

Soil fertility management in indigenous homegardens of Central Amazonia, Brazil

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Abstract Homegardens in an upland forest area in the Kwata-Laranjal indigenous territory (state of Amazonas, central Amazonia) were studied to assess how their management contributes to soil fertility. The characteristics of the homegarden soil were compared with those of adjacent primary and secondary forest, at soil depth of 0–10, 10–20 and 20–30 cm. Significant homegarden effects were observed, which raised pH (H₂O) (4.3–4.4 at 0–20 cm) and phosphorus content (5–14 mg kg⁻¹ at 0–30 cm); and decreased the content of calcium (0.1 cmol_c kg⁻¹ at 20–30 cm). At the same time, levels observed in homegardens for aluminum (3.0–3.2 cmol_c kg⁻¹), organic carbon (11–13 g kg⁻¹), calcium (0.24–0.38 cmol_c kg⁻¹ at 0–20 cm), magnesium (0.08–0.20 cmol_c kg⁻¹) and potassium (0.06–0.10 cmol_c kg⁻¹) were not significantly different from those of primary and secondary

forest. These results indicate that the management of these homegardens contributes to maintain or increase soil fertility. However, feasible management options to increase the content of these soils in carbon, calcium, magnesium and potassium are highly desirable.

Keywords Soil management · Nutrients · Organic carbon · Primary and secondary forests

Introduction

Agroforestry represents a key pathway for the reorientation of agricultural land use in Amazonia, towards combining productivity and sustainability, while improving access to adequate alimentation and human wellbeing (Porro et al. 2012). Several recent publications explore this approach. Studying 38 farms in the states of Pará and Maranhao (eastern Amazonia, Brazil), Cardozo et al. (2015) concluded that, compared to pastures with babassu palm (*Attalea speciosa* Mart.) and slash-and-burn cultivation, all other agroforestry systems presented a higher income/cost ratio and more satisfaction to the farmer. In the same states, comparing agroforestry with spontaneous forests, Leite et al. (2016) concluded, that agroforestry biomass was statistically similar with mature rainforests, while litter and topsoil nutrients were higher than in secondary forests, confirming agroforestry's

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“ecological sustainability and potential as alternative to slash-and-burn”. In Pará, oil palm (*Elaeis guineensis* Jacq.) plantations are expanding. Preliminary results show that organic agroforestry with oil palm as principal crop may be a sustainable option (Carvalho et al. 2014).

In agroforestry: (a) tree crowns and litter layer protect the soil against the direct impact of rain and sun; (b) diverse, permanent, deep root systems enhance nutrient cycling; (c) trees build up a larger carbon stock than other forms of agriculture (Kim et al. 2016; Leite et al. 2016; Schroth et al. 2002); (d) trees can be a source of natural enemies of herbivorous insects and contribute to their control in horticultural crops (Harterreiten-Souza et al. 2014). Comparing 20 slash-and-burn farmers with 20 agroforestry farmers (West Java, Indonesia), Rahman et al. (2017) concluded that agroforestry can increase farm income and turn it less dependent of price fluctuations, while diminishing deforestation. In this case, tree planting can also lead to heritable property rights on the tree-planted land.

Among the different types of agroforestry, the homegarden is possibly the most widespread one, being found in many regions around the world (Kumar and Nair 2004). Homegardens, one of the oldest forms of managed land-use systems (Kumar and Nair 2004), contribute to food security, availability of medicinal plants (Albuquerque et al. 2005; Amaral and Neto 2008; Castro et al. 2009; Costa and Mitja 2010), maintenance of soil fertility (Alfaia et al. 2004; Menezes et al. 2008; Pinho et al. 2011), income generation (Souza et al. 2012; Tremblay et al. 2015) and biodiversity conservation (Alcudia-Aguilar et al. 2017; Cardozo et al. 2015; Mattsson et al. 2015; Wiehle et al. 2014).

Homegardens are an important component of the land use system of the inhabitants of the Kwata-Laranjal Indigenous Territory (central Amazonia), members of the Munduruku and Sateré-Mawé ethnic groups. Their 0.11–0.76 ha sized homegardens mainly produce a variety of fruits and medicinal plants, less important are poultry and annual crops as sweet cassava (*Manihot esculenta* Crantz.) and maize (*Zea mays* L.). We studied the effect on soil fertility of the management of these homegardens, comparing them to surrounding secondary and primary forests.

We choose to compare these three land “use” systems (homegarden, secondary forest, primary

forest), as they constitute important landscape components, managed in very different ways. Homegardens are intensively used and managed. In secondary forests, on the other hand, use and management are almost absent. Here, the natural recovery of the plant cover is decisive for the vegetation’s development. Primary forest was included as a sort of control, because in these almost undisturbed forests clearcutting and burning of the vegetation never occurred and management activities are virtually absent. The development of primary forests depends of natural processes, such as nutrient cycling and natural succession. By studying the soil of these three systems, we aimed to obtain a better understanding of the effects of agroforestry and those of the natural reconstitution of secondary forest, through comparison to primary forest.

Materials and methods

Characterization of the study area

The areas studied are in the Kwata-Laranjal Indigenous Territory (municipality of Borba, state of Amazonas) (Fig. 1). In 2007, this Indigenous Territory had 1719 inhabitants, members of the Munduruku and Sateré-Mawé ethnic groups. The recent revision of the soils of Amazon by Quesada et al. (2011) classifies the upland soil of this Indigenous Territory as Ferralsol (Oxisol) with the following characteristics: acid, chemically poor and in most cases very deep, resulting in excellent drainage. The region’s natural vegetation can be characterized as Dense Rain Forest (ISA 2000). The climate is tropical with high rainfall, a mean annual temperature of 27.3 °C and minimum and maximum temperatures of 22.0 and 32.7 °C.

Selection of the studied sites

Together with farmers of the indigenous territory, four homegardens were selected, four secondary forests and four primary forests, all in upland (unflooded) areas, pertaining to the villages Aru and Kwata on the Canumã river and to the villages Laranjal and Cipózinho on the Mari–Mari river. The studied homegardens belonged to indigenous farmers who volunteered to participate in the research.

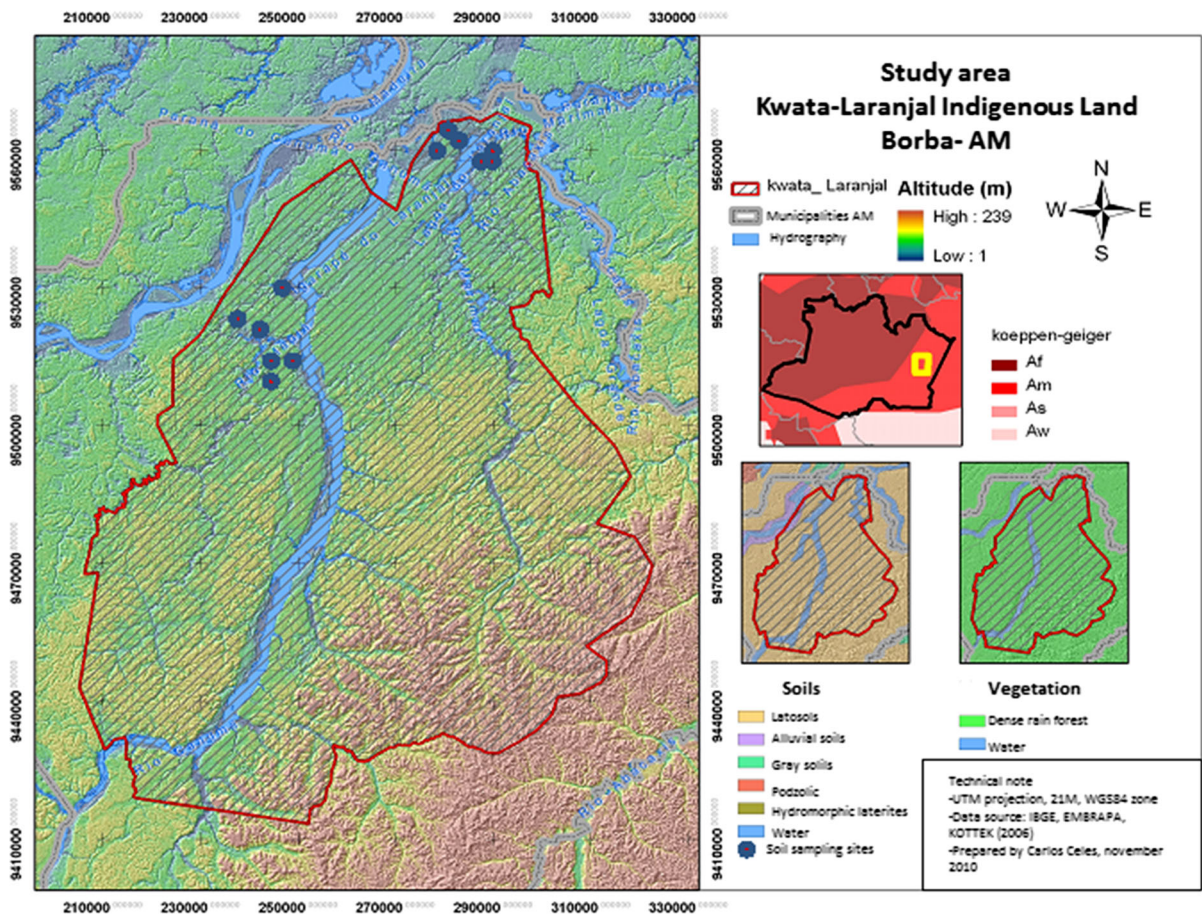


Fig. 1 Large map on *left side* Kwata-Laranjal indigenous territory and the twelve studied sites. Small map in *upper half of right side* climate of the state of Amazonas. The **bold black line** indicates the state border

History of the studied sites

The homegardens sampled were 10–45 years old, with an average of 25. All homegardens were established following the traditional system of slash-and-burn (cutting and burning the vegetation, either primary or secondary forest). Two homegardens were established after secondary forest, one after primary forest. For the fourth this information is not available, as it existed already when the actual occupants started to live here. In the initial phase of three of the homegardens, cassava cultivation was combined with the installation of fruit trees. In one, secondary forest was cut and burned to plant only fruit trees.

The secondary forests studied were 10–30 years old, with a mean of 21, their age being close to that of the studied homegardens. The studied secondary forests resulted from the natural regeneration of

abandoned cassava fields. The studied sites of primary forests are used for hunting, to obtain some timber for local use and to collect forest products.

Soil sample collection

In the homegardens, soil samples were collected in the area with a greater accumulation of organic matter, just beyond the area of the bare earth “yard” constantly swept and weeded. In this area, a 30 × 10 m plot was marked at a 2-m distance from the edge of the swept yard. In secondary and primary forests, the 30 × 10 m plots were set up at a distance of at least 100 m from the border of these forests. The plots in secondary and primary forest were 300–3000 m distant from the nearest village.

The 30 × 10 m sampling plots were divided into three subplots of 10 × 10 m, to obtain repeated

measurements. In each subplot seven subsamples of soil at depths of 0–10 and 10–20 cm were collected. These samples were mixed to form a composite sample for each depth. For the 20–30 cm depth, only four samples per plot were collected to form a composite sample, as, at this depth, soil variability is less. The composite samples were analyzed in the Thematic Soil and Plant Laboratory of the National Institute for Amazonian Research (INPA, Manaus, Amazonas). The averages of the three subplot samples are the variables describing the twelve sites.

Laboratory analysis of soil samples

The pH (H₂O and KCl), levels of macronutrients P, K, Ca, Mg, organic carbon and available Al were measured according to the methodology described by Embrapa (1997). Soil pH (H₂O) was determined in water with a soil/water ratio of 1/2.5. After measuring the pH (H₂O), 1.86 g of KCl was added to each sample to determine the pH (KCl). The exchangeable cations Ca²⁺, Mg²⁺ and Al³⁺ were extracted with 1N KCl, while P and K were extracted with double acid (0.0125 M H₂SO₄ + 0.05 M HCl). The organic carbon was determined by Walkley & Black-titrated with ammonium ferrous sulfate hexahydrate (Fe(NH₄)₂(SO₄)₂·6(H₂O)). The physical soil characteristics were obtained by separating the soil in clay (particle diameter <0.002 mm), silt (0.002–0.06 mm) and sand (0.06–2 mm), after which the obtained materials were dried and weighted.

Data analysis

For each soil depth, one-way analyses of variance were done for the different soil parameters. The twelve residual values of each analysis were checked for “normality” with the Shapiro–Wilk test ($p < 0.05$). When normality was not rejected and the ANOVA gave a significant result ($p < 0.05$), significant differences between the different forms of land use were detected with Tukey’s range test ($p < 0.05$). Variables which didn’t show normality were transformed with $y = \log(1 + x)$ to repeat the above given testes. When this transformation didn’t result in normality, the Kruskal–Wallis test ($p < 0.05$) was used to detect eventual differences between the forms of land use. With the average of each chemical soil parameter, a

BIPLOT GGE chart was built for each soil depth, to visualize the relation between land use and soil characteristics. Analyses were performed with R software.

Results and discussion

Acidity, exchangeable aluminum and soil organic carbon

The two ways of pH determination gave contradictory results. For all three soil depths, pH (KCl) didn’t show significant differences between the forms of land use, while the ANOVA of pH (H₂O) gave a significant result for soil depth 0–10 cm ($p = 0.000$) and 10–20 cm ($p = 0.027$). (The mean values at the different soil depths of all chemical soil variables and eventual significant differences between the forms of land use are shown in Fig. 2.)

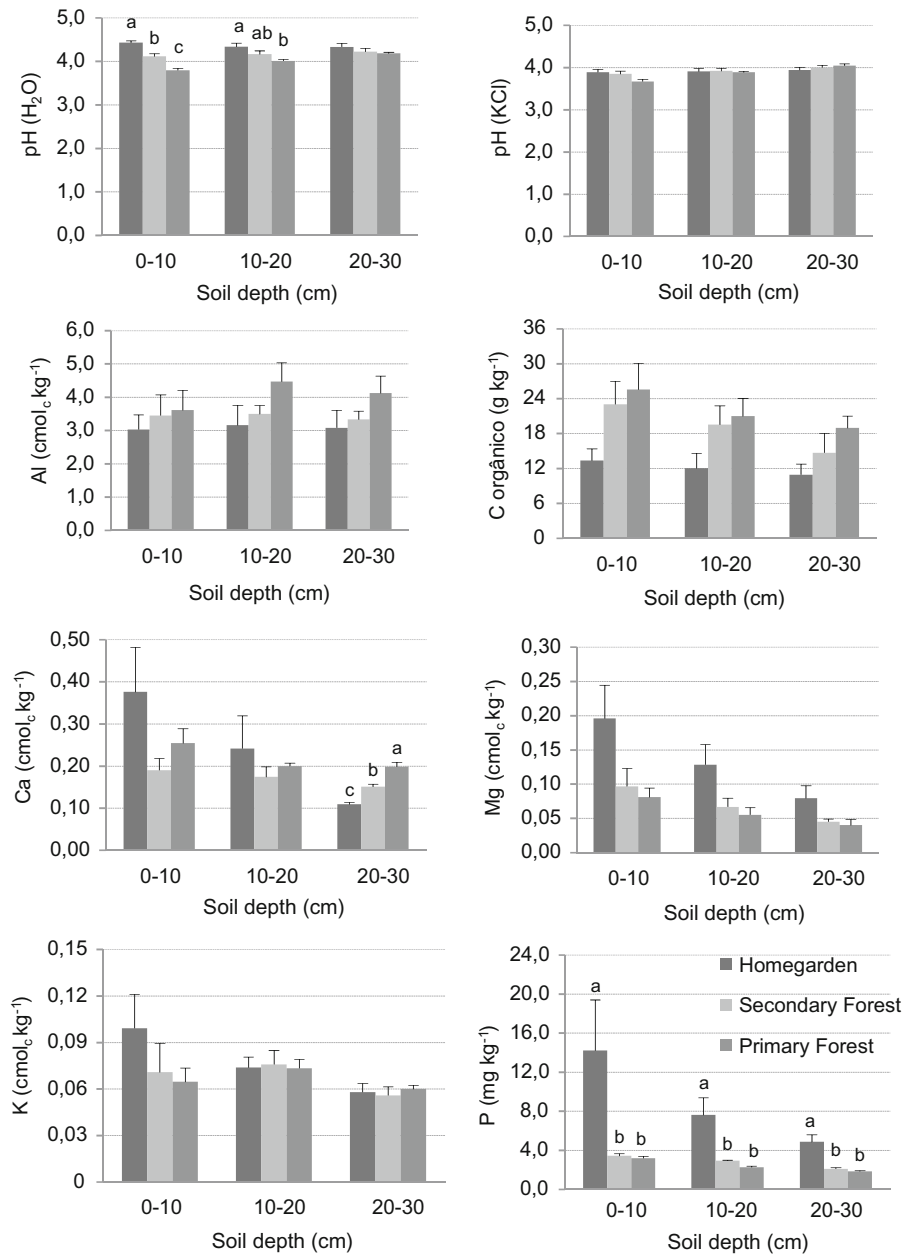
At 0–10 cm depth, the pH (H₂O) in secondary forest (3.85) was significantly higher than that of primary forest (3.79). Apparently, even after more than 20 years, the effect of burning and cutting the original forest vegetation, followed by cassava cropping, is still notable in the diminished acidity of the uppermost soil layer of the secondary forest, which developed after these occurrences.

At 0–10 cm, the pH (H₂O) of the homegarden (4.43) was significantly higher than the pH (H₂O) of secondary forest. This difference will be caused by aspects of the homegarden management. The studied indigenous farmers sweep their homegarden and burn organic waste as branches and leaves. The ash resulting from burning plant material contributes to neutralizing soil acidity, raising the pH (Pinho et al. 2011). These cleaning activities are done to reduce the risks caused by venomous animals (snakes, scorpions, etc.), that may hide in the litter.

Menezes et al. (2008) and Moreira et al. (2009), comparing soils of agroforestry with adjacent forests in the states of Rondonia and Amazonas (Brazilian Amazonia), also observed the highest soil pH in areas with agriculture and agroforestry.

At 10–20 cm depth, the only significant difference was between the pH (H₂O) of the homegarden (4.33) and the primary forest (4.01). The less acid soil of the homegarden can be explained by the above described management.

Fig. 2 Values of pH (H₂O), pH (KCl), organic carbon, aluminum, calcium, magnesium, potassium and phosphorus for the soil of homegarden, secondary forest and primary forest at three depths. Columns represent the mean of four sites and lines the standard error of the mean. Land uses with the same letter do not differ from each other, according to Tukey’s range test ($p < 0.05$)



The observed pH (H₂O) values in secondary and primary forest at 0–20 cm depth (3.8–4.2) are below the average (4.3) of the pH (H₂O) for Amazonas’ upland soil, given by Moreira and Fageira (2009) in their state-wide synthesis of the data of more than 3000 soil samples at 0–20 cm. According to the criterion (pH < 5.3) of Cochrane et al. (1985) for tropical soils, these low pH (H₂O) values correspond to low soil fertility.

The ANOVA tests for aluminum were not significant. The observed levels (3.0–4.5 cmol_c kg⁻¹) are much higher than the criterion for “very high” (>2.0) of the before mentioned study of Moreira and Fageria (2009), which informs that 25% of Amazonas’ soils have a “very high” Al level. The observed values are also much higher than the level (>1.5) considered by Cochrane et al. (1985) as corresponding to good soil fertility. These very high Al values might mean that

these soils will show toxicity for plants not adapted to so much exchangeable Al in the soil. In studies of Amazonia, Sanchez et al. (1983), Edena et al. (1991) and Alfaia et al. (2004) observed lower aluminum levels in homegardens and secondary forests, which shows that clearing and burning the vegetation can decrease the soil's Al concentration.

However, some studies have expressed doubts as to the applicability of the here used extraction method (KCl 1N) for soils with a high aluminum content, as those studied here (Gama and Kiehl 1999; Marques et al. 2002), implying a divergence between the high extractable aluminum content of these soils and the effective activity of Al in the soil solution and, therefore, its toxic effect on plants.

The observed organic carbon levels (11–26 g kg⁻¹) correspond to medium soil fertility according the criterion (8–26) of Cochrane et al. (1985). No significant differences were found between the three land use systems.

As mentioned before, the studied farmers burn organic waste, a practice which does not promote the organic carbon content of the homegarden's soil.

In Rondonia, Alfaia et al. (2004) observed that in general the organic C-levels in agroforestry were similar to those in the forest, while being higher in agroforestry implanted in Oxisol than in Inceptisol. In this case, the use of pueraria (*Pueraria phaseoloides* (Roxb.) Benth.), a nitrogen-fixing cover crop, in most of the agroforestry fields probably contributed to higher levels of soil organic matter (S. Alfaia, pers. observation). In the Araçá Indigenous Territory (state of Roraima, northern Amazonia), Pinho et al. (2011) observed a higher organic carbon content in homegardens than in the adjacent savanna ('lavrado'), but this can be due to this savanna having a lower biomass than neighboring primary forest and generally a poor soil.

Macronutrients (calcium, magnesium, potassium and phosphorus)

The encountered calcium levels (0.11–0.38 cmol_c kg⁻¹) correspond with soils of low fertility according to the criterion (<0.4) of Cochrane et al. (1985). Moreira and Fageria (2009) inform that 65% of Amazonas' soils have this low Ca level. Only at 20–30 cm depth the calcium levels were significantly different ($p < 0.000$) between the forms of land use. Although, generally, homegardens have a more fertile

soil than the surrounding natural vegetation, at 20–30 cm the homegarden's Ca level was significantly less than that of secondary forest, while the secondary-forest's Ca level was significantly less than that of primary forest (Fig. 2). The significant lower Ca level in the homegardens at 20–30 cm may be related to the intensive use of the homegarden and resulting faster nutrient cycling. In a study of 5-year old, fertilized, experimental, on-station agroforestry system (Manaus), Tapia-Coral et al. (2005) observed that in general, the C/nutrient ratio of agroforestry litter is lower than that of secondary-forest litter, indicating a faster nutrient recycling in agroforestry. According to Luizão (2007), the high decomposition rate of agroforestry litter generates quick release and nutrient uptake by roots. In this way, absorption in the 0–20 cm soil layer by roots of short-cycle plants can reduce the Ca amount going to lower layers, explaining the homegarden's significant lower Ca level at 20–30 cm depth. Contrary to the here presented results, in Inceptisols in Amazonas, Moreira et al. (2009) noted a higher calcium content in soils under agroforestry than under secondary and primary forest.

The magnesium content didn't show significant differences between the three land use systems (Fig. 2), while, besides one higher value (0.20 cmol_c kg⁻¹), the encountered values (0.04–0.20 cmol_c kg⁻¹) correspond to low soil fertility, according to the criterion (<0.2) of Cochrane et al. (1985). According to Moreira and Fageria (2009), some 50% of Amazonas' soils have these low Mg levels. The lack of significant differences between the studied forms of land use can be due to the very low values in the studied primary forest (0.04–0.09). On soils, so poor in magnesium as in the current case, it may be more difficult to detect the management effect on the soil's magnesium content. In Rondonia, Alfaia et al. (2004) and Menezes et al. (2008) observed significant increases of exchangeable magnesium in agroforestry in places with a higher Mg level in the primary-forest soil (0.1–0.2 and 0.1–0.5, respectively, at 0–20 cm depth).

The values for potassium (0.06–0.10 cmol_c kg⁻¹) of the three land use systems indicate low soil fertility, according to the criterion (<0.15) of Cochrane et al. (1985). No significant differences between the three systems were encountered (Fig. 2). According to Moreira and Fageria (2009), 75% of Amazonas' soils have an exchangeable potassium level below 0.11. Tapia-Coral et al. (2005) observe that "leaching was

likely the main reason of lower K concentrations in the litter layer on the soil, especially in the leaves, during the wet season, when this process becomes stronger.” A study in Roraima’s savanna region showed that a secondary-forest fallow does not result in a K increase in the soil (Pinho et al. 2012).

Anyhow, the behavior of potassium in soils under agroforestry in Amazon is by no means clear cut. Comparing agroforestry with adjacent old-secondary and primary forest in Amazonas, Moreira et al. (2009) didn’t find differences in the soil’s potassium content, while in Rondonia Menezes et al. (2008) didn’t find significant differences between agroforestry and primary forest. On the other hand, in the state of Acre (Amazonia), Alfaia et al. (2004) encountered higher K levels in primary forest than in agroforestry, attributing the decrease in the latter to nutrient export through fruit harvest.

The ANOVA for phosphorus gave very significant results for all three soil levels (0–10 cm, $p < 0.006$; 10–20 cm, $p < 0.002$; 20–30 cm, $p < 0.001$). At all three depths, the homegardens had a much higher phosphorus level than the secondary and primary forests, in all cases this difference being statistically significant, while there was no significant difference between secondary and primary forest (Fig. 2). The encountered phosphorus content of the studied homegardens in the 0–20 cm layer ($8\text{--}14\text{ mg kg}^{-1}$) corresponds to high soil fertility according to the criterion (>7) of Cochrane et al. (1985), while the content in the 20–30 cm layer (5) corresponds to the medium fertility criterion (3–7) of these authors. In the 0–10 cm layer, the P content in secondary and primary forest (3.4 and 3.2 respectively) corresponds to the above given criterion for medium soil fertility, while the P contents of these forests in the 10–30 cm layer (1.8–2.9) indicate low soil fertility (<3). According to Moreira and Fageria (2009), 50% of Amazonas’ soils have less than 2.7 exchangeable phosphorus.

Other studies also encountered a higher phosphorus content under agroforestry than under native vegetation (Leite et al. 2016; Moreira et al. 2009; Pinho et al. 2011). However, in this regard homegardens must be considered as a special case; besides a more intensive management, the deposition of organic waste around the house certainly contributes to the rapid increase of this nutrient (Pinho et al. 2011). On the other hand, in the already mentioned study of Alfaia et al. (2004) in Rondonia, phosphorous content was higher in primary

forest than in agroforestry, possibly the result of nutrient export through fruit harvest.

The homegarden’s soil fertility can be improved?

Although somewhat more fertile than the forest, the homegarden’s values for pH, Ca, Mg, K correspond to low soil fertility and the soil’s organic carbon-content to medium fertility. It is of interest to find management forms which improve the soil fertility of these homegardens. Proposed improvements should be feasible in the conditions of this Indigenous Territory, distant from mayor markets and service centers.

In the opinion of Leite et al. (2016), the large differences between homegardens show the important potential for improved management. Cardozo et al. (2015) agree and consider that investments in research and extension for the improvement of homegardens would be a highly efficient way to promote poverty reduction and food security. Leite et al. (2016) suggest the study of the composition, spacing and pruning of homegardens, Cardozo et al. (2015) species selection, organic matter management and nutrient cycling.

Biplot analysis

The given Biplot analyses explained from 54 to 58% of the total variance. This percentage represents most of the variability of the soil characteristics of the studied land use systems. In this way, Biplots are useful to explain the relationship between forms of land use and soil fertility.

Biplot analysis is a modification of principal component analysis in which the observation of the relationship between levels of a factor permits insights into the interaction between the factors (Oliveira et al. 2015). In this case, the factors are the soil parameters and land use type. Three biplots were constructed, one for each soil depth (Fig. 3).

For the 0–10 cm soil layer, the Biplot explained 58% of the total variance (Fig. 3a). In the graph, a straight band of a certain width can be drawn from the bottom left-side to the upper right, separating the homegardens on its right side and the primary and secondary forests on its left (F and Cap labels respectively). The vectors for macro- and micronutrients and pH (H_2O) are situated on the right side, corresponding to higher levels in the homegardens. The soil-carbon vector is on the left side, illustrating

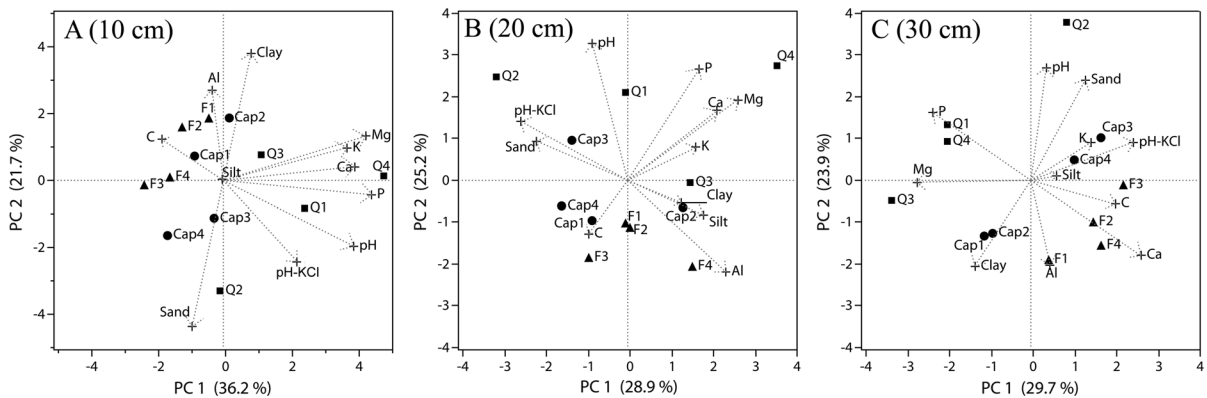


Fig. 3 Biplots for depth 0–10 cm (map A), 10–20 cm (map B) and 20–30 cm (map C) showing: 1 the vectors of the chemical [P, K, Ca, Mg, C, Al, pH and pH (KCl)] and physical (sand, silt,

and clay) soil parameters; 2 the localization in the Biplot of the four sites of each land use system (*Q* homegarden, *Cap* secondary forest, *F* primary forest)

the lower C-concentration in homegardens. The vector representing aluminum is very small, not contributing to the differences between the forms of land use.

At 10–20 cm depth, the Biplot uses 54% of the total variance (Fig. 3b). Again, primary and secondary forests are on one side and homegardens on the other. Just as in the surface layer, at 10–20 cm depth several chemical soil-characteristics are positively correlated with homegarden, but carbon remains correlated with primary and secondary forests. In this case, the vector representing aluminum is large, but its relation to land use is not clear since homegardens behavior is heterogeneous.

For 20–30 cm depth, the Biplot explained 54% of the total variance (Fig. 3c). The contrast between homegardens, primary and secondary forests is clear; being secondary forests an intermediate type between homegardens and primary forests. The homegardens are still positively correlated with high values of pH (H₂O), P and Mg, but the calcium vector is in the direction of primary and secondary forests, in accordance with the greater Ca content here, together with carbon and aluminum. The potassium vector has quite a neutral behavior, not favoring any side, suggesting that, homegarden management has no effect on the content of this element in this layer.

Conclusions

The Biplots explained 54–58% of the total variance. They indicate the soil characteristics that contributed

most to differentiate homegardens from secondary and primary forests: pH, organic carbon, aluminum, calcium, magnesium and phosphorus. The values for pH, Ca, Mg, K and P (at 10–30 cm depth) in the studied secondary and primary forests indicate a low soil fertility. The high Al content of these soils can indicate Al toxicity, but it is possible that the used extraction method doesn't give adequate results in these high-Al soils. The encountered organic-carbon content and P (at 0–10 cm depth) correspond to medium soil fertility. The secondary forest's pH in the 0–10 cm layer was significantly higher than that of the primary forest, showing that even after more than 20 years the effects of cutting and burning the original forest (and the followed cassava cultivation) are still notable. The obtained forest-soil values are common for most Amazonas' upland soils and in agreement with what can be expected from the soil class (Ferralsol, Oxisol) present in this indigenous territory.

The homegarden's data indicate a somewhat better soil fertility except to C and Ca. At all soil depths, phosphorous was significantly higher than in the forest, indicating high (0–20 cm layer) and medium soil fertility (20–30 cm layer). The homegarden's pH was significantly higher in the 0–20 cm layers, but still corresponding with low fertility. On the other hand, the Ca content of the 20–30 cm level was significantly lower than that of secondary forest. A possible explication of that is the fast decomposition of the homegarden's litter layer. The somewhat better fertility of the homegarden is probably caused by the frequent burning of plant residues. It is highly

desirable to find ways to improve the soil fertility of the homegardens even more.

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