evaluated metrics that remained unchanged, such as SOC and P indicate that the capacity of soils to sustain productivity without carbon penalty has been largely preserved despite coca cultivation. Similarly, the lower BD in mid-aged coca plots suggests that these soils are not highly compacted, likely due to an increase in earthworm activity stimulated by liming, which enhances soil porosity (Hartmann et al., 2024). At such low topsoil pH, the observed pH increase likely did not critically increase respiration as the CCS ranging 80–100 Mg C/ha did not differ between coca plantations and reference forests.

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 likely mitigated soil erosion, compaction and degradation compared to annual cropping systems (Crews and 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 lowered EC, and to a much lesser extent, lowered N contents. Lower EC might be linked to reductions in root secretion, as well as to increased nutrient leaching. Forested areas typically have greater root density, more diverse root exudates and a more closed nutrient cycle (Staszel-Szlachta et al., 2024), which may contribute to higher EC values. In contrast, coca plantations like the ones evaluated involve lower planting densities, potentially leading to reduced root activity, more leaching and consequently, lower EC.

On the other hand, 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-

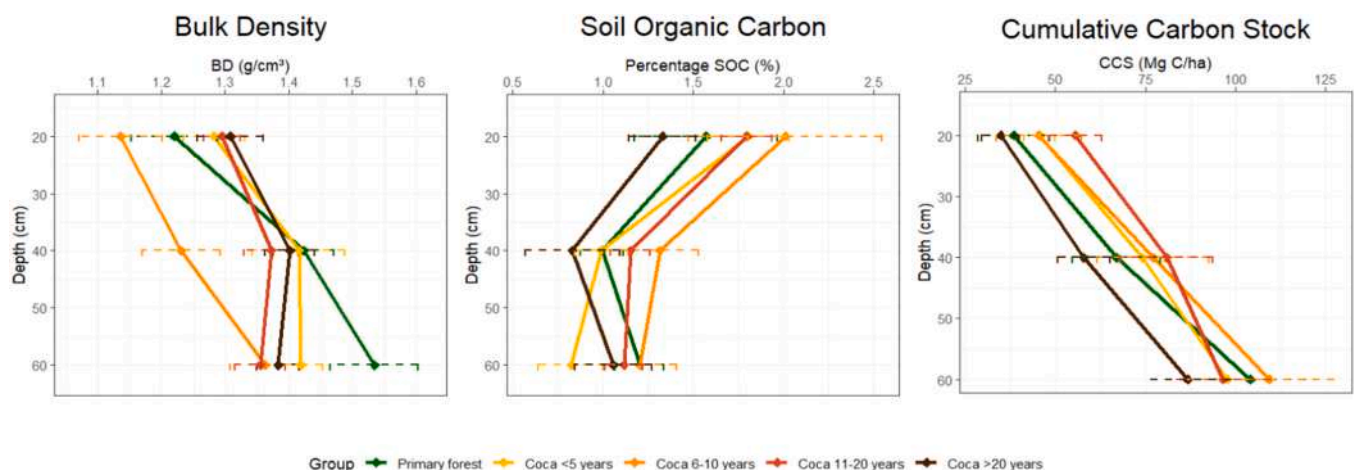


Fig. 4. Profiles (means $\pm$ SE) BD, SOC and CCS varying with depth for the reference rainforest and soils with cultivated coca.

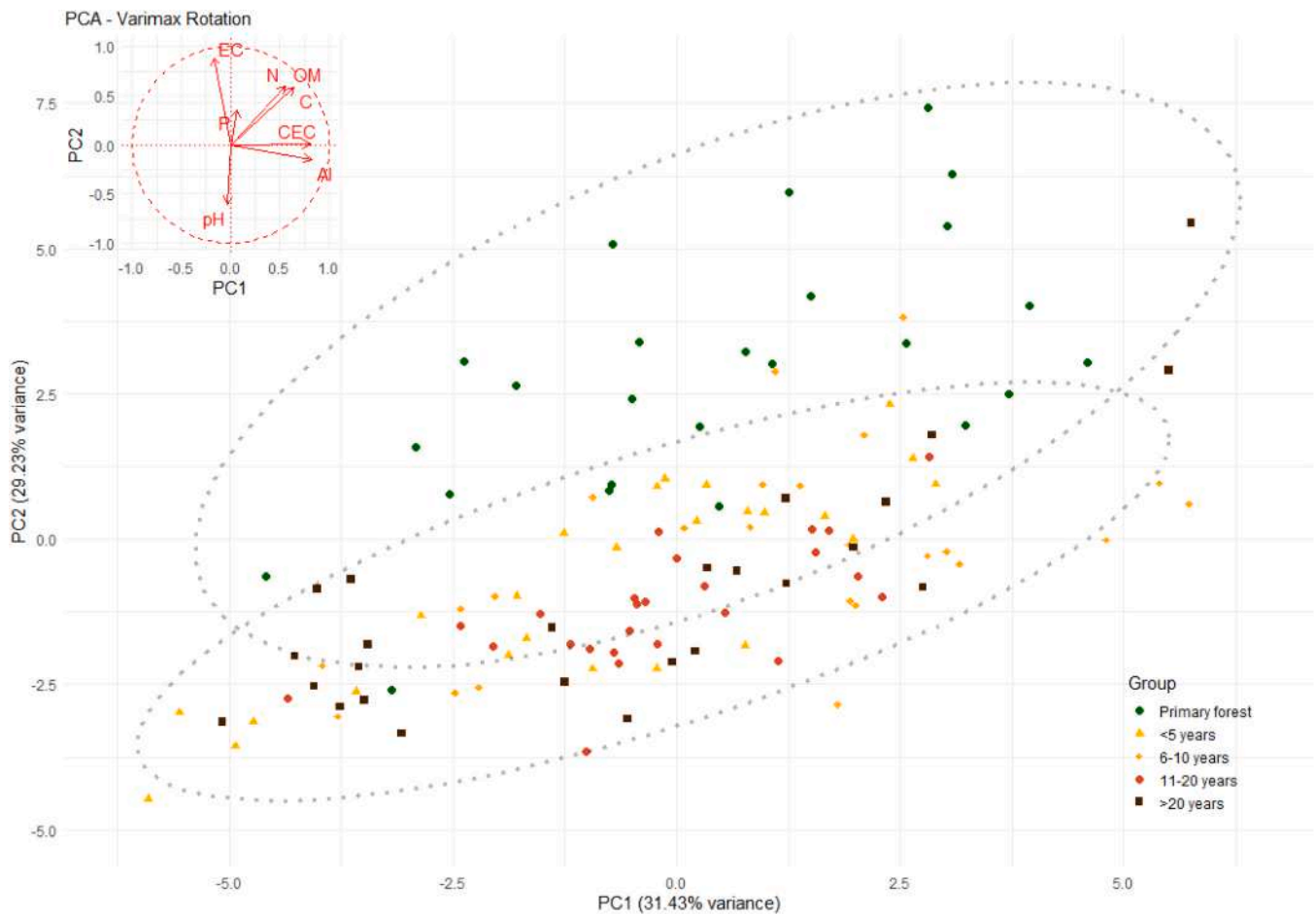


Fig. 5. PCA Biplot of soils' chemical and physical properties reveals that the conversion of primary forest to coca plantations shifts properties towards smaller PC1, i.e., lower CEC and lower C, and towards a smaller PC2, i.e., higher pH, lower EC, lower N.

fixing agroforestry trees to enhance soil fertility. Local species such as *Inga edulis* (guaba) have already shown promising results in abandoned coca fields supporting both soil fertility and crop productivity (Lu et al., 2022). Providing technical support and financial incentives to farmers can encourage the implementation of 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; Unlu and Kapti, 2012). 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 this study offers a more comprehensive assessment than previous research, it remains an observational analysis rather than an experimental one. As a preliminary attempt to evaluate soil quality under intensive coca cultivation, these findings highlight the need for further research using additional soil quality metrics and a large sample size. Comparative analyses with alternative management uses, such as agroforestry systems or traditional food crops could also provide a better understanding of the trade-offs and ecological implications of coca cultivation.

CRediT authorship contribution statement

Manrique Hernán: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Gabriel Velasquez:** Supervision, Methodology, Investigation, Conceptualization. **Edwin Becerra:** Supervision, Project administration, Methodology, Investigation, Conceptualization. **Adenka Muñoz:** Methodology, Investigation, Formal analysis, Data curation. **Robrecht Van Der Bauwhede:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Formal analysis, Conceptualization. **Olivier Honnay:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hernan Manrique reports financial support was provided by Research Foundation Flanders. If there are other authors, they declare that they have no known competing financial interests or personal relationships

that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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