Agroforest Syst
DOI 10.1007/s10457-010-9336-5

Islands of fertility: Soil improvement under indigenous homegardens in the savannas of Roraima, Brazil

Rachel C. Pinho · Sonia S. Alfaia · Robert Pritchard Miller · Katell Uguen · Leovone D. Magalhães · Marta Ayres · Viviane Freitas · Ralph Trancoso

Received: 6 November 2009 / Accepted: 2 July 2010

Abstract Homegardens are a common feature of indigenous dwellings in the savannas of Roraima, northern Brazil. In order to evaluate the effect of homegardens on soils, samples were taken in 5 sites each in the categories *new homegardens* (0–10-years old), *established homegardens* (15–35-years old) and *old homegardens* (more than 40-years old) and in adjacent savanna in Araçá Indigenous Land, Roraima, Brazil. For comparison, samples were also taken in forest islands located nearby, on a different soil type, under 10-year-old forest fallows and high forest. P and K showed the greatest increases over time in homegarden soils, in comparison with levels found in adjacent savanna and under forest. Ca and Mg also increased in comparison to adjacent savanna, but levels were less than found in forest soils, most likely due to the different parent material. Zn and Fe also showed increases in homegarden soils over time. Cu and Mn levels showed little relation to homegarden age, suggesting greater effects of factors of soil formation than anthropogenic influences. Values for pH were slightly higher in homegardens than in adjacent savanna, while Al was lower, although these changes were poorly fit by regression models. Soil organic matter increased over time under homegardens, but still was lower than levels found under fallows and forest. Soil fertility improvement under indigenous homegardens can be attributed mainly to deposition of residues around dwellings, although further investigation is needed on the role of trees in accessing nutrient pools at greater depths in savanna soils.

Keywords Lavrado · Macuxi · Wapixana · Soil nutrients · Fallow

R. C. Pinho (✉) · S. S. Alfaia · K. Uguen · M. Ayres · V. Freitas
INPA—Instituto Nacional de Pesquisas da Amazônia—AM/RR, Manaus, Brazil
e-mail: rachel.pinho@gmail.com

R. P. Miller · L. D. Magalhães · R. Trancoso
FUNAI—Fundação Nacional do Índio, Brasilia, Brazil

Introduction

Homegarden agroforestry systems, consisting of the cultivation of fruit trees and other useful plants around dwellings, are widespread in most of the tropics (Nair 1993; Kumar and Nair 2004). Homegardens have attracted a great deal of attention from researchers, who have shown that their importance is not limited to food security, and secondarily, to household income, but also includes their use as a laboratory for farmer experimentation and a starting point for more extensive agroforestry systems (Coomes and Ban 2004; Miller et al. 2006; Yamada and Osaqui 2006).

The principal focus of most homegardens studies concerns their floristic composition; nutrient dynamics, in contrast, have been little explored (Kumar and

Nair 2004). Nonetheless, it is generally accepted that homegardens are characterized by closed nutrient cycling, due to the presence of different tree species, each with peculiar rooting characteristics and varied leaf litter nutrient content, often complemented by a stratum of understory shrubs and herbs. The positive effects of trees on soil properties also result in greater absorption of rain water and less surface runoff (Beer et al. 2003). Thus, with regards to nutrient cycling and erosion control, homegardens have been compared to closed canopy forests. However, the lack of concrete data on nutrient dynamics for homegardens in the different regions where they occur means that important questions, such as how nutrient imports or exports affect their sustainability and productivity, remain unanswered.

As a first step in addressing this paucity of information on nutrient dynamics in homegardens, the present study proposed to examine how homegardens in Araçá Indigenous Land, in the savannas of Roraima, northern Brazil, are able to prosper in the otherwise infertile soils of the region. As a yardstick for nutrient dynamics, the study examined soil nutrient levels in a sample of 15 homegardens of different ages. The working hypothesis employed was that these homegardens, and the processes they engender, result in the accumulation of nutrients over time. In the following sections, we discuss the study site, briefly characterizing the homegardens studied; the methods employed in soil sampling; and the results obtained.

Materials and methods

The study area

Roraima, Brazil's northernmost state, contains an area of approximately 40 000 km^2 of savannas. These savannas are contiguous with the Rupununi savannas of Guyana, and are floristically similar to the larger "Llanos" region of Venezuela and adjacent "Llanos Orientales" of Colombia. In the Roraima savannas, locally known as "Lavrado", the predominant vegetation is grassland with a variety of grasses and herbs, and varying densities of the short *caimbé* (*Curatella americana*—Dilleniaceae) and *mirixi* (*Byrsonima crassifolia*—Malpighiaceae) trees. Other tree species may be locally important, but rarely outnumber these two species. Besides savannas, the Lavrado region encompasses other vegetation formations, such as deciduous dry forests found on scattered hills and mountains or as forest islands in savanna. Gallery forests, often dominated by the *buriti* palm (*Mauritia flexuosa*), are found along streams and rivers (Barbosa et al. 2007). A significant portion of the Lavrado consists of "hyperseasonal" savannas that become water saturated or even flooded in the rainy season, only to completely dry out in the dry season.

Annual precipitation in the Lavrado varies from approximately 1100 mm to 1700 mm. The climate is "Aw" according to Köppen's classification, with a well-defined dry season, generally between December and March. Less than 10% of the annual precipitation occurs in this season (Barbosa 1997).

Lavrado soils are varied, but in general have low levels of nutrients and organic matter, showing low pH and aluminum saturation (Vale and Souza 2005). In Araçá Indigenous Land, soils are predominantly sandy in texture, with red-yellow Argissols occurring under savannas, and dark red Argissols occurring under the forest islands, according to the Brazilian System of Soil Classification (Brasil 1975; Embrapa 2006). With few exceptions, the indigenous peoples of the Lavrado practice agriculture in the patches of forest types described above. Besides their importance for agriculture, these forests supply building and craft materials, wild foods, and game habitat.

In Brazil, Roraima is the state with the greatest percentage of indigenous peoples in its population, on the order of 10%. Of the 32 officially recognized Indigenous Lands in Roraima, 28 occur in the Lavrado, occupying about half of the area of this region of savannas. Araçá Indigenous Land, where the study was carried out, covers 50, 013 hectares in the municipality of Amajari, and is located approximately 110 km from the state capital, Boa Vista. Araçá was officially demarcated in 1982, and now has around 1490 inhabitants, belonging to four ethnic groups (Macuxi, Wapixana, Taurepang and Sapará) and living in five communities: Araçá, Guariba, Mangueira, Mutamba and Três Corações (Fig. 1).

Characteristics of indigenous homegardens in the savannas of Roraima

The Macuxi, Wapixana, Taurepang, Ingarikó and Sapará tribes are savannas dwellers, and have developed

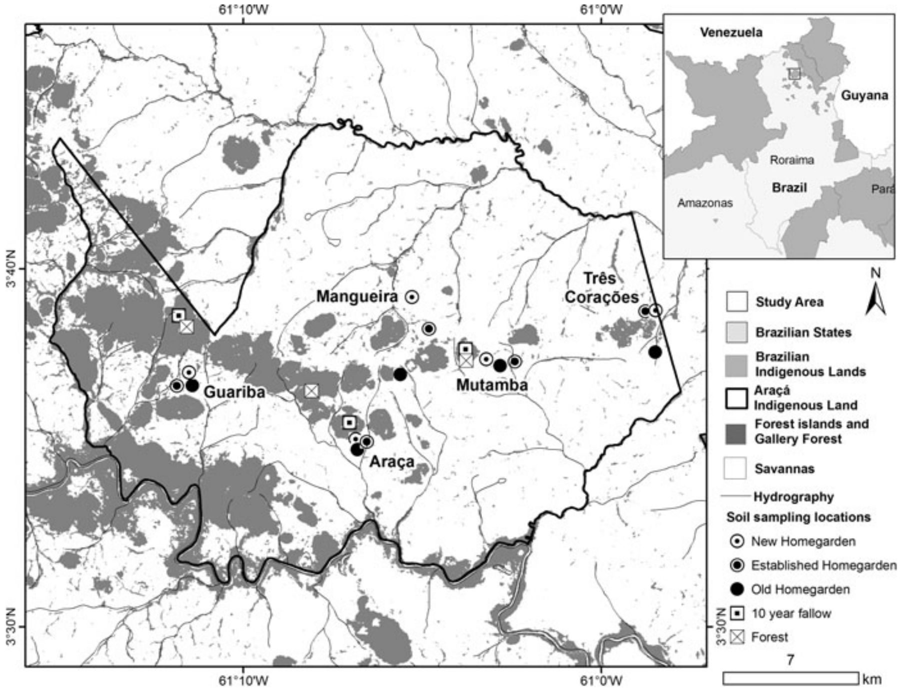


Fig. 1 Location of Araçá Indigenous Land, Roraima, Brazil, indicating communities and soil sampling sites

a number of cultural adaptations to this environment, including the establishment of homegardens around their houses. Although Central Amazonia is considered to have been a center of plant domestication in prehistoric times, with widespread cultivation of fruit trees (Lathrap 1977; Clement 1999; Miller et al. 2006), scant information is available concerning agroforestry practices in the savannas of Roraima, either in prehistory or in historical times. Nevertheless, the practice of establishing homegardens around dwellings in the savanna is widespread in the region, as observed by three of the authors in a survey of 9 indigenous lands in the region, as well as in other lands that were visited (Miller et al. 2008).

As such, information gathered on homegardens in Araçá Indigenous Land can be considered as reasonably representative of practices in the Lavrado region. Sixty homegardens, distributed in five villages, were surveyed in this study, with physical measurements and species counts complemented by interviews with the inhabitants, who were asked about age and history of the homegarden, origin of planting material, uses of the different species, and management practices (Pinho 2008). Homegarden size was found to vary between 451 and 35 173 m^2 (mean = 4935 m^2). Of the total of 79 tree and shrub species identified in homegardens, 45 produce edible fruit. Lime (*Citrus aurantifolia* Swing.), araçá (*Psidium guineense* SW.), mango (*Mangifera indica* L.), guava (*Psidium guajava* L.), and cashew (*Anacardium occidentale* L.) were present in more than 80% of the homegardens. The greater part of the fruit is used for domestic consumption, although 40%, 15%, and 8% of the homegardens surveyed produce, respectively, limes, mangos and oranges for sale.

Homegardens are established by planting seeds or seedlings of fruit trees around a new dwelling, invariably built in open savanna, in an area cleared of grasses. Management may consist of watering seedlings in the first year to ensure their survival, weeding, occasional applications of cow manure as fertilizer, and pruning for aesthetic or functional reasons. In some homegardens, leaf litter and other organic matter may be used as mulch around seedlings. Although nitrogen-fixing legumes, such as the ice-cream bean (*Inga edulis*) and pigeon pea (*Cajanus cajan*), are found in some homegardens, they are generally cultivated for their edible parts or other uses, and not for their ability to improve soils.

In the 60 homegardens surveyed, size, species richness and total number of plants were found to be directly related to homegarden age ($P < 0.01$). Of the 79 tree or shrub species found in homegardens, 21 are spontaneous and are maintained because of some useful property, edible fruit being cited in 46% of these cases. Older homegardens commonly exhibit species native to nearby forests islands or riparian forests, arising from seeds discarded following fruit consumption. This is generally the case for the palms *Acrocomia aculeata*, *Astrocaryum tucuma*, and *Mauritia flexuosa*, as well as the dicotyledonous *Byrsonima crassifolia*, *Genipa americana*, *Hymenaea courbaril*, and *Spondias mombin*. Other native species may arise from seeds dispersed by livestock, wildlife, and wind.

The homegardens studied represent an interesting mix of species and processes, with initial planting of more drought-tolerant trees such as mango and cashew eventually providing conditions for the establishment of less resistant species, via planting or natural regeneration (volunteers). Some very old homegardens may begin to resemble forest islands in terms of species composition, with the presence of a number of native species. Figure 2 illustrates the range of situations observed, from an incipient homegarden being established around a dwelling in the savanna, to a homegarden approximately 50-years old, as well as the view from within a homegarden.

Fig. 2 Homegardens in Araçá Indigenous Land, Roraima, Brazil: **a** Dwelling recently established in savanna, with trees planted in the area cleared of grasses around the house (incipient homegarden); **b** Old homegarden, approximately 50-years old. The house built in open savanna next to the homegarden is typical of the reoccupation of such older sites; **c** View of the interior of an established homegarden

Soil sampling in homegardens, adjacent savanna and forest islands

The 60 homegardens surveyed in the five villages of Araçá Indigenous Land were stratified into three categories according to age: *new homegardens* (0–10-years old), *established homegardens* (15–35-years old), and *old homegardens* (more than 40-years old). In each of the five communities, one homegarden was selected randomly in each category for soil sampling, for a total of 15 homegardens. For each homegarden sampled, a sample was taken in adjacent savanna, for a total of 15 savanna samples (Fig. 1).

Soil samples in the homegardens were taken outside the periphery of the periodically swept and weeded bare earth "yard" that surrounds the dwelling, with a 10 × 15 m plot marked out in a location with greater density of trees. This plot was subdivided into three sub-plots of 10 × 5 m. In each sub-plot seven soil samples were taken at the depths of 0–10 cm, and 10–20 cm, and mixed to obtain composite samples. For the composite sample of 20–30-cm depth, four samples were taken in each sub-plot. The composite samples from the three sub-plots were analyzed separately and averaged to obtain the values for each plot.

A similar plot was laid out in the adjacent savanna, at a distance of 10 m from the edge of the homegarden, as measured from the outermost domestic plant. An identical procedure to that described above was used to sample the savanna soil.

Soil sampling in forest islands was done in 10-year-old secondary forest fallows and in high forest, in three different sites used by members of the communities Araçá, Guariba and Mutamba. A 45 × 45 m plot was laid out in each environment (fallow and forest) in each of the three sites. Each plot was divided into three subplots of 15 × 45 m, and in each subplot 10 soil samples were taken at the depths of 0–10 cm, 10–20 cm, and 20–30 cm, and mixed to form a composite sample. Each composite sample was analyzed separately, and the value averaged to obtain a mean.

Chemical analysis of soil samples was carried out at INPA's Soil Laboratory (Manaus) according to methods described by Embrapa (1997). Soil pH was determined in H_2O in a ratio of soil:water of 1:2.5. The exchangeable cations Ca^{+2}, Mg^{+2}, and Al^{+3} were extracted with 1N KCl, while P, K, Cu, Zn, Mn, and Fe were extracted with double acid (0.0125 M H_2SO_4 + 0.05 M HCl). Organic C was determined by using a Carlo Erba auto-analyser for carbon, hydrogen and nitrogen, and percent organic matter was estimated by multiplying this value by 1.724. Nitrogen was not included in the study due to technical problems with laboratory equipment at INPA at the time when soil samples were taken.

For the statistical analysis of the results of soil analysis Bray-Curtis ordination (Polar ordination) with Euclidian distance was used to control the influence of spatial variability of the natural environment. The data were normalized by maximum and analyses were carried out separately for each depth class with PC-ORD®. To test changes in levels of nutrients, pH, Al and organic matter by age of homegarden, regressions were fitted with Excel® using the mean obtained for each depth sampled. The critical value used for significance was $P \leq 0.05$. Samples from the savanna adjacent to each homegarden were considered to represent age = zero for the regressions. Overall means for each environment (savanna, homegardens, fallow and forest) were analyzed with Systat 12®. In the case of a homegarden on a site with abundant lateritic concretions (ferric oxide), a strong leverage effect was observed in the statistical analysis, so this homegarden and the adjacent savanna plot were excluded from the regression. Other apparent outliers were not excluded as no clear reason could be found for their behavior.

Results and discussion

Natural soil variability

The results of the Bray-Curtis ordination (Fig. 3) clearly indicate the difference between the two principal natural environments in the study area, with the savanna (triangles) and forest islands with and without intervention (squares) appearing in distinct regions of the graphs, reflecting the influence of different parent materials and soil types. Although the savanna samples were taken in locations broadly distributed over the study area, in five villages, they present similar results with regard to soil fertility, and the three depth classes of all 15 samples are grouped in the same region of the graphs. The homegarden samples tend to separate from the group of savanna samples and move towards the direction of the forest samples with increasing age–new homegardens group closely with the savanna samples, while old homegardens are furthest away. However, this does not mean that old homegardens necessarily achieve equality with forest soils, as human occupation enriches levels of P and K, both of which are low in the forest soils. In the following paragraphs, we discuss in details the changes observed in levels of nutrients, pH, Al, and organic matter.

Macronutrients

P and K exhibited the greatest increases over time in homegardens, with soil under old homegardens showing P levels more than 20-fold greater than adjacent savanna (Fig. 4). Even in new homegardens, P levels were sevenfold greater than in savanna, suggesting that there is a rapid increase in this nutrient in the first few years following initial occupation of the dwelling and establishment of the homegarden. Levels found in adjacent savanna varied little between 0.3 and 3 mg kg^{-1}; the oldest homegarden (90 years) sampled, in contrast, reached 110 mg kg^{-1}(Fig. 8). According to Woods (2003), P is a key indicator of anthropic effects on soils, as it is found in many of the materials related to human occupation and also shows great stability in the soil. In Thailand, Gajaseni and Gajaseni (1999) found greater levels of P inside homegardens, in comparison to areas outside the homegardens.

Mean values for P in the surface horizon of Araçá Indigenous Land homegarden soils ranged from 14.3 to 43.7 mg kg^{-1}, and are slightly less than those found in Indonesia by Kehlenbeck and Maass (2004), with means between 15 and 122 mg kg^{-1} for homegardens between 21 and 65 years old, or for homegardens more than 50 years old studied in the Amazon floodplain by Alfaia et al. (2008), where values ranged from 97 to 245 mg kg^{-1}. However, it should be pointed out that both these sites have soils that are naturally more fertile than the savanna soils of Roraima (Melo et al. 2003).

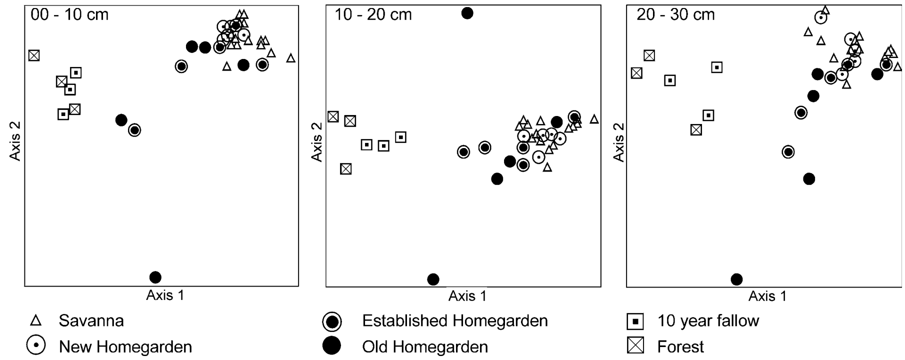


Fig. 3 Bray-Curtis Ordination with Euclidian distance of soil fertility analysis by different environments at three depth classes

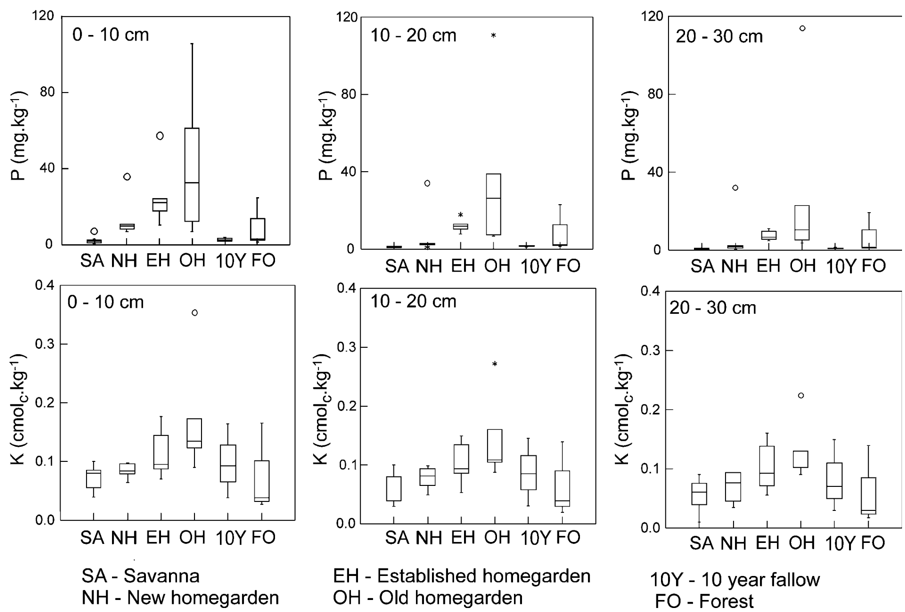


Fig. 4 Levels of P and K in soils of different environments, by depth, in Araçá Indigenous Land, Roraima, Brazil (□ = outlier at $P = 0.01$; * = outlier at $P = 0.05$; box = central 50% of data (2nd and 3rd quartile); central line = median; outside lines = 1st and 4th quartile)

P values varied greatly between homegardens in the same age class, especially in old homegardens, where there was a 15-fold difference between the lowest and highest values, at the depth of 0–10 cm. At 10–20 cm, and 20–30 cm this difference was even greater (Fig. 4). This was also observed for other nutrients, such as Ca and Zn (a 12-fold difference at 0–10-cm-depth), and is probably due to the varied history of older homegardens, which may be successively abandoned and reoccupied during their life-cycles. Abandonment occurs when a family moves away, or when an elder dies, with reoccupation occurring any number of years later. When a site is reoccupied, the new dwelling is invariably constructed in the adjacent savanna, and over time the group of fruit trees planted around the new house may eventually coalesce with the old homegarden. As such, patterns of nutrient deposition, level of management of the vegetation, introduction of new species, and number of occupants all change over time, contributing to heterogeneity in soil characteristics of the old homegardens. The choice of tree species that are planted or otherwise managed in the homegarden may have a significant effect on soil, as even individual trees can alter or improve soils in different ways (Rhoades 1997; Zinke 1962).

In forest soils, P averaged 9.7 mg kg^{-1} at 0–10 cm, a level 4.5 times less than that found under old homegardens, while soil under fallows showed levels similar to that of the savannas. In natural systems, litter deposition is regarded as a principal factor in supplying P to the soil (McGrath et al. 2000), however, in this case, 10 years of forest fallow were not sufficient to restore P to original levels.

Although older homegardens presented the highest average levels of K, the surface layer, with 0.17 $cmol_c\ kg^{-1}$, is considered only as "average" for tropical soils, according to Cochrane et al. (1985). The other soils examined presented levels considered as "low", with less than 0.15 $cmol_c\ kg^{-1}$, which may be due to their sandy texture (Freitas 2008). However, homegardens of all classes showed means for K similar to those found by Glaser et al. (2004) in anthropogenic dark earths (*terra preta de índio*) in the Central Amazon. Although Tomé (1997) affirmed that levels of K are generally related to the amount of organic matter in soils, the homegardens studied all had lower levels of organic matter than the forests or fallows, and yet showed higher K values. This may be due to the practice of frequently burning small piles of leaf litter in different parts of the homegarden, a practice quite different from that observed in slash-and-burn fields, where fires are more intense and cations in the ashes may be more subject to leaching.

Homegarden management practices also contribute to increases in levels of Ca and Mg. Older homegardens have levels of these elements six times greater than surrounding savanna soils at all depths, and twice that of new homegardens for the upper layer (0–10 cm). However, in soils under fallows and forest the levels of Ca and Mg were almost three times as high as under homegardens (Fig. 5). Only a small portion of soils in Roraima exhibit levels higher than 2 $cmol_c\ kg^{-1}$ of Ca and 0.5 $cmol_c\ kg^{-1}$ of Mg (Melo et al. 2003), as was the case for soils under fallows and forest, where levels ranged from 3.4 to 4.26 $cmol_c\ kg^{-1}$ of Ca and 0.55 to 0.75 $cmol_c\ kg^{-1}$ of Mg, at 10–20 cm depth. The high levels of these elements can be attributed to the soil parent material, as most of the forest islands in Araçá Indigenous Land are associated with an underlying basalt dike (Melo et al. 2003).

Ca is one of the principal elements present in ashes obtained from burning plant materials (Borlini et al. 2005). However, according to Woods (2003) the greater portion of Ca in anthropogenic soils comes from the slow decomposition of bones, with levels of up to 41.8 $cmol_c\ kg^{-1}$ found in some dark earths in Central Amazonia (Glaser et al. 2004). In Araçá homegardens, however, Ca levels were more modest, achieving a maximum of 4 $cmol_c\ kg^{-1}$ in the surface layer of old homegardens, similar to values found by Kämpf et al. (2003) in a review of various anthropogenic soils in Amazônia. Alfaia et al. (2008) found Ca levels of up to 10.4 $cmol_c\ kg^{-}1$ in 50-year-old homegardens; however, these were located on the *várzea* floodplain, where soils have high natural fertility.

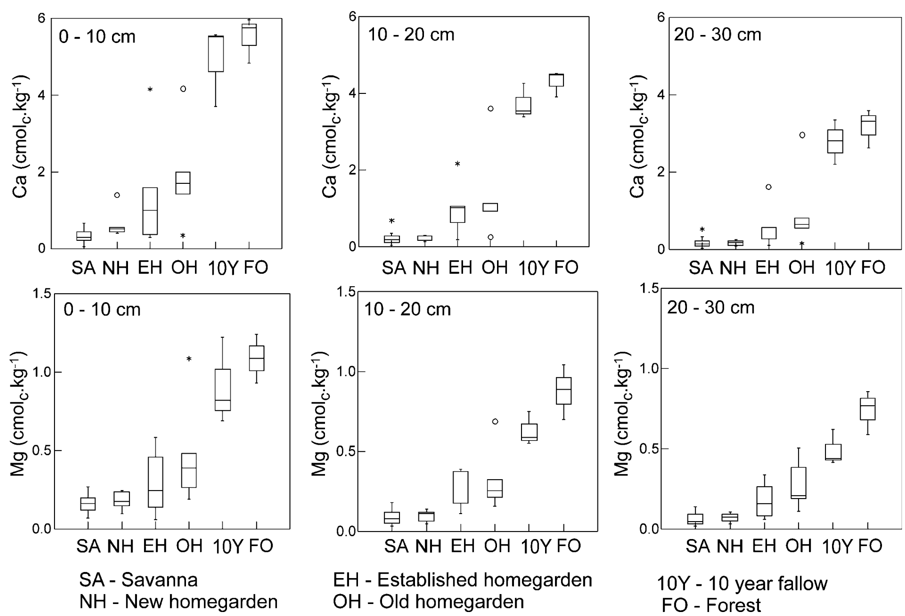


Fig. 5 Levels of Ca and Mg in soils of different environments, by depth, in Araçá Indigenous Land, Roraima, Brazil (□ = outlier at $P = 0.05$; * = outlier at $P = 0.01$; box = central 50% of data (2nd and 3rd quartile); central line = median; outside lines = 1st and 4th quartile)

Micronutrients

Both established and old homegardens show high levels of Zn, similar to levels found in forests and fallows (Fig. 6). In new homegardens, the level of this element is still low, similar to that found in savanna soils, suggesting that several years of homegarden existence are necessary to show effects as to accumulation of this nutrient. Zn, as did most macronutrients, showed little variation in the savanna samples, which were generally lower than levels found in homegardens (Fig. 9).

The average level of Fe found in old homegardens was similar to that found in fallows and forest (Fig. 6). However, while four old homegardens had values between 22.5 and 68 mg kg^{-1}, similar to the variation seen in the other categories of homegardens and savanna, one homegarden showed 501.2 mg kg^{-1} Fe. In this particular case, the homegarden was on a site with abundant lateritic concretions (ferric oxide). In order to eliminate the leverage effect of this strong outlier on the statistical analysis, this homegarden and the adjacent savanna plot were excluded from the regression. According to Woods (2003), soil Fe is usually not increased by anthropic activities, unless these are associated with the discarding of significant quantities of the metal, indicating that in the study area Fe levels have a greater relationship with underlying soil characteristics.

Cu and Mn showed similar means for homegardens and adjacent savanna, both inferior to levels found in fallows and forest (Fig. 7). As in the case of Fe, Cu and Mn showed a great deal of variation in adjacent savannas, with levels similar to those found in homegardens of all ages, suggesting that these nutrients also may be more influenced by soil parent material than by anthropic influences. However, even the lowest values for Cu and Mn were well superior to 0.15 and 8 mg kg^{-1}, respectively, the levels considered "satisfactory" by Cochrane et al. (1985) for tropical soils, suggesting that soils in the region are naturally well-supplied with Cu and Mn.

Acidity, aluminum, and organic matter

With regard to soil acidity, pH values were slightly higher in homegardens than in adjacent savanna, varying from 5.4 to 5.5 in the upper layer of homegardens, as compared to a variation from 4.9 to 5.6 in the upper layer of savannas (Fig. 8). Soils under fallows and forest reached pH values greater than 6.0, most likely due to their different parent material, richer in Ca. The values of pH found under the homegardens are considered lower than that

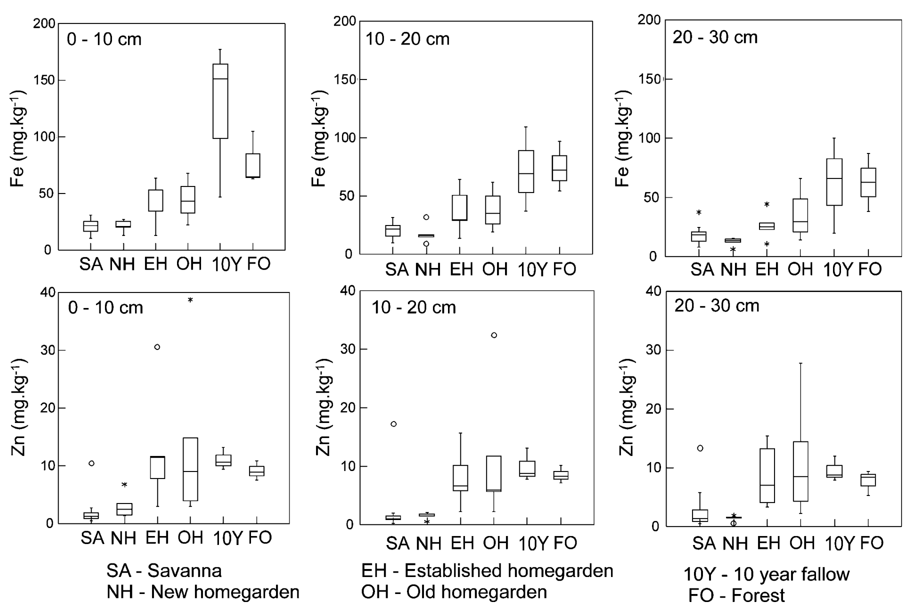


Fig. 6 Levels of Fe and Zn in soils of different environments, by depth, in Araçá Indigenous Land, Roraima, Brazil (□ = outlier at $P = 0.01$; * = outlier at $P = 0.05$; box = central 50% of data (2nd and 3rd quartile); central line = median; outside lines = 1st and 4th quartile)

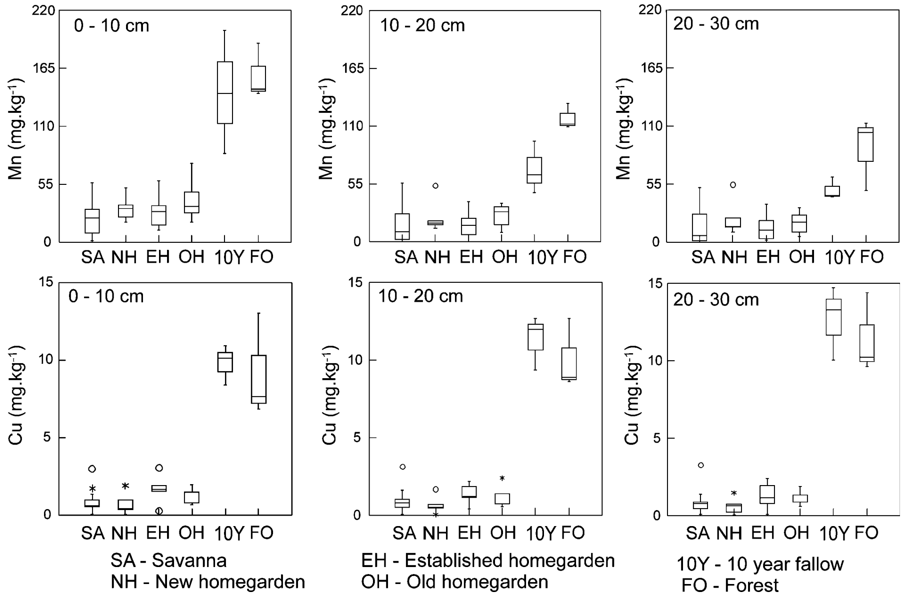


Fig. 7 Levels of Mn and Cu in soils of different environments, by depth, in Araçá Indigenous Land, Roraima, Brazil (□ = outlier at $P = 0.01$; * = outlier at $P = 0.05$; box = central 50% of data (2nd and 3rd quartile); central line = median; outside lines = 1st and 4th quartile)

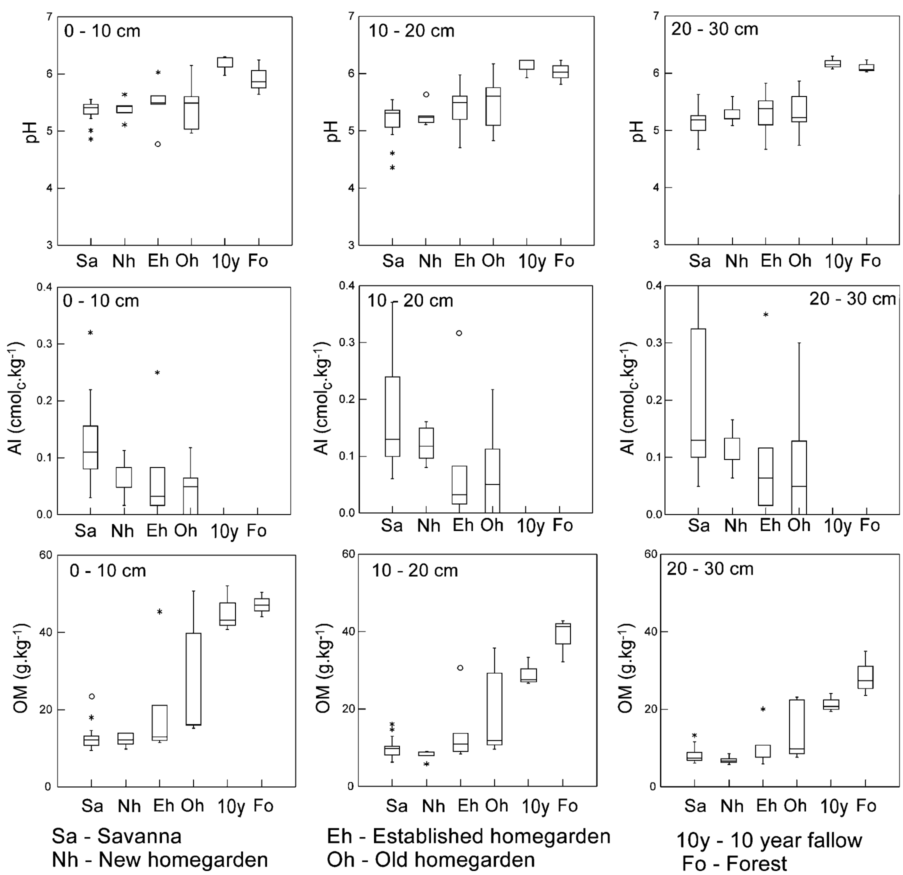


Fig. 8 Levels of pH, Al and organic matter in soils of different environments, by depth in Araçá Indigenous Land, Roraima, Brazil (□ = outlier at $P = 0.01$; * = outlier at $P = 0.05$; box = central 50% of data (2nd and 3rd quartile); central line = median; outside lines = 1st and 4th quartile)

recommended for most agricultural crops (Plaster 1997; Prasad and Power 1997), however, they are higher than levels found in most Amazonian soils (Alfaia et al. 2007; Dematte 2000).

The slight increase in pH under homegardens (Fig. 8) can be attributed to Ca inputs in the form of bones and ashes, and to a lesser extent, buffering by organic matter. Ashes are produced from firewood as well as by the common practice of burning leaves and other plant material gathered together when the area adjacent to the dwelling is swept or the homegarden is weeded. Studies by Alfaia et al. (2008) in the *várzea* floodplain along the Amazonas and Solimões Rivers found higher pH values in cultivated areas, when compared to high forest and secondary forest fallows, suggesting that the practice of burning is the principal factor in neutralizing soil acidity. OM produced by the homegardens may have a buffering effect on soil pH due to several processes, which include the increase in CEC and the size of the exchange complex from humification of OM additions, the formation of complexes with Al^{3+}, and the release of ionic forms of Ca and Mg in the soil solution, thus reducing the activity of H^+ (Miyazawa et al. 1993).

All areas sampled, under savanna or homegardens, showed levels of Al not higher than 0.4 $cmol_c$ Kg^{-1}, which is below that considered toxic to most crops, according to Cochrane et al. (1985). Even so, the homegarden soils presented levels of Al lower than that found in adjacent savanna, suggesting that the various management practices employed have an effect in limiting the toxicity of this element, by fixing, chelating or keeping Al out of solution (Fig. 8). In areas under fallow and forest, exchangeable Al was practically absent, which can be explained by the pH values greater than 5.5 (Sousa et al. 2007).

Soils under new homegardens showed levels of organic matter similar to that found in savanna soils (Fig. 8). Levels of organic matter increased over time, with old homegardens having twice the level as that found in savanna soils. However, levels superior to 45 g kg^{-1}, considered as "high" for tropical soils by Cochrane et al. (1985), were only found in the upper soil layers under fallows and forest, with 45.3 and 47.1 g kg^{-1}, respectively. Old homegardens, in comparison, reached average values of only 27.6 g kg^{-1} in the surface layer.

The low level of organic matter found in the majority of homegardens may be related to the sandy texture of their soils. In sandy soils, decomposition is generally more rapid because organic matter is more accessible to microorganisms, in contrast to clayey soils, where organic matter may be more effectively tied up in soil aggregates. The soils under fallows and forest showed the highest levels of organic matter, probably due to the greater quantities of litter being deposited on the soil surface, as well their higher clay content. In a slightly less deciduous forest located approximately 50 km to the southwest, albeit on sandy soils, Scott et al. (1992) measured an annual litter deposition rate of 4.6 t h^{-1}. In the Araçá homegardens, trees cover is less dense than in the forest or fallow, and leaves are commonly swept together and burned.

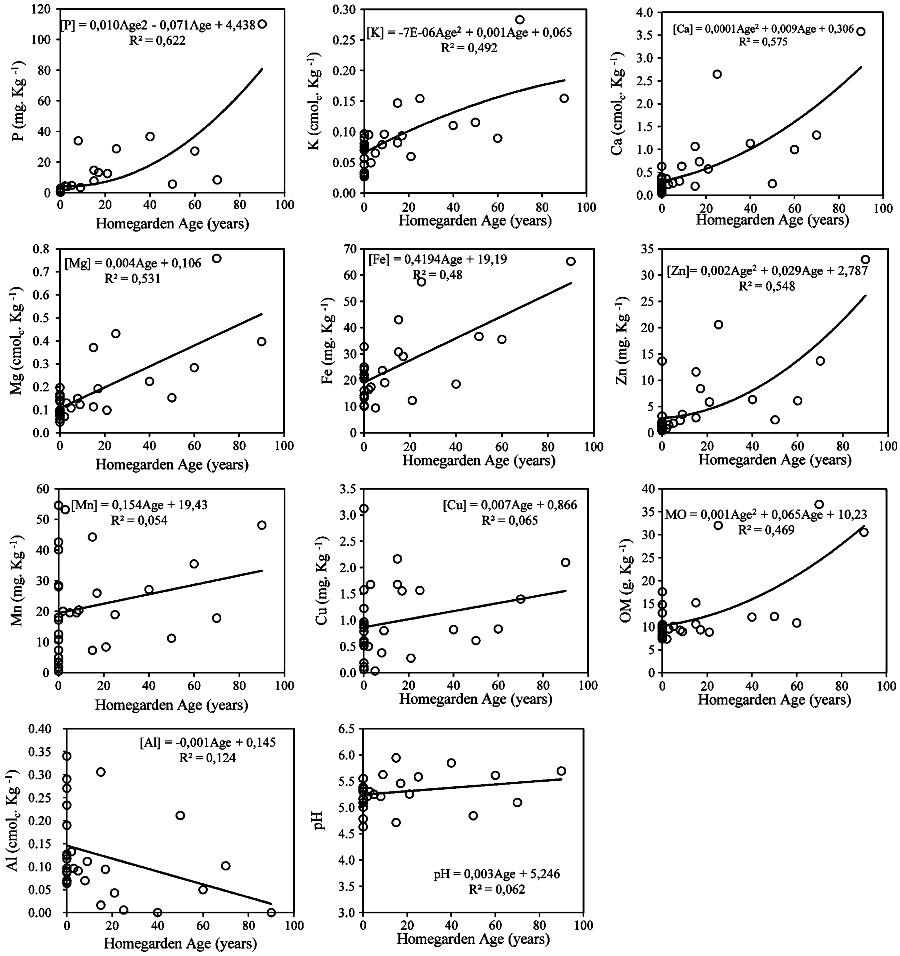
Regressions models for soil fertility improvement by homegardens

When compared to adjacent savanna, the initial analysis of soil fertility indicators (nutrients, pH, Al and organic matter) in indigenous homegardens clearly pointed to an increase in fertility along a chronosequence, with an apparently proportional relationship between increase in some nutrients and homegarden age. For this reason, the relation between levels of these fertility indicators and homegarden age was explored using linear and second-order exponential regressions (Fig. 9).

The regressions for macronutrients revealed a clear increase accompanying homegarden age, with an average of 55% of the observed variance attributable to homegarden age. All regressions reached probability significance values established ($P \leq 0.05$). The greatest coefficients ($r^2 = 0.62$ and $r^2 = 0.57$) were obtained for P and Ca, respectively, with second-order polynomial equations. The regressions for Mg and K also presented satisfactory fits with linear and second-order polynomial equations ($r^2 = 0.53$ and $r^2 = 0.49$).

For the micronutrients analyzed, the regressions for Fe and Zn also presented satisfactory adjustments with linear and second-order polynomial equations ($r^2 = 0.48$ and $r^2 = 0.55$). On average, 51.5% of the observed variance for these micronutrients can be explained by homegarden age. The linear regressions for Mn and Cu, however, did not present satisfactory

Fig. 9 Regressions models for levels of nutrients, pH, Al and organic matter versus homegarden age ($n = 30$; $P \leq 0.05$; adjacent savanna was considered as "age = zero")



fit with homegarden age as the independent variable, with only 6% of the variance explained by homegarden age.

Organic matter was modeled with a second-order polynomial equation, with a satisfactory fit obtained ($r^2 = 0.47$). With regard to parameters related to soil acidity (pH and Al), fits were unsatisfactory. The linear regression for Al explained 12.4% of the variance, with an inverse relation with homegarden age. Although the regression for pH explained only 6.2% of variance, with a slight increase with homegarden age, this increase can be considered relevant, considering that pH is measured on a log scale.

The regression models indicate that for all macronutrients analyzed, with exception of K, levels will double approximately 25 years after homegarden establishment. At 50 years, soils under old homegardens will have triple the Ca level found under nearby savanna, and P levels will be almost six times that found in savanna soils. After 90 years, the models suggest that homegardens will have 18 times more P than savanna. In the case of K, increment occurs more slowly, and 50 years are necessary for levels to double. The model for K increment is the only model to suggest a tendency for stabilization under older homegardens. In the remaining nutrients—with exception of Mn and Cu, for which variations are related chiefly to parent material, and pH, measured on a log scale—the models indicate that even 90 years after homegarden establishment, nutrient increment will continue to increase, so that it is difficult to estimate when stabilization occurs. For Zn, the model suggests a more modest, but still important increment, with levels doubling around 45 years after homegarden establishment, and tripling after 90 years.

Although the models provide a reasonable representation of the process of nutrient increment over time, the unique dynamics of individual homegardens cannot be disregarded. For example, a 22-year-old homegarden presented levels of Fe and Ca much greater than the other homegardens in its age class, and only slightly lower than levels found in a 90-years-old homegarden.

Application of results

When compared to adjacent areas of savanna, soils under homegardens in Araçá Indigenous Land showed a marked improvement in fertility over time. In some cases, nutrients reached levels similar or greater to that found under fallows or forest in nearby forest islands, which are associated with naturally more fertile soils. This increase in nutrients over time is most likely the result of the deposition of organic residues around dwellings. These residues have their origin in foods and other materials brought in from the surrounding landscape, such as agricultural products from fields in forest islands, fish from rivers, cattle manure from the savanna, thatch from *buriti* palms growing in gallery forests, and firewood, among others.

Expansion of homegardens into savanna in order to increase fruit production may benefit from the adaptation of some of the processes discussed in this paper—rather than wait for homegardens to slowly improve soil fertility over time, a more direct route can be taken by farmers, through the use of locally available materials such as ashes, manure, bones, and compost as fertilizers in planting pits and for subsequent care of trees, along with green manures and mulches to increase soil organic matter.

Although a number of homes sell a portion of their fruit production, principally limes, mangos and oranges, at the moment this export of nutrients does not appear to affect the sustainability of the homegarden systems. Should such production be increased, however, it may be possible that nutrient exports need to be balanced by greater inputs. Further research is needed, therefore, on ascertaining the quantities of fruit that are sold, and the quantities of nutrients involved.

Conclusions

This study made use of conventional soil science methods and statistics to characterize the essentially human-driven system of establishment of homegardens on the nutrient-poor soils of the savannas of Roraima, and their subsequent expansion and effects on soil properties. Although this process of soil improvement involves basically the accumulation of nutrients collected from various ecosystems, the effect of individual behavior and choice on homegarden history means that a great deal of variation is possible, as this was observed especially in the older homegardens. Nevertheless, the general trend observed was the improvement of soil characteristics over time, with homegardens becoming islands of fertility in the otherwise poor savanna soils.

Besides the deposition of organic residues, it is also possible that the observed increase in soil nutrients may be partially due to uptake by deep rooting homegarden trees, and subsequent cycling of nutrients in the form of leaf litter, fruit and branches. However, further research is necessary to verify this hypothesis, perhaps through the sampling of savanna soils at greater depths. Exploration of how nutrients are distributed spatially in homegardens, i.e., whether specific activities create "hotspots", and how long these persist over time, also represents an interesting line for further investigations.

In general, the study indicates a unique pattern of human interaction with the landscape, intrinsic to indigenous occupation of the savannas of Roraima, and reinforces current demands for the provision of adequate extensions of lands for indigenous peoples.

Acknowledgments This study was part of a broader project of research/extension with farming systems in Araçá Indigenous Land, funded by the European Union through the Guyagrofor Project—*Development of Sustainable Agroforestry Systems Based on Indigenous and Maroon Knowledge in the Guyana Shield Region*, coordinated by Alterra Institute, Wageninen University. Additional support was provided by the Instituto Olhar Etnográfico's AGROFLORR Project, funded by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). Both projects were carried out in collaboration with the Conselho Indígena de Roraima (CIR) and with support of local leaders and community members. The first author was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES). We also thank INPA technicians João Bosco Cintrão and José Edivaldo Chaves for assistance in soil sampling.

References

Alfaia SS, Uguen K, Rodrigues MRL (2007) Manejo da fertilidade dos solos na Amazônia. In: Moreira FMS, Siqueira JO, Brussaard L (eds) Biodiversidade do solo em ecossistemas brasileiros. UFLA, Lavras, pp 117–141

Alfaia SS, Neves AL, Ribeiro GA, Fajardo JDV, Uguen K, Ayres MIC (2008) Caracterização dos parâmetros químicos dos solos de várzea em diversos sistemas de uso da terra ao longo da calha dos rios Solimões/Amazonas. In: Noda SN (ed) Agricultura familiar na Amazônia das águas. EDUA, Manaus, pp 67–89

Barbosa RI (1997) Distribuição das chuvas em Roraima. In: Barbosa RI, Ferreira EJG, Castellón EG (eds) Homem, Ambiente e Ecologia no Estado de Roraima. INPA, Manaus, pp 325–335

Barbosa RI, Campos C, Pinto F, Fearnside PM (2007) The "Lavrados" of Roraima: biodiversity and conservation of Brazil′s amazonian savannas. Funct Ecosyst Commun 1(1):29–41

Beer J, Harvey C, Ibrahim M, Harmand JM, Somarriba E, Jiménes F (2003) Servicios ambientales de los sistemas agroflorestales. Agroforesteria en las Américas 10(37–38):80–87

Borlini MC, Sales HF, Vieira CMF, Conte RA, Pinatti DG, Monteiro SN (2005) Cinza da lenha para aplicação em cerâmica vermelha. Parte I: características da cinza. Cerâmica 51:192–196

BRASIL (1975) Projeto RADAMBRASIL–Levantamento dos Recursos Naturais, vol 8. Ministério das Minas e Energia, Rio de Janeiro, p 427

Clement C (1999) 1492 and the loss of Amazonian crop genetic resources. I. The relation between domestication and human population decline. Econ Bot 53(2):188–202

Cochrane TT, Sánchez LG, Azevedo LG, Porras JA, Garver CL (1985) Land in tropical America, vol 3. CIAT

Coomes OT, Ban N (2004) Cultivated plant species diversity in a home garden of an Amazonian peasant village in northeastern Peru. Econ Bot 58:420–434

Dematte JLI (2000) Solos. In: Salati E, Absy ML, Victoria RL (eds) Amazônia: Um ecossistema em transformação. INPA, Manaus, pp 119–162

EMBRAPA (1997) Manual de métodos de análise de solo, 2nd edn. 212 p

EMBRAPA (2006) Sistema brasileiro de classificação de solos, 2nd edn

Freitas VMB (2008) Dinâmica do nitrogênio em capoeiras e florestas em savanas de Roraima. Dissertation, Instituto Nacional de Pesquisas da Amazônia, Manaus

Gajaseni J, Gajaseni N (1999) Ecological rationalities of the traditional homegarden system in the Chao Phraya Basin, Thailand. Agrofor Syst 46:3–23

Glaser B, Zech W, Woods WI (2004) History, current knowledge and future perspectives of geoecological research concerning the origin of Amazonian anthropogenic dark earths (Terra Preta). In: Glaser B, Woods WI (eds) Exploration in Amazonian Dark Earths. Springer, Heidelberg, pp 9–17

Kämpf N, Woods WI, Sombroek W, Kern D, Cunha TJF (2003) Classification of Amazonian dark earths and other ancient anthropic soils. In: Lehmann J, Kern D, Glaser B (eds) Amazonian Dark Earths: origin, properties, management. Kluwer Academic Publishers, Dordrecht, pp 77–102

Kehlenbeck K, Maass BL (2004) Crop diversity and classification of homegardens in Central Sulawesi, Indonesia. Agrofor Syst 63:53–62

Kumar BM, Nair PKR (2004) The enigma of tropical homegardens. Agrofor Syst 61:135–152

McGrath DA, Duryea ML, Comeford NB, Cropper WP (2000) Nitrogen and phosphorus cycling in an Amazonian agroforest eight years following forest conversion. Ecol Appl 10(6):1633–1647

Melo VF, Gianluppi D, Uchoa SCP (2003) Características edafológicas dos solos do estado de roraima (Boletim de Pesquisa e Desenvolvimento 1). Embrapa Roraima, Boa Vista, p 28p

Miller RP, Penn JW, Leeuwen J (2006) Amazonian homegardens: their ethnohistory and potential contribution to agroforestry development. In: Kumar BM, Nair PKR (eds) Tropical homegardens: a time-tested example of sustainable agroforestry. Springer, Heidelberg, pp 43–60

Miller RP, Uguen K, Pedri MA, Creado ESJ, Martins LL, Trancoso R (2008) Levantamento Etnoambiental das Terras Indígenas do Complexo Macuxi-Wapixana, Roraima, v. 1. FUNAI/PPTAL/GTZ, Brasília, p 192

Miyazawa M, Pavan MA, Calegari A (1993) Efeito de material vegetal na acidez do solo. Revista Bras Ciência Solo 17:411–416

Nair PKR (1993) An introduction to agroforestry. Kluwer Academic Publishers, Dordrecht, p 499

Pinho RC (2008) Quintais agroflorestais indígenas em área de savana (Lavrado) na Terra Indígena Araçá, Roraima. Dissertation, Instituto Nacional de Pesquisas da Amazônia

Plaster EJ (1997) Soil science & management, 3rd edn. Delmar Publishers, Albany, p 402

Prasad R, Power JF (1997) Soil fertility management for sustainable agriculture. CRC Press, Boca Raton, p 356

Rhoades CC (1997) Single-tree influences on soil properties in agroforestry: lessons from natural forest and savanna ecosystems. Agrofor Syst 35:71–94

Scott DA, Proctor J, Thompson J (1992) Ecological studies on a lowland evergreen rain forest on Maraca Island, Roraima, Brazil. II—Litter and nutrient cycling. J Ecol 4:705–717

Sousa DMG, Miranda LN, Oliveira SA (2007) Acidez do solo e sua correção. In: Novais RF, Alvarez VVH, Barros NF, Fontes RLF, Cantarutti RB, Neves JCL (eds) Fertilidade do Solo. SBCS, Viçosa, pp 205–274

Tomé JB Jr (1997) Manual para interpretação de análise de solo. Agropecuária, Guaíba, p 247

Vale JF Jr, Souza MIL (2005) Caracterização e distribuição dos solos das savanas de Roraima. In: Barbosa RI, Xaud HAM, Costa e Sousa JM (eds) Savanas de Roraima: etnoecologia, biodiversidade e potencialidades agrossilvipastoris. FEMACT, Boa Vista, pp 79–92

Woods WI (2003) Development of anthrosol research. In: Lehmann J, Kern D, Glaser B (eds) Amazonian Dark Earths: origin, properties, management. Kluwer Academic Publishers, Dordrecht, pp 3–14

Yamada M, Osaqui HML (2006) The role of homegardens in agroforestry development: lessons from Tomé-Açú, a Japanese-Brazilian settlement in the Amazon. In: Kumar BM, Nair PKR (eds) Tropical homegardens: a time-tested example of sustainable agroforestry. Springer, New York, pp 299–316

Zinke PJ (1962) The pattern of influence of individual forest trees on soil properties. Ecology 43:130–133