Geoderma 357 (2020) 113952

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

# Effect of rosewood plantation chronosequence on soil attributes in Central Amazonia

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ARTICLE INFO

Handling Editor: Morgan Cristine L.S.

*Keywords:*
Amazon planted forest
Endangered tree
Species conservation
Recovery areas
Silviculture

ABSTRACT

Rosewood (*Aniba rosaeodora* Ducke) is an endangered Amazonian tree species that produces a commercially valuable essential oil, used mainly in cosmetics and fine fragrances production. The species can also be used in reforestation programs, which generate jobs and as a source of income and reduce the pressure of exploitation on natural rosewood populations. The objective of this study was to verify the influence of rosewood stands on physical and chemical soil attributes. This study was conducted at a rural farm in the Maués municipality, 350 km from Manaus, Amazonas State, Brazil. Samples were collected in five areas; 4-, 10- and 20-year-old rosewood stands, and 15- and 60-year-old secondary forests. The latter two served as control treatments, reflecting natural spontaneous succession conditions over time. Soil was sampled at 10 equidistant points within each area to measure physicochemical attributes, and at the center of each one, a soil profile was dug for description and classification of morphological characteristics. Based on the profile description, the soils were classified as Xanthic Hapludox. The results show that soil conditions under 20-year-old rosewood stand resembled those beneath the 60-year-old secondary forest, and likewise for the soil under the 10-year-old rosewood stand and the 15-year-old secondary forest. The soil bulk density ranged from 0.81 to 0.99 $g\,cm^{-3}$ among all areas and no significant difference was found ($P = 0.052$). With exception to 4-year-old stand, the organic matter (2.68–5.87%) and carbon stock (18.57–31.71 $Mg\,ha^{-1}$) did not differ significantly between stands and control treatments. For the soil macronutrients, nitrogen (0.10–0.22%), phosphorus (1.17–11.70 $mg\,kg^{-1}$), calcium (0.03–0.31 $mg\,kg^{-1}$) and magnesium (0.02–0.16 $mg\,kg^{-1}$) were higher or equal in the rosewood stands in comparison to the two controls, while the potassium values (0.03–0.36 $mg\,kg^{-1}$) were significantly higher in 60-year-old secondary forests only compared to the 10-year-old rosewood stands ($P = 0.005$). The soil beneath the 4-year-old rosewood stand, however, differed from the other four areas, having significantly higher natural clay content (> 600 $g\,kg^{-1}$) and higher topsoil chemical concentrations, associated with the more recent burning. This result represents the first step in addressing concern about sustainable soil use in rosewood forestry economics. Consequently, this kind of rosewood plantation can be recommended as an appropriate use of historically exploited areas, providing economic return from local biodiversity.

## 1. Introduction

The rosewood (*Aniba rosaeodora* Ducke, Lauraceae) is an Amazonian tree species that was, for decades, over-exploited for its essential oil, which is in high demand in the world's fine perfumery industry (Fidelis et al., 2012; Krainovic et al., 2017a). The exploitation of this species initially followed a classic extractivist model, with individuals of all ages and sizes cut indiscriminately and with no attempt to regenerate populations (Sampaio et al., 2007). As a result, rosewood is now considered as an endangered species in the wild (IUCN, 2015).

In Brazil, existing legislation permits the commercialization of rosewood essential oils only when they have been obtained from commercial plantations (MMA, 2014; Krainovic et al., 2017a). Rosewood plantations have helped reduce the pressure on natural populations

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https://doi.org/10.1016/j.geoderma.2019.113952
Received 21 November 2018; Received in revised form 24 August 2019; Accepted 30 August 2019
Available online 10 September 2019

while maintaining genetic variability in the species and promoting income generation and employment (Krainovic et al., 2018). Thus, decision makers need guiding principles for the investment of limited resources into the cultivation of this species, and technical criteria must be developed. In addition, plantation forestry is among the options proposed by IPCC for mitigating deforestation and carbon emissions in the Amazon (IPCC, 2007; Fearnside et al., 2009; Fearnside, 2012). However, monoculture tree plantations can have negative effects on soil quality (Ferré et al., 2014). Soil quality is usually considered to have three main aspects: physical, chemical, and biological properties. All three aspects are important in assessing the extent of land degradation—e.g., the effects of land-use change and consequent ecosystem perturbation (Holubík et al., 2014) on C (carbon) and N (nitrogen) stocks and fluxes—or of amelioration, and for identifying management practices for sustainable land use (Dexter, 2004).

Understanding soil nutrient relationships, such as how soil nutrient supplies respond to growing forests over time, is important for managing successional forests, tree plantations, agroforestry systems and shifting cultivation agriculture (Richter et al., 1994). In the case of rosewood, the cultivated stands occupy the space that was once Amazonian forest, and their extraction by the removal of above ground biomass (whole tree, or the crown by pruning) can lead to a considerable removal of nutrients, which may decrease soil fertility and limit future productivity (Krainovic et al., 2017b; McMahon et al., 2019). Regarding physical aspects, textural porosity is barely affected by soil management; structural porosity, however, is sensitive to management factors such as tillage and cropping (Dexter, 2004; Spinelli et al., 2017). Such management systems, when mismanaged, may lead to poor workability, low water infiltration rates, modification of the water retention curve, and increased mechanical resistance of the soil to root growth, which may inhibit the absorption of nutrients. Consequently, impoverishment of soil bio-physical and chemical properties, a known effect of inappropriate land-use, may lead to environmental degradation (St. Clair and Lynch, 2010) at different scales and intensities (Cram et al., 2015) over time.

One way to obtain the knowledge of such soil changes over time is to study chronosequences (Chen et al., 2014). The essential elements of such studies are as follows: two or more stages of evaluation, multiple stand characteristics that vary across stages, at least one independent verification of time series, and standardized measurements (Walker et al., 2010). With these aspects in mind, this study aimed to compare soil nutrient relationships between land management systems, with a chronosequence of rosewood cultivation in the central Amazonian region, and the physical and chemical aspects of the soils on which rosewood stands grow.

## 2. Material and methods

### 2.1. Area description and plant materials

This study was conducted in five selected areas (Table 1) within a rural farm (03°32′44″S, 57°41′30″W) in the municipality of Maués, Amazonas State, Brazil. The administrative center of the municipality lies some 350 km west of Manaus, the Amazonas State capital. The climate in Maués is hot and humid, with regular and abundant rainfall and an annual rainfall of 1997 mm. The annual mean temperature is 27.2 °C (World Bank Climate Change Knowledge Portal | for global climate data and information, 2019).

During the 1950s, the pristine forest was slash-burned and converted to a commercial cultivation of guarana (*Paullinia cupana* Kunth, Sapindaceae). by the late 1970s, though, these plantations were converted to pastures of *Brachiaria* (Train.) and *Griseb sp.* (Poaceae). Later on, at the beginning of the 1990s, nursed seedlings originating from the natural rosewood population seed bank in the Maués region were established periodically, giving rise to rosewood stands and regeneration areas of different ages. Since the seedlings establishment in the field, the regenerated understory vegetation within the rosewood stands has undergone annual mowing.

All study areas are located on the banks of the Maués-Açu river, in a totally flat topography, and their borders are, at most, 100 m apart. Most of the original vegetation had been destroyed over the past few decades by excessive and intense farming, long-term overgrazing, and clearcutting for timber (Krainovic et al., 2017b). At present, the native vegetation has the physiognomy of secondary forest at different successional stages. The predominant soil textural class (particle size) of all study areas is clay, and the soils possibly suffer the same dynamics and directions of pedogenic evolution. All the study areas have the necessary characteristics, i.e. different stages and several characteristics that may vary along these stages, for conducting a chronosequence study (Walker et al., 2010) and an assessment of ecosystem restoration (Chen et al., 2014; Zhang et al., 2019). Such a study should improve our understanding of the interactions between soil and the plant community.

The studied soil profiles showed a similar horizon sequence ($Ah_1$, $Ah_2$, Ah-B, B1 and B2) and were classified as Xanthic Hapludox with gently rolling relief (Soil Survey Staff, 2014). They were also classified as dystrophic Red-Yellow Latosol according to the Brazilian Soil Classification System (EMBRAPA, 2006). All profiles were classified as very deep (C horizon depth $>$ 2 m) and have similar conditions in terms of transitional horizons, with a gradual distinctness and a wavy topography between borders (A/B and Ah/ B); homogeneous relief and good drainage, preventing the occurrence of reducing conditions (Araújo et al., 2010; Quesada et al., 2011); relatively homogeneous color, with reddish and/or yellowish hues (predominantly hues of 10YR ranging from 7.5YR to 10YR); and small variations in the classification of soil

**Table 1**
Description of study areas near Maués, Amazonas, Brazil.

| Soil management system | Description: cultivated and forest areas |
|---|---|
| Rosewood plantations (cultivated for four years): C4. | Rosewood seedlings planted in 2006, at 3.0 × 4.0 m spacing, following cutting and burning of the original vegetation. Litter layer Oh with 7 cm depth, and annual mowing during the dry season. Individual rosewood plants had a mean height of 4.41 ± 0.74 m (N = 10), and average diameter of 8.23 ± 1.78 cm. Total area = 0.4 ha. |
| Rosewood plantations (cultivated for ten years): C10. | Rosewood seedlings planted in 2000, at 3.0 × 4.0 m spacing, following cutting and burning of the original vegetation. Litter layer Oh with 5 cm depth, and annual mowing during the dry season. Individual rosewood plants had a mean height of 8.30 ± 1.63 m (N = 10), and average diameter of 11.63 ± 1.63 cm. Total area = 0.4 ha. |
| Rosewood plantations (cultivated for twenty years): C20. | Rosewood seedlings planted in 1990, at 5.0 × 5.0 m spacing, following cutting and burning of the original vegetation. Litter layer Oh with 5 cm depth, and annual mowing during the dry season. Individual rosewood plants had a mean height of 9.45 ± 1.92 m (N = 10), and average diameter of 13.27 ± 1.93 cm. Total area = 0.5 ha. |
| Secondary forest (fifteen years old): SF15. | Spontaneous forest, naturally regenerating with no human intervention. Thick leaf litter layer with 6 cm depth, vegetation predominantly trees and shrubs. Used as reference 1 (young spontaneous vegetation over time). Total area = 0.4 ha. |
| Secondary forest (sixty years old): SF60. | Native forest, naturally regenerating with no human intervention. Late secondary forest. Thick leaf litter (Oh = 10 cm depth), vegetation dominated by trees up to 30 m tall. Used as reference 2, older than SF15. Total area = 2 ha. |

and consistency (Table A.1).

### 2.2. Field sampling and laboratory methods

In each study area, the first soil sample was collected from a random point, and subsequent samples were collected at other, equidistant points within that area. Soil sampling and testing procedures have been described by Lemos and Santos (1996).

#### 2.2.1. Physical soil attributes

Ten single samples were collected in the wet season, at two depths: 0–10 cm and 10–20 cm. For soil bulk density (BD), 100 disturbed samples were collected using a 98 $cm^3$ volumetric ring. BD was calculated based on the ratio between dry mass of the soil samples (*dms* - dried at 105 °C) and the volumetric ring volume (*vrv*) - (BD = *dms* / *vrv*). The final BD value was the mean of the ten samples (10 pseudoreplicates) from each of the two depths at each of the five areas, totaling 100 samples. To quantify particle size distribution (PSD) for each area, we used the pipette-method particle-size analysis (Gee and Bauder, 1986). Another ten samples from each depth were homogenized and split into three composite samples, totaling 30 samples. The classification was done using percentages of clay (< 0.002 mm), silt (0.002 to 0.05 mm), and sand (0.05 to 2.0 mm) in the basic soil texture classes according to Soil survey field and laboratory methods manual (Burt and soil survey staff, 2014). In the center of each area, a soil profile pit was dug to allow morphological classification and soil description in accordance with the criteria established in the Keys to Soil Taxonomy (Soil Survey Staff, 2014).

#### 2.2.2. Chemical soil attributes

Soil samples for testing chemical attributes were obtained with a soil auger. In each area, 10 single samples were collected at the following depths: 0–10 cm; 10–20 cm; 20–30 cm; 30–40 cm. For each depth, the samples were homogenized and split into five composite samples per area, totaling 100 samples. All analyses were done at the Thematic Soil and Plant Laboratory (LTSP) of the National Institute for Amazonian Research - INPA. We obtained values for total nitrogen (N), pH in water, pH in KCl, exchangeable $Al^{3+}$, and contents of available P, $K^+$, $Ca^{2+}$, $Mg^{2+}$, $Zn^{2+}$, $Cu^{2+}$, $Mn^{2+}$, $Fe^{2+}$, $H^+ + Al^{3+}$, and organic matter (OM) by wet oxidation-redox titration method (Walkley-Black), considered valid if organic C is > 8% (Soil Survey Staff, 2014). Values (%) for C and N were determined by dry combustion using a VARIO MAX CN analyzer. The Murphy-Riley method (Murphy and Riley, 1962) was used to obtain values for P, with readings made using a UV–VIS 120–01 Shimadzu spectrophotometer. The concentration of other elements were determined using atomic absorption spectrophotometry via an air-acetylene flame, according to the methodology outlined in the Manual of Soil Analysis Methods (Teixeira et al., 2017). The magnitude of concentration of soil chemical attributes was classified following Moreira and Fageria (2009). With these data, we calculated the sum of bases (SB), effective cation exchange capacity ($CEC_{eff}$), total cation exchange capacity (CEC), base saturation (BS) and aluminum saturation (Al%). The soil carbon stock (CS) was calculated by multiplying organic carbon content (C), soil bulk density (BD), and depth of the layer (h): $CS = C \times BD \times h$.

### 2.3. Statistical methods

Multivariate statistical methods were used to test differences and similarities between soil attributes under different treatments. The principal component analysis (PCA) was used to characterize the ordination trends with the aid of graphic biplots of the first two principal components. This method reduces the dimensionality of the data, providing a smaller set of linear combinations of the obtained variables while still retaining most of the variation provided by the original variables, and makes it possible to evaluate the qualitative interactions of a variety of attributes simultaneously. The variables used in PCA were N, P, $K^+$, $Ca^{2+}$, $Mg^{2+}$, $Al^{3+}$, OM, SB, DpH (pH KCl - pH $H_20$), $CEC_{eff}$, BS and Al%. The points on the biplot graph of these variables are ordered by score values along the components 1 and 2. We ran a variance analysis (ANOVA) to evaluate the variation in the chemical attributes' scores along the first PCA component; in the original chemical attribute data; and in C, BD, CS and PSD. Means were tested for statistically significant differences, at a significance level of P = 0.05, and presented as percent of control mean. Post-hoc Tukey HSD (at P = 0.05) tests were applied to separate treatment means. The PCA and ANOVA were complemented with hierarchical grouping analysis, using Euclidean distance as a measure of data dispersal and the Ward method for grouping analysis. To aid the identification of within-group homogeneity and between-group heterogeneity, results were formatted as a dendrogram (Oliveira et al., 2015). All statistical analyses, conducted with *R* software (R Core Team, 2018), tested the hypothesis that this kind of land use may cause changes in the soil attributes.

## 3. Results

### 3.1. Physicochemical soil attributes

For all the study areas, soil particle size distribution was classified as clay. In each area, the clay fraction was predominant and increased with depth, ranging from 417 g $kg^{-1}$ in SF60 to 625 g $kg^{-1}$ in C4 (Table 2). Sand content was significantly lower in the C4 (Fig. 1a) compared to the other areas. Inversely, C4 had silt and clay contents significantly higher than the other areas (Fig. 1b and c), varying between 118 and 122 g $kg^{-1}$ and between 603 and 625 g $kg^{-1}$ respectively for each particle.

Organic carbon content (C) decreased with increasing depth, and although values are broadly similar in all areas (Table 2), they were significantly higher in C4 (P < 0.01; Fig. 1d), except in comparison with SF60 (P = 0.185). The BD ranged between 0.81 and 0.99 g $cm^{-3}$ among all areas. Despite lower BD values in C4, no significant difference was found (P = 0.052; Fig. 1e). The carbon stock results ranged between 20.74 and 31.71 Mg $ha^{-1}$ in all areas, and C4 again differed significantly from C10, SF15 and C20, though not from SF 60 (P = 0.397; Fig. 1f).

#### 3.1.1. Fertility soil attributes

Results of chemical analysis (Table 3) were consistent with the

**Table 2**
Physical attributes and variables with influence on soils under rosewood plantations and secondary forests: Total sand content, silt, clay, silt/clay (S/C), soil bulk density (BD), organic carbon (C) and carbon stock (CS).

| *Depth* | *Sand* | *Silt* | *Clay* | *S/C* | *BD* | *C* | *CS* |
|---|---|---|---|---|---|---|---|
| Cm | —— g $kg^{-1}$ —— | | | | g $cm^3$ | % | Mg $ha^{-1}$ |
| Rosewood plantations – four years old: C4. | | | | | | | |
| 0–10 | 279 | 118 | 603.2 | 0.20 | 0.93 | 3.4 | 31.71 |
| 10–20 | 253 | 122 | 625.2 | 0.19 | 0.81 | 2.8 | 22.60 |
| Rosewood plantations – ten years old: C10. | | | | | | | |
| 0–10 | 448 | 99 | 453.3 | 0.22 | 0.97 | 2.5 | 24.64 |
| 10–20 | 396 | 91.4 | 512.3 | 0.18 | 0.88 | 2.1 | 18.57 |
| Rosewood plantations – twenty years old: C20. | | | | | | | |
| 0–10 | 416 | 105 | 479.7 | 0.22 | 0.92 | 2.5 | 23.46 |
| 10–20 | 374 | 92.4 | 533.5 | 0.17 | 0.96 | 2.2 | 20.74 |
| Secondary forest – fifteen years old: SF15. | | | | | | | |
| 0–10 | 492 | 83.6 | 424.2 | 0.20 | 0.93 | 2.6 | 24.27 |
| 10–20 | 440 | 83.1 | 477.3 | 0.17 | 0.97 | 2.2 | 21.53 |
| Secondary forest – sixty years old: SF 60. | | | | | | | |
| 0–10 | 484 | 98.6 | 417.0 | 0.24 | 0.88 | 3.1 | 27.72 |
| 10–20 | 449 | 99.3 | 452.2 | 0.22 | 0.99 | 2.9 | 21.68 |

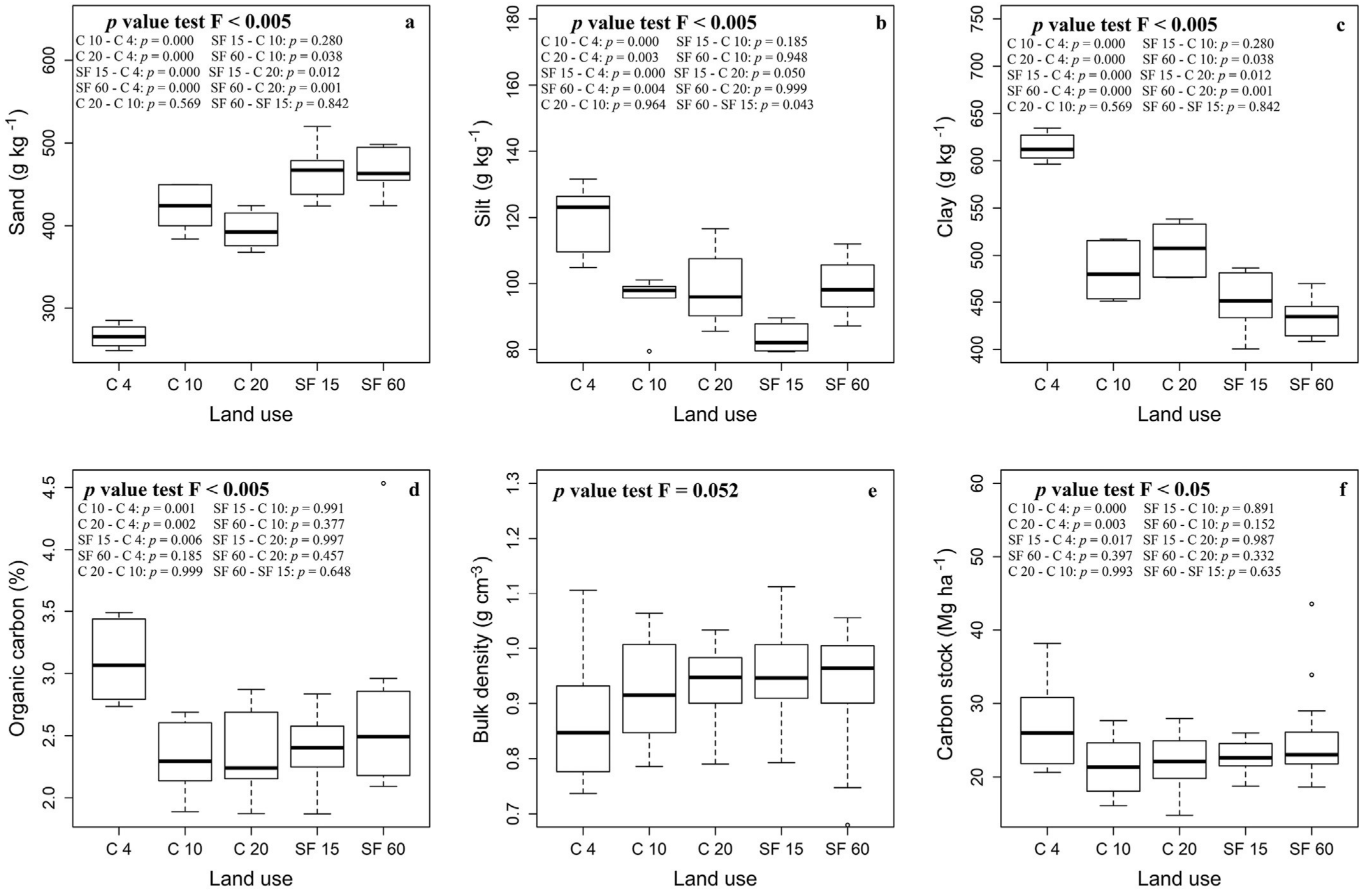


**Fig. 1.** Box plots and P values of mean tests comparing a) sand content; b) clay content; c) silt content; d) organic carbon (C); e) soil bulk density (BD); f) soil stock carbon and attributes data from rosewood plantations and secondary forest areas.

known low fertility of Amazonian Oxisols (Moreira and Fageria, 2009). The analysis of variance for each nutrient between different land use types is showed in Fig. A.1 (Appendices).

N levels were higher in C4 than in C10 and SF15 areas ($P < 0.05$ Fig. A.1a). N levels (0.10–0.22%) often vary greatly over short distances, leading to varied results, because N in its $NO^{-3}$ form is very soluble in water and, therefore, can be leached by rainwater into the subsoil (Raij, 1991).

The concentrations of available phosphorus varied among the areas: Very low concentrations ($\leq 2.7$ mg kg$^{-1}$) occurred in C20, SF15 and SF60 below 30 cm, and in C10 below 20 cm. Low concentrations (2.8–5.4 mg kg$^{-1}$) occurred in C4 at 30–40 cm; in C10, C20 and SF15 at 10–20 cm; and in SF60 at 0–10 cm. Medium concentrations (5.5–8.0 mg kg$^{-1}$) occurred in C4 at 20–30 cm, and in C10, C20 and SF15 at 0–10 cm. High concentrations (8.1–12.0 mg kg$^{-1}$), however, were found only in C4, in the 0–10 and 10–20 cm layers. In general P concentrations were higher in C4 and no significant difference was founded between the other areas ($P > 0.05$; Fig. A.1b). The above ranking follows that proposed by Moreira and Fageria (2009) for soils with particle size distribution classified as clay.

The soils have low levels of exchangeable bases ($Ca^{2+} < 0.4$; $Mg^{2+} < 0.15$; $K^{+} < 0.15$ cmol$_c$ kg$^{-1}$), except for $Mg^{2+}$ and $K^{+}$ in the upper soil layer of C4 (0.16 cmol$_c$ kg$^{-1}$) and SF 60 (0.36 cmol$_c$ kg$^{-1}$), respectively. As a result of low levels of exchangeable cations, the sum of bases (SB) was classified as either very low ($\leq 0.45$) or low (0.46–1.65), ranging from 0.1 to 0.6 cmol$_c$ kg$^{-1}$. The highest levels of exchangeable bases were found in soil layers in the C4 area. The $K^{+}$ concentration was higher in SF60 area with significant difference with C10 ($P = 0.005$; Fig. A.1c) while in general, a significant difference was founded between C4 and the other areas for $Ca^{2+}$ and $Mg^{2+}$ (Fig. A.1d and A.1e).

The results for base saturation (BS) indicated a nutrient-poor character ($BS < 35\%$) with very low base saturation ($\leq 20.0$) in all areas. CEC values ranged from moderate (4.31–8.60 cmol$_c$ kg$^{-1}$) to high (8.61–15.00 cmol$_c$ kg$^{-1}$) and were within the range (3–15 cmol$_c$ kg$^{-1}$) for soils with high levels of kaolinite (Wutke and Camargo, 1975).

The pH levels of soil in water were very low ($pH < 4.5$), according to soil reaction classes. pH increased with soil depth, ranging from 3.6 to 4.1 in C4, and from 3.7 to 4.0 in SF60, in the uppermost and deepest sampled layers, respectively. There were some exceptions, often due to disagreement between the two methods of calculating pH. The DpH, used to estimate load equilibrium, revealed net negative charge values in all layers of the study areas (land uses). The exchangeable aluminum contents of the five areas were high (1.01–2.00) and very high (> 2.00), ranging from 1.8 cmol$_c$ kg$^{-1}$ in SF60 to 3.1 cmol$_c$ kg$^{-1}$ in C4. The aluminum saturation was considered very high (> 75%) in all soil layers of all study areas.

The secondary forest soils appear to be similar to those under rosewood plantations. This is shown in the PCA biplot graph (Fig. 2), where there is either total or partial overlap of all data sets. PCA analyses, performed separately for each depth, showed the same ordering trends as for all the data together (Appendices, Figs. A.2 to A.5).

The first two principal components (PC1 and PC2) accounted for 76.3% of the total data variance and showed gradients between major and minor values that correlate with the axes (components). PC1 explained 59.7% of the total data variance, correlating positively with 10 of the 12 variables but negatively with the other two variables, Al% and DpH. The gradient of nutrient content along PC1 had strong positive correlation with the sum of bases (loading = 0.35) and was influenced mainly by the values of $Mg^{+2}$, P and $Ca^{+2}$, but also somewhat by $Al^{+3}$

**Table 3**
Chemical attributes of soils under rosewood plantations and secondary forest environments.

| Depth | pH | | DpH | N | OM | P | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ | $Al^{3+}$ | H + Al | SB | CEC | | BS | AlS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $H_2O$ | KCL | | | | | | | | | | | eff | pot | | |
| cm | | | | — % — | | mg $kg^{-1}$ | | cmol$_c$ $kg^{-1}$ | | | | | | | — % — | |
| Rosewood plantations – four years old: C4. | | | | | | | | | | | | | | | | |
| 0–10 | 4.16 | 3.62 | −0.54 | 0.22 | 4.37 | 11.7 | 0.08 | 0.31 | 0.16 | 3.10 | 11.30 | 0.6 | 3.6 | 12 | 5 | 87 |
| 10–20 | 3.99 | 3.67 | −0.31 | 0.18 | 3.64 | 9.43 | 0.06 | 0.19 | 0.08 | 3.00 | 9.94 | 0.3 | 3.3 | 10 | 3 | 90 |
| 20–30 | 4.27 | 3.80 | −0.46 | 0.14 | 3.26 | 5.97 | 0.04 | 0.20 | 0.06 | 2.40 | 8.13 | 0.3 | 2.7 | 8.4 | 4 | 89 |
| 30–40 | 4.33 | 4.09 | −0.23 | 0.14 | 2.79 | 4.17 | 0.05 | 0.15 | 0.05 | 2.30 | 7.29 | 0.3 | 2.6 | 7.5 | 3 | 90 |
| Rosewood plantations – ten years old: C10. | | | | | | | | | | | | | | | | |
| 0–10 | 3.99 | 3.70 | −0.28 | 0.18 | 4.38 | 7.24 | 0.06 | 0.07 | 0.09 | 2.90 | 10.5 | 0.2 | 3.1 | 11 | 2 | 93 |
| 10–20 | 4.21 | 3.91 | −0.29 | 0.14 | 3.72 | 3.77 | 0.04 | 0.05 | 0.05 | 2.50 | 8.29 | 0.1 | 2.6 | 8.4 | 2 | 95 |
| 20–30 | 4.31 | 4.03 | −0.28 | 0.12 | 3.77 | 2.08 | 0.03 | 0.05 | 0.05 | 2.30 | 7.29 | 0.1 | 2.5 | 7.4 | 2 | 108 |
| 30–40 | 4.41 | 4.06 | −0.35 | 0.11 | 3.02 | 1.20 | 0.03 | 0.05 | 0.03 | 2.00 | 6.13 | 0.1 | 2.2 | 6.2 | 2 | 83 |
| Rosewood plantations – twenty years old: C20 | | | | | | | | | | | | | | | | |
| 0–10 | 3.94 | 3.91 | −0.03 | 0.18 | 5.87 | 6.26 | 0.11 | 0.06 | 0.08 | 2.80 | 9.54 | 0.3 | 3.0 | 9.8 | 3 | 92 |
| 10–20 | 4.16 | 4.08 | −0.08 | 0.15 | 4.80 | 3.14 | 0.05 | 0.06 | 0.05 | 2.40 | 7.99 | 0.2 | 2.5 | 8.2 | 2 | 94 |
| 20–30 | 4.17 | 4.06 | −0.11 | 0.14 | 3.95 | 3.12 | 0.08 | 0.05 | 0.06 | 2.40 | 8.08 | 0.2 | 2.6 | 8.3 | 2 | 93 |
| 30–40 | 4.24 | 4.03 | −0.21 | 0.12 | 3.49 | 1.67 | 0.06 | 0.06 | 0.06 | 2.20 | 6.56 | 0.2 | 2.3 | 6.7 | 3 | 93 |
| Secondary forest – fifteen years old: SF15. | | | | | | | | | | | | | | | | |
| 0–10 | 3.98 | 3.76 | −0.21 | 0.18 | 4.49 | 5.72 | 0.07 | 0.03 | 0.05 | 2.40 | 9.25 | 0.2 | 2.5 | 9.4 | 2 | 93 |
| 10–20 | 4.09 | 3.82 | −0.27 | 0.14 | 3.82 | 3.42 | 0.03 | 0.03 | 0.03 | 2.30 | 8.36 | 0.1 | 2.4 | 8.5 | 1 | 96 |
| 20–30 | 4.16 | 3.85 | −0.31 | 0.14 | 3.83 | 2.77 | 0.04 | 0.03 | 0.03 | 2.30 | 8.18 | 0.1 | 2.4 | 8.3 | 1 | 97 |
| 30–40 | 4.34 | 3.90 | −0.44 | 0.11 | 3.10 | 1.51 | 0.03 | 0.03 | 0.02 | 2.10 | 7.08 | 0.1 | 2.2 | 7.2 | 1 | 96 |
| Secondary forest – sixty years old: SF 60. | | | | | | | | | | | | | | | | |
| 0–10 | 4.00 | 3.73 | −0.26 | 0.22 | 5.43 | 5.20 | 0.36 | 0.07 | 0.09 | 2.50 | 8.78 | 0.5 | 3.0 | 9.3 | 6 | 83 |
| 10–20 | 4.20 | 3.91 | −0.29 | 0.14 | 3.77 | 2.98 | 0.06 | 0.05 | 0.06 | 2.10 | 8.30 | 0.2 | 2.3 | 8.5 | 2 | 93 |
| 20–30 | 4.31 | 3.97 | −0.34 | 0.13 | 3.66 | 2.38 | 0.06 | 0.06 | 0.05 | 2.00 | 7.52 | 0.2 | 2.2 | 7.7 | 2 | 83 |
| 30–40 | 4.48 | 4.02 | −0.46 | 0.10 | 2.68 | 1.17 | 0.12 | 0.04 | 0.04 | 1.80 | 6.38 | 0.2 | 2.0 | 6.6 | 3 | 100 |

**DpH** = (pH KCl - pH H20); **CEC:** eff: effective cation exchange capacity, pot: potential cation exchange capacity; **BS:** Base saturation; **N:** Nitrogen; **MO**: Organic matter **P**: Phosphorus; $\mathbf{K^+}$: Potassium; $\mathbf{Ca^{2+}}$: Calcium; $\mathbf{Mg^{2+}}$: Magnesium; **H + Al**: Acid saturation expressed in hydrogen + aluminum; **SB**: sum of bases; **AlS:** Aluminum saturation.

(loading > 0.30). PC2 explained 16.6% of the total data variance, had the highest negative correlation with base saturation (BS) (loading = −0.43), and was strongly influenced by $K^+$ (loading = −0.34) and $Ca^{+2}$ (loading = −22). The other eight of the twelve variables, but especially Al% and CEC (loading = 0.39 and 0.33, respectively), correlated positively with PC2. The highest nutrient content was found in C4, and the soil chemical attributes under this area showed distinct ordination, resulting in less overlap with other areas, which was confirmed by differences found in the analysis of variance. The results indicate that C4 soils differed from those of all other areas ($P < 0.01$), while the other areas did not differ significantly among themselves (Fig. 3). In general, the same trend was observed in the results of the ANOVA with original chemical attribute data (Fig. A.1).

The hierarchical grouping analysis (Fig. 4) shows grouping consistent with the PCA data, the ANOVA results, and mean tests. The dendrogram confirms our results showing two groups. The first group consisted of C4, while the other comprised all other areas. This second group contained two subgroups, showing similarity clusters for cultivated and secondary forests. The second sub-group is distinguished by further clustering: C20 and SF60 are highly proximate, suggesting that the soil beneath older rosewood plantations closely resembles that under natural forest; the soil under SF15 has a closer resemblance to C10.

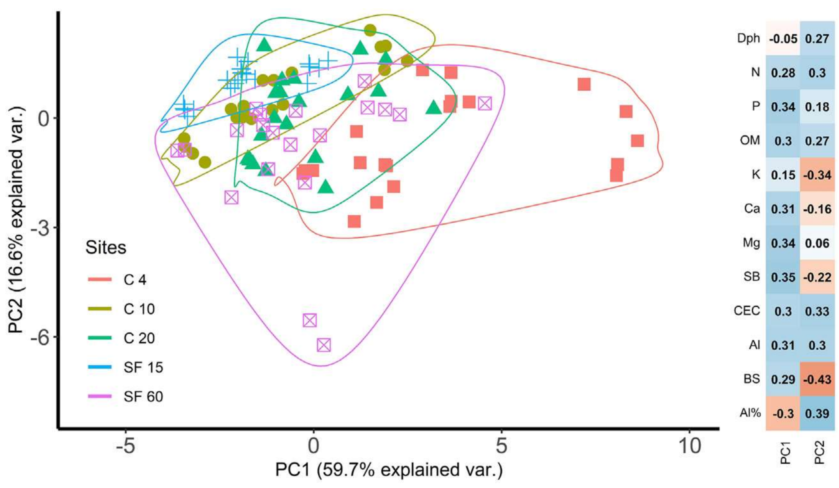


**Fig. 2.** Biplot graph with first two principal components (PC 1 and PC 2) showing the ordering of soil chemical attribute data from rosewood plantations and secondary forest areas. The bar represents the loading values in the principal components. Positive values are in blue and negative in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

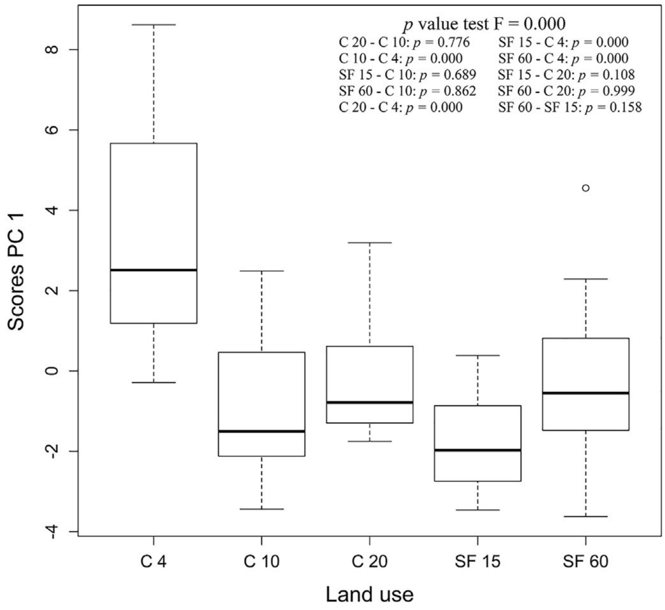


**Fig. 3.** Box plot and P values of mean tests comparing PC 1 scores from the ordering of chemical soil attributes.

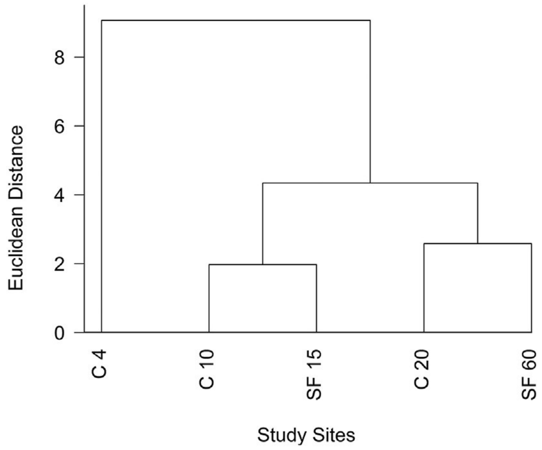


**Fig. 4.** Euclidean distance dendrogram showing the grouping among rosewood plantations and secondary forest areas.

## 4. Discussion

### *4.1. Particle size distribution, bulk density, and organic carbon*

Particle size variations between clay and clay-sand are common in tropical Oxisols (Santos et al., 2018), and although the particle size classification was the same for all areas, clay content in C4 was significantly higher (> 600 g $kg^{-1}$) than in the other study areas. Negative charge was recorded despite the intense weathering commonly seen in tropical latitudes. This confirms the kaolinite mineralogical nature of the clays that compose the colloidal layer of soil, retaining nutrients in even highly weathered soils (De Souza Braz et al., 2013; Pal and Marschner, 2016).

Oxisols have lower silt content in relation to clay. The silt/clay ratio, a parameter used to evaluate the state of soil evolution, was lower than 0.7 (Ker, 2013). This reinforces the interpretation of the chemical attributes as indicating a low level of natural fertility, which is common in tropical regions (Moreira and Fageria, 2009; Ker, 2013).

Soil bulk density plays an important role in hydrological processes, which are essential to the supply and storage of water, nutrients and oxygen in the soil (Primavesi 2002), reflecting the importance of organic matter and clay content. Although not statistically significant, the low BD value found in the subsurface layer of C4 can be explained by its high value of soil carbon. C4 also had the highest clay content, the soil variable that, by itself, has the highest predictive power for variation in soil density (Barros and Fearnside, 2015). According to the USDA (2008), the ideal soil bulk density for plant growth in clay soils is below 1.10 g $cm^{-3}$, and this was found both in secondary forests and in plantation areas, where Kuykendall (2008) found no physical properties that could decelerate nutrient absorption by plants. In addition, BD values were lower than the threshold considered to limit root growth, suggesting that there was no impact on this soil property after 20 years of cultivation. Given that density values between 0.80 and 1.20 mg $m^{-3}$ are characteristic of non-cultivated soil (USDA 2008), our results confirm the absence of impact by the rosewood stands on BD levels.

Another important attribute influencing BD is soil organic matter (OM), which contributes to the formation of aggregates, pore space in the structured layer, and nutrient cycling in Amazonian soils (Luizão, 2007; Marques et al., 2015; Marques et al., 2016). OM can be maintained in the soil through biochemical processes associated with the climate of the Amazon region (Araujo et al., 2017). Yet while such mechanisms can maintain a stable soil OM content, human intervention can result in elevated soil organic matter levels (Raij, 1991). OC levels reflect the accumulation of decomposed leaves and branches (OM) on the soil surface. In the plantations, however, decomposition of rosewood leaves and branches is slow, as the terpene content from secondary metabolism (Krainovic et al., 2018) has a low decomposition rate (Adamczyk et al., 2018). It was, instead, the annual mowing of the naturally regenerated vegetation that contributed to the observed organic matter in the plantations and maintained the organic carbon at levels similar to those found in mature rosewood stands and in spontaneous areas.

The land-use history of area C4 reveals that its higher organic carbon content is related to the decomposition of forest leaf litter prior to removal of the natural vegetation—exceeding that of the other areas—and to the time that elapsed between the initial slash-and-burn of original vegetation and the soil sampling campaign. Thus, to address the concept of chronosequence and its link to soil development, we included another important variable: a disturbance at some point along the time series. Removal of the natural vegetation led to root decomposition and organic acid exudation in the deeper layers, which then contributed to acidification—a common tendency linked to afforestation (Holubík et al., 2014)—helping to slow mineralization (Malavolta, 1987; Moreira and Costa, 2004; Chen et al., 2017) and increase organic matter retention. In fact, the resemblance between C4 an SF60 was not expected, due the tree species' effect on soil carbon stocks (Lorenz and Thiele-Bruhn, 2019), but the elapse of time after conversion in C4 explains the lack of significant difference between these areas.

### *4.2. Land use effects on soil nutrients*

Although there are no published nutritional recommendations for the rosewood plant, the apparent health of the studied stands suggest that the soil nutrient levels are adequate and meet the plant's requirements. The leaves were free of the light green to yellow coloring that often indicates low N concentrations and generalized chlorosis (Dechen and Nachigall, 2007), and no other visual symptoms were present, suggesting that the measured nutrient levels do not restrict the development of rosewood over time. The higher levels of $Ca^{2+}$, $Mg^{2+}$ and P in the C4 area, compared to the other areas, reflect their recent release from ash derived from burned wood, which can increase soil fertility temporarily (Moreira and Fageria, 2009; De Souza Braz et al., 2013). In general, the levels of exchangeable bases are in line with results of previous research, which reported that soil nutrient stocks do not threaten sustainability of plantation forests over time, and that stocks are maintained after multiple rotations in Brazilian Eucalyptus plantations (McMahon et al., 2019), even with organic certification of rosewood production. In the particular case of $K^+$, depletion may occur within 2–3 years of cultivation (Gomes de Souza et al., 2007), which explains the significantly higher content in area SF60, the hypothesis being that $K^+$ levels return to normal through nutrient cycling after the initial growth.

The higher nutrient levels in C4, compared to the other land uses, reflect a strong affinity of cations for the exchange surfaces present in the soil (Oliveira et al., 2015). The colloidal particles generally exhibit a balance of negative charges (-), which facilitate the soil's adsorption and retention of oppositely charged ions (Breiner et al., 2006; Novais and Mello, 2007) and reduce the potential for leaching. Phosphate adsorption increases with high clay contents (Souza et al., 2009), and it may also be influenced by the oxidation of iron and aluminum, two elements that occur at elevated concentrations in weathered tropical soils (Rolim Neto et al., 2004). However, the extent of this influence is not fully comprehended (Barthès et al., 2008). A more recent study suggests, contrary to some findings regarding the matter, that particle size distribution, among other soil properties, has little importance for carbon retention and stabilization (Araujo et al., 2017) and, therefore, for soil quality.

Low P content is one of the main factors limiting the development of Amazonian agriculture. P levels in the upland soils of the Brazilian Amazon are, on average, $< 5\ mg\ kg^{-1}$ (Da Silva and de Souza Falcao, 2004; Sohng et al., 2017). In the state of Amazonas, they are $< 5.4\ mg\ kg^{-1}$ (Moreira and Fageria, 2009). A deficiency of this element results in undersized plants; the appearance of necrosis on the leaves, fruit and stems; and leaves that are twisted and a reddish-purple color (Dechen and Nachigall, 2007; Gan et al., 2016). The absence of such symptoms in the studied area suggests that the natural P concentrations are, at least in the sampled top layer of all land uses, sufficient for rosewood growth.

Furthermore, acid soils with a predominance of clay 1:1 (kaolinite), such as those studied here, can have high $Al^{3+}$ activity (Gomes de Souza et al., 2007). High levels of exchangeable aluminum can impair the absorption of nutrients even when they are abundant and available in the soil (Mariano et al., 2015). The levels of acidity recorded in the current study may be explained by the relationship between acidity in Amazonian soils and both the nature of the parent material and the removal of basic cations through crop uptake (Gomes de Souza et al., 2007). Moreover, Moreira and Fageria (2009) posit that areas under cultivation may have a tendency for increased acidity over time, as a result of the progressive decrease in bases. However, our chronosequence results did not show that effect. Rather, pH levels increased with depth, which can be attributed to the decreased concentration of organic acids.

Effective soil management requires an understanding of the temporal and spatial alterations caused by changes in land use (Lindell et al., 2010). In one tropical rain forest in the north of Nigeria, Adejuwon and Ekanade (1988) observed that, after 15 years of different crops (fallow, cocoa and kola), soil chemical properties were significantly different from those in the adjacent forest, with a significant reduction of OC, N, $Ca^{+2}$ and $Mg^{+2}$ ($P < 0.01$). For tropical soils with a clay fraction dominated by kaolinite, OM contributes about 20–90% of the CEC, mainly in the surface layers (Ketrot et al., 2013; Khawmee et al., 2013). Although monocultures tend to have a lower rate of return of nutrients to the soil surface via cycling (Adejuwon and Ekanade, 1988), our results show no such reduction of C, N, $Ca^{+2}$ and $Mg^{+2}$ in the soil over time.

In the Peruvian Amazon, Lindell et al. (2010) compared soils cultivated for over 10 years (farm fields, coffee plantations and pastures) to soils of secondary forests, obtaining results similar to the present study. Paul et al. (2010) also found similar results for secondary forests and plantations: PCA analysis found a clear separation between pastures and forest environments, and ANOVA and Tukey test on PC1, based on eight nitrogen-related soil properties, showed significant differences, with reforested areas being intermediate between pasture and forest.

PCA analysis is considered highly effective in distinguishing the most significant variables in pedogenic processes; such was the case here, even though the PCA did not specifically differentiate soils by land use type. The C10, C20 and SF15 environments almost entirely overlapped SF60, while C4 showed partial superimposition over SF60, without a distinct characterization for each treatment. The separation of C4 in the biplot graph is explained by the use of fire in the latest conversion of forest to rosewood stand, and by the high SB value and high clay content in the area (clay $> 600\ g\ kg^{-1}$; $P < 0.05$). It is noteworthy that, in C4, most of the SB values were due to significantly higher $Ca^{+2}$ and $Mg^{+2}$ values, which, in addition to P concentration, showed a high correlation with PC1. Finally, the clustering demonstrated the natural characteristics of C4 and the similarity between older rosewood cultivation and spontaneous areas.

Recent publications highlight the opportunity for above ground biomass management in rosewood plantations (Krainovic et al., 2017a, 2017b). This supply chain can benefit from the various chemical qualities of the essential oil extracted from different harvest rotations (Krainovic et al., 2018). However, this type of management leads to a great export of nutrients (Krainovic et al., 2017b). Thus, the sum of the results of all analyses shows that rosewood cultivation is not responsible for the differences observed between land use types. Thus, the main hypothesis is rejected, and rosewood cultivation in small commercial plantations does not change soil properties, at least not on the time scale and in the kind of production and management systems investigated here. Thus, these results may serve as a basis for the development of alternative restoration proposals that provide greater integration of markets with local socio-economic development, balancing the ecosystem services market with that of goods and services necessary for the maintenance of populations in rural areas.

## 5. Conclusions

Soils underneath mature rosewood plantations are physically and chemically similar to those beneath secondary forests, suggesting that the species may serve as a viable land use alternative for restoration programs. Additionally, the soil layers under plantations have nutrient values that are not adverse to rosewood growth. After 20 years of conversion from native forest to small productive rosewood stands, soil attributes have not suffered a qualitative reduction, even with management of the aboveground biomass. This study shows that the poor, highly weathered soils of the Amazon region can remain in a physicochemical state similar to the soils under secondary forests, even after anthropic use. However, there is a need for studies that control for the initial state of fertility and other experimental variables to unravel the exclusive effect that the planting regimen has on the soils. Replications of research using different rosewood plantation types under different soil and climate conditions, and with different historical usages, would also be highly desirable.

## Acknowledgements

Authors thank Mr. Carlos and Zanoni Magaldi for the opportunity to conduct the study at their property; they also thank CNPq - National Counsel of Technological and Scientific Development, FAPEAM - Foundation Support Research in the State of Amazonas (grant 016/2013 - POSGRAD 2013 - INPA), and FAPESP - Foundation Support Research in the State of São Paulo (grant 2016/05219-9) for funding.

## Appendix A

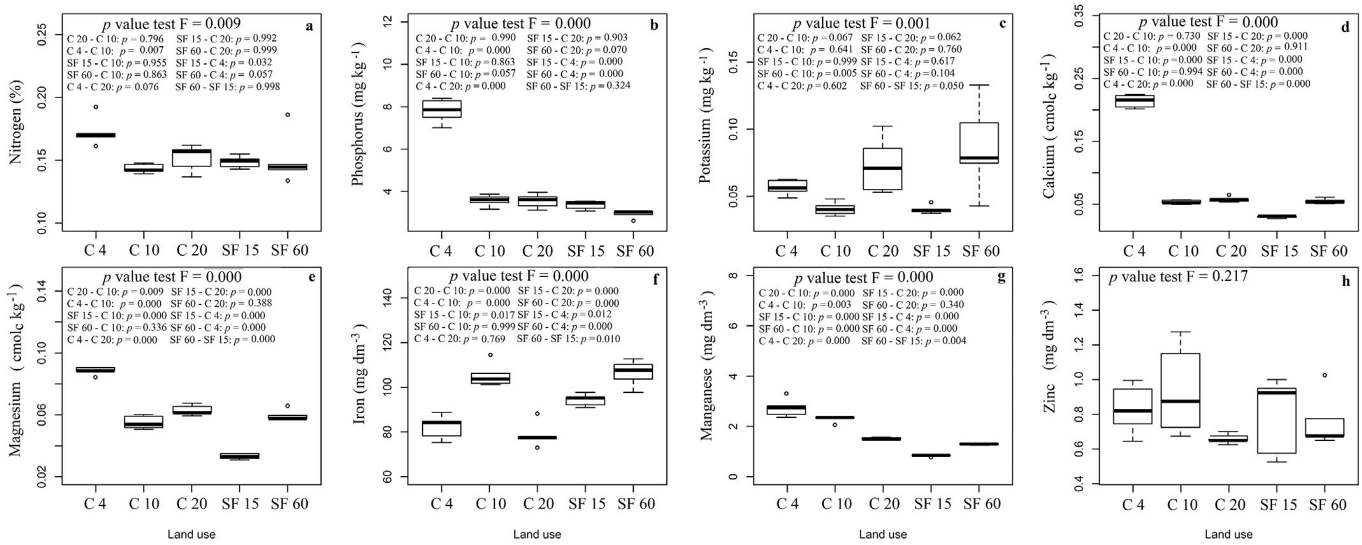


**Fig. A.1.** Box plot and P values of mean tests comparing soil chemical attribute data for land use types in the five study areas. a) Nitrogen; b) Phosphorus; c) Potassium; d) Calcium; e) Magnesium; f) Iron; g) Manganese Zinc and; h) Zinc.

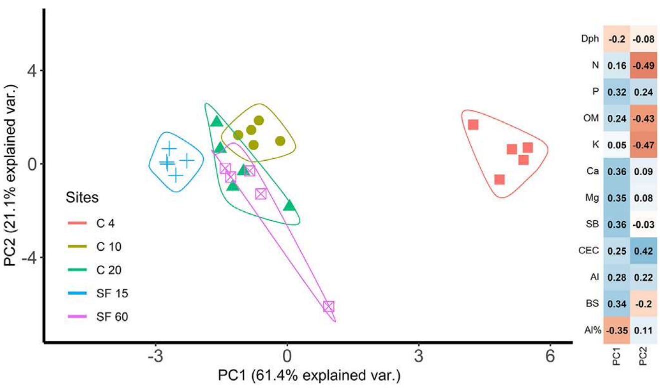


**Fig. A.2.** Ordination of rosewood plantations and secondary forest areas in terms of soil chemical attributes (0–10 cm depth). The bar represents the loading values in the principal components. Positive values are in blue and negative in red.

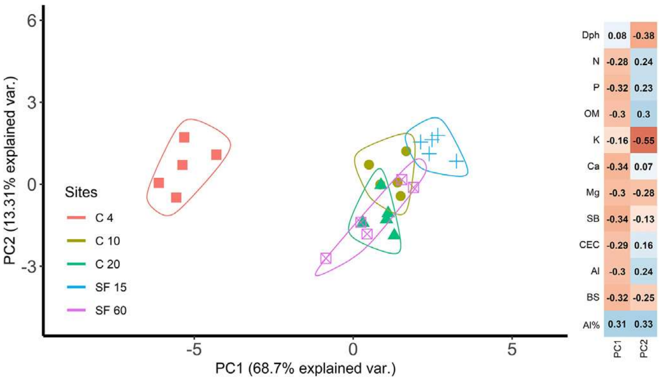


**Fig. A.3.** Ordination of rosewood plantations and secondary forest areas in terms of soil chemical attributes (10–20 cm depth). The bar represents the loading values in the principal components. Positive values are in blue and negative in red.

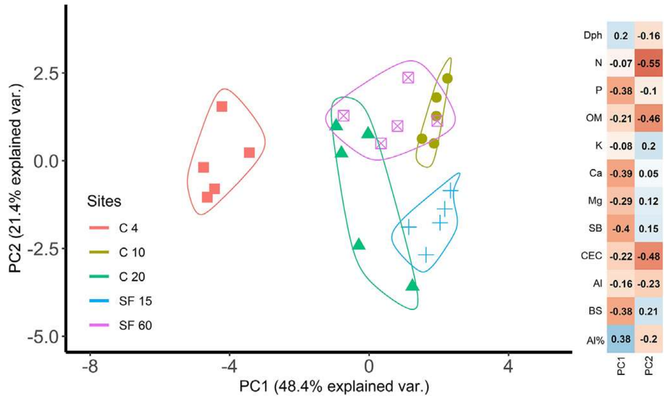


**Fig. A.4.** Ordination of rosewood plantations and secondary forest areas in terms of soil chemical attributes (20–30 cm depth). The bar represents the loading values in the principal components. Positive values are in blue and negative in red.

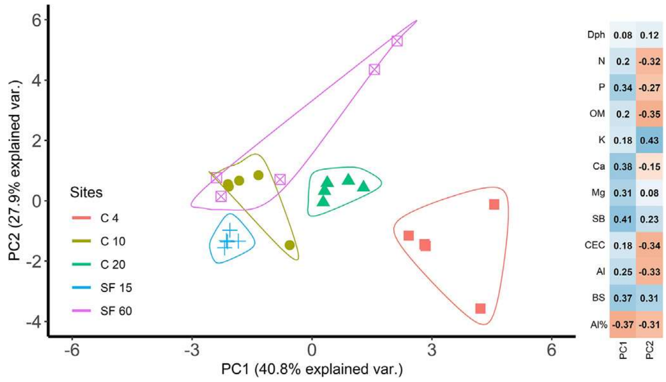


**Fig. A.5.** Ordination of rosewood plantations and secondary forest areas in terms of soil chemical attributes (30–40 cm depth). The bar represents the loading values in the principal components. Positive values are in blue and negative in red.

Table A.1
Morphological attributes of soils under rosewood plantations and secondary forest environments: color (moist), structure, consistency (dry, moist and wet) and texture.

| Hor. | Depth (m) | Color (moist) | Structure[a] | Consistency[b] | | | Textural class |
|---|---|---|---|---|---|---|---|
| | | | | Dry | Moist | Plasticity[c] and Stickiness[d] | |
| Profile 1: Rosewood plantations four years old - C4 | | | | | | | |
| $Ah_1$ | 0–0.08 | 10 YR 3/1 | 1GR | LO | FR | NPL NST | Clay loam |
| A $h_2$ | 0.08–0.29 | 10 YR 3/2 | 1GR | LO | FR | SPL NST | Clay loam |
| Ah-B | 0.29–0.65 | 10 YR 5/4 | 1sb | SO | FI | PL NST | Clay |
| $B_1$ | 0.65–0.98 | 10 YR 6/8 | 1sb | SHA | FI | PL NST | Clay |
| $B_2$ | 0.98–1.37 | 10 YR 7/8 | 2sb | SHA | FI | PL SST | Clay |
| $B_3$ | 1.37–1.90 + | 7.5 YR 7/8 | 2sb | SHA | VFI | PL SST | Clay |
| Profile 2: Rosewood plantations ten years old - C10 | | | | | | | |
| $Ah_1$ | 0–0.10 | 7.5 YR 3/2 | 1GR | SO | VFI | NPL NST | Clay |
| A $h_2$ | 0.10–0.26 | 10 YR 3/2 | 1GR | SO | VFI | SPL SST | Clay |
| Ah-B | 0.26–0.45 | 10 YR 4/3 | 3sb | SO | VFI | SPL SST | Clay |
| $B_1$ | 0.45–0.70 | 10 YR 5/6 | 2sb | SO | VFI | SPL SST | Clay |
| $B_2$ | 0.70–0.95 | 10 YR 5/6 | 2sb | SO | VFI | PL SST | Clay |
| $B_3$ | 0.95–1.40 | 10 YR 6/6 | 2sb | SO | VFI | PL SST | Clay |
| $B_4$ | 1.40–1.70 + | 10 YR 6/6 | 2sb | SO | VFI | PL SST | Clay |
| Profile 3: Rosewood plantations twenty years old - C20 | | | | | | | |
| $Ah_1$ | 0–0.09 | 10 YR 3/2 | 1GR | SO | FI | SPL SST | Sandy clay |
| A $h_2$ | 0.09–0.35 | 10 YR 3/2 | 1GR | SO | VFI | SPL SST | Clay |
| Ah-B | 0. 35–0.65 | 10 YR 5/4 | 1GR | SHA | FI | SPL NST | Clay |
| $B_1$ | 0.65–1.07 | 10 YR 6/6 | 2sb | SHA | FI | PL SST | Clay |
| $B_2$ | 1.07–1.70 + | 10 YR 6/8 | 2sb | SHA | FI | PL SST | Clay |
| Profile 1: Secondary forest fifteen years old - SF15 | | | | | | | |
| $Ah_1$ | 0–0.16 | 10 YR 2/2 | 1GR | SO | FR | SST | Clay loam |
| A $h_2$ | 0.16–0.34 | 10 YR 3/2 | 1GR | SO | FR | SST | Clay loam |
| Ah-B | 0.34–0.58 | 10 YR 3/4 | 1GR | SO | FR | PL S | Clay |
| $B_1$ | 0.58–0.92 | 10 YR 5/6 | 2BLsb | SHA | FR | PL S | Clay |
| $B_2$ | 0.92–1.39 | 7.5 YR 6/8 | 2BLsb | SHA | FR | PL S | Clay |

(*continued on next page*)

Table A.1 (*continued*)

| Hor. | Depth (m) | Color (moist) | Structure[a] | Consistency[b] | | | Textural class |
|---|---|---|---|---|---|---|---|
| | | | | Dry | Moist | Plasticity[c] and Stickiness[d] | |
| $B_3$ | 1.39–1.90 + | 7.5 YR 6/8 | 2BLsb | HA | FR | PL S | Clay |
| Profile 5: Secondary forest sixty years old - SF60 | | | | | | | |
| $Ah_1$ | 0–0.10 | 10 YR 3/2 | 1GR | SO | FI | PL SST | Clay |
| A $h_2$ | 0.10–0.27 | 10 YR 4/2 | 1GR | SO | FI | PL SST | Clay |
| Ah-B | 0. 27–0.59 | 10 YR 5/4 | 1GR | SO | FI | VPL SST | Clay |
| $B_1$ | 0.59–0.93 | 10 YR 6/6 | 2sb | SO | FI | VPL SST | Clay |
| $B_2$ | 0.93–1.56 + | 10 YR 6/6 | 2sB | SO | FI | VPL SST | Clay |

Colors - 10 YR 2/2: Very dark Brown; 10 YR 3/2: Very dark grayish brown; 10 YR 3/4: Dark yellowish brown; 10 YR 5/6: Yellowish brown; 7.5 YR 6/8: Reddish yellow; 10 YR 4/2: Dark grayish brown; 10 YR 5/4: Yellowish brown; 10 YR 6/6: Brownish yellow; 10 YR 3/1: Very dark gray; 10 YR 3/2: Very dark grayish brown; 10 YR 6/8: Brownish yellow; 10 YR 7/8: Yellow; 7.5 YR 7/8: Reddish yellow; 7.5 YR 3/2: Dark brown; 10 YR 4/3: Brown.

[a] **Structure**: 1 - weak; 2 - moderate; 3 - strong; GR: granular; sb: subangular blocky.

[b] **Consistency**: LO: loose; SO: soft; SHA: slightly hard; HA: hard; VFR: very friable; FR: friable; FI: firm; VFI: very firm.

[c] **Plasticity**: NPL: non-plastic; SPL: slightly plastic; PL: plastic; VPL: very plastic.

[d] **Stickiness**: NST: non-sticky; SST: slightly sticky; S: sticky; VST: very sticky.

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