AGROFORESTRY TREES INCREASE PHOSPHORUS AVAILABILITY IN AN OXISOL OF THE BRAZILIAN HUMID TROPICS

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Summary

We investigated the effect of land-use, i.e., agroforestry systems (AGR), pasture (PAS), and secondary forest (SEC), and specific agroforestry tree species, i.e., áraça-boi (*Eugenia stipitata*), Brazil nut (*Bertholletia excelsa*), cupuaçu (*Theobroma grandiflorum*), and pupunha (*Bactris gasipaes*), on P availability of acid upland soils of the central Amazon basin.

The land-use systems were established in 1991 and underwent different management regimes, with low-input fertilization in AGR and PAS, and no fertilization in SEC. A modified sequential P extraction was used to determine P availability, and total N and other nutrients were also measured.

Para ser publicado en Acta Amazonica (Brasil)

Pupunha increased resin P and Brazil nut increased bicarbonate organic P. Fertilization increased the hydroxide organic P. Áraça-boi increased hydroxide organic P. Pupunha and Brazil nut increased soil available P (sum of available Hedley fractions – AP) and fertilization increased moderately available P (sum of moderately available Hedley fractions – MAP). This suggests the use of pupunha and Brazil nut in agroforestry systems with moderate fertilization better maintain AP and MAP in soils of the central Brazilian Amazon than other tree species and land-use systems studied.

Keywords: Amazon, *Bactris gasipaes, Bertholletia excelsa,* Phosphorus fractions, Oxisol

Title in Portuguese: Árvores de sistemas agroflorestais aumentam a disponibilidade de fosforo num Oxisol dos tropicos humidos do Brasil.

Abstract (In the instructions it notes to list a summary and an abstract. Is one supposed to be in Portuguese and the other in English?)

We investigated the effect of land-use, i.e., agroforestry systems (AGR), pasture (PAS), and secondary forest (SEC), and specific agroforestry tree species, i.e., áraça-boi (*Eugenia stipitata*), Brazil nut (*Bertholletia excelsa*), cupuaçu (*Theobroma grandiflorum*), and pupunha (*Bactris gasipaes*), on P availability of acid upland soils of the central Amazon basin.

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Introduction

Phosphorus is extremely limiting to agricultural production throughout many parts of the tropics, especially the upland soils of the Brazilian Amazon (Dematê and Dematê, 1997). The highly weathered Oxisols of the Central Brazilian Amazon have considerably less available P and total P than Oxisols in other regions of South America, which is caused by low total P contents in the parent material, and not primarily by a high P fixation (Lehmann et al., 2001b). However, it is thought that effective agricultural management can improve soil P availability (Lehmann et al., 2001b; Solomon et al., 2002; Tiessen and Moir, 1993), and possibly decrease the need for fertilizers that are often expensive and difficult to obtain.

Agroforestry systems have been suggested as an alternative to slash-and-burn agriculture and as a strategy to improve soil chemical and physical characteristics of degraded lands, especially degraded pastures, in the Amazon basin (Fernandes et al., 1995). The use of perennial tree crop systems may also lower economic risk and increase diversity of the agricultural system, improve standard of living, and decrease deforestation pressures (Fernandes and Matos, 1995; Lal, 1991; McGrath et al., 2000b; Sanchez et al., 1985).

To date, most agroforestry studies in the Amazon have focused on a select and limited number of species, due to the nature of the research, and few have focused on nutrient cycling (McGrath et al., 2001b; Schroth et al., 2001; 2000), with equally few focusing on P fractionation (Lehmann et al., 2001b; McGrath et al., 2001a; 2000b; Solomon and Lehmann, 2000).

Sequential P fractionation is a method used to quantify pools/fractions of P according to their bioavailability (Hedley et al., 1982; Tiessen and Moir, 1993).

The objectives of this study were: 1) to quantify the effects of 10-year-old Central Amazonian agroforestry, pasture, and secondary forest systems in addition to agroforestry tree species on available and total soil P pools, and 2) to determine the effect of these systems and tree species on soil nutrients.

Methods and Measurements

Site description

The study area is located in central Amazônia on an upland soil at the EMBRAPA-CPAA field station located along highway BR-174, 53 km north of Manaus (2°30'36'' S and 2°30'42'' S and 60°01'29'' W and 60°01'46'' W (Coolman, 1994)), in the State of Amazonas, Brazil. The natural vegetation is evergreen tropical rainforest and the soil is a fine, isohyperthermic, Xanthic Hapludox (US Soil Taxonomy) with a pH of 4.3, available P of 2.5 mg P kg^{-1} soil (Mehlich-1), organic C of 2.6 mg g^{-1}, total N of 2 mg g^{-1}, and 356.7, 77.8, and 35.2 mg of Ca, Mg and K, respectively, kg^{-1} soil in the top 15 cm (McKerrow, 1992). Soil bulk density is 0.96 g cm^{-3} (Coolman, 1994) and was used in calculations throughout this study. The climate is humid tropical and the mean annual rainfall is 2500 mm, and mean annual temperature is 26.2 °C. The mean relative air humidity is 83.9% (Tapia-Coral et al., 1999).

The site is a former *Brachiaria decumbens* pasture that was grazed for four to eight years prior to being abandoned. The scrub forest that regenerated on the abandoned pasture was slashed and burned in 1991, three to five years post-abandonment, and four agroforestry prototype systems were established (Figure 1)(Fernandes et al., 1995). Three of the four existing systems were studied, with sampling focused on soils beneath specific trees and grasses, representing useful and profitable species for local economies, within those systems.

The agroforestry system (AGR) was fertilized with Triple Super Phosphate (20.1% P), KCl (49.8% K), lime (40.0% Ca), and urea (45% N) to provide 15.8 kg N ha^{-1} yr^{-1}, 23.7 kg P ha^{-1} yr^{-1}, 12.3 kg K ha^{-1} yr^{-1}, and 4.7 kg Ca ha^{-1} yr^{-1} for the period of 1991, when the systems were established, through 2001, when sampling was conducted (Table 1). The pasture (PAS) received fertilization over the same time period with the same products, in addition to ammonium sulfate (21% N; 23% S), at the rate of 4.6 kg N ha^{-1} yr^{-1}, 5.7 kg P ha^{-1} yr^{-1}, 0.5 kg K ha^{-1} yr^{-1}, 1.6 kg S ha^{-1} yr^{-1}, and 80.0 kg Ca ha^{-1} yr^{-1} (Table 1). PAS was originally grazed for 7 days with a 21-day rest period. Stocking rates and grazing periods were adjusted with varying plant-growing conditions. The secondary forest (SEC) was left to grow post-burn since 1991, without chemical amendments.

Sample collection

Soil samples were taken within a 1 m radius from the base of tree and grass species. Each soil sample was a composite of five soil samples. Beneath each of the tree species in AGR and SEC, nine soil samples were taken from the entire sampling area, with three soil samples per block (3 samples X 3 blocks = 9 samples total per tree). In PAS, 18 soil samples were taken from the entire sampling area, with six soil samples per block (6 samples X 3 blocks = 18 samples total). The species sampled in AGR were *Theobroma grandiflorum* Schumann, *Bactris gasipaes* Kunth, *Bertholletia excelsa* Humb. & Bonpl., and *Eugenia stipitata* McVaugh. PAS was sampled beneath *Brachiaria humidicola* Rendle, and SEC was sampled around the base of *Vismia* and *Cecropia* trees. Species were chosen because of their utility and profitability.

Sampling was random by tree species within each block. Soils were sampled at 0-15 cm depth, air-dried and sieved through a 2 mm sieve. Soils were contaminated with a high frequency of small charcoal pieces, which were removed to the greatest extent possible.

Analyses

Samples were sequentially extracted and analyzed according to a modified sequential phosphorus extraction (Hedley et al., 1982; Tiessen and Moir, 1993) (Table 2), that closely followed the extraction procedure detailed by Tiessen and Moir (1993). However, residual P was extracted using concentrated HNO_3 and $HClO_4$ at 200 °C in a sand bath until dry, because of P impurities in locally available H_2SO_4.

Because P fraction differences between soil of the land-use systems studied and soil beneath individual AGR tree species were significant, but not numerous, we grouped P fractions into inorganic P (Pi) and organic P (Po) and availability groups to determine if different or additional trends existed.

Hedley P fractions were summed as total Pi and total Po by adding mean P in inorganic and organic fractions, respectively, by species and land-use system. Phosphorus fractions were also grouped by availability into available P (AP), moderately available P (MAP), and resistant P (RP). Phosphorus in each availability group was determined through summation of mean P by individual AGR species and land-use systems. AP is the sum of P in the resin fraction and the bicarbonate inorganic and organic fractions. MAP is the sum of P in the hydroxide inorganic and organic fractions and the dilute acid fraction, and RP is the sum of P in the concentrated acid inorganic and organic fractions and the residual fraction.

Nutrient analysis

Exchangeable K was analyzed using a double acid extraction (0.05 M HCl and 0.0125 M H_2SO_4) and exchangeable Ca, Mg, and Al with 1 M KCl (EMBRAPA, 1999). Total soil N was determined by the Kjeldahl technique (EMBRAPA, 1999).

Statistical Analysis

The results were compared by analysis of variance (repeated measures, general linear model) using a completely randomized design. The SAS System and Minitab computer software were used to determine statistical differences (SAS Institute, Inc., Cary, NC). The repeated measures tool within The SAS System was used to account for repeated measures (nine extracts per sample for Hedley fractions) of the dependent variable for each sample. Where the variances were not homogeneous, a logarithmic transformation was applied. Differences were considered significant at $P < 0.05$.

Results

Phosphorus pools

Soil beneath pupunha contained four and six times more resin P than PAS and SEC soil, respectively (Table 3). Soil beneath Brazil nut contained six times more bicarbonate organic P than SEC soil. AGR soil, including soil beneath all species studied, contained about two times more hydroxide organic P than SEC soil. Soil beneath áraça-boi contained more hydroxide organic P than PAS and SEC soils, while PAS soil contained more hydroxide organic P than SEC soil. There was more total P (sum of Hedley fractions) in soils beneath áraça-boi, Brazil nut, and cupuaçu than in SEC soils.

Po was greater in AGR soil than in SEC soil (Table 3), and soils beneath áraça-boi, Brazil nut, and pupunha contained more Po than SEC soils also.

AP was greater in AGR soil than PAS and SEC soils (Table 4), and soils beneath Brazil nut and pupunha contained more AP than SEC soil. Although AGR soil did not contain more MAP than SEC soil, individually, soil beneath all species studied in AGR and PAS soil contained more MAP than SEC soil. For all land-use systems, MAP was greater than either AP or RP.

Soil nutrient concentrations in land-use systems and agroforestry species

Calcium was significantly greater in AGR and PAS soils than in SEC soils (Table 5), and soils beneath Brazil nut and pupunha contained more exchangeable Ca than SEC soils. SEC soils contained five and six times less exchangeable Ca than soils beneath pupunha and Brazil nut, respectively, and eight times less exchangeable Ca than PAS soil. PAS soils also contained more exchangeable Ca than soil beneath áraça-boi, close to three times more.

There was more K in AGR soil and soils beneath individual AGR species than in SEC soil. PAS soil contained more Mg than SEC soil, and soils beneath Brazil nut and pupunha contained more Mg than SEC soil. Comparing soils beneath individual AGR species, soil beneath pupunha contained more Mg than soil beneath cupuaçu. PAS soil had significantly less Al than SEC soils and soil beneath áraça-boi and Brazil nut. Additionally, soil beneath cupuaçu and pupunha contained less Al than soil beneath áraça-boi and SEC soil. Soil acidity was less beneath pupunha than beneath áraça-boi and Brazil nut.

Discussion

Phosphorus pools

Resin P was increased by tree species and fertilization, i.e., pupunha increased resin P where fertilization minimally increased resin P (Table 3). It may be that pupunha, being adapted to acidic and chemically poor soil (Sanchez and Salinas 1981; FAO 1986), affects surrounding soil through efficient nutrient cycling. Fernandes and Sanford (1995) suggested that pupunha may be able to access less soluble forms of soil P after observing significantly lower hydroxide organic P in soil beneath a 30 year old pupunha orchard than in soil beneath adjacent Costa Rica forests. Additionally, soil P pools were significantly increased by the transformation of P by litterfall, throughfall, and stemflow of pupunha in a Central Amazonian agroforestry system, due to relatively high foliar concentrations of pupunha (Lehmann et al., 2001b; Schroth et al., 2001).

Additionally, pupunha has surface roots that extend approximately 5 to 25 cm above the soil surface (personal observation). They are notable because they have a gelatinous covering, which is seasonal in its existence. Where these roots make contact with the soil surface, there is a change in the physical appearance of the soil, making it richer in color, with a seemingly 'worked' texture, influenced possibly by soil macrofauna or microbial biomass. Erick C. M. Fernandes suggests the gelatinous root covering might be a labile and easily assimilated source of C, which draws soil fauna to feed upon it. However, no studies have investigated the gelatinous covering on pupunha surface roots.

Resin P in soil beneath all AGR species and SEC soil was greater than a representative mean for Amazonian soils (McGrath et al., 2001b). Additionally, resin P, bicarbonate inorganic P, and bicarbonate organic P values were consistently greater than those of 6-year-old pupunha and cupuaçu plantation agroforestry systems in the Brazilian states of Acré and Rondônia (McGrath et al., 2001a). However, in a study of single agroforestry tree effects on P fractions north of Manaus, Brazil, each of our P fraction values were consistently less in SEC soil than soil beneath *Vismia* in their study. Additionally, each of our P fraction values were consistently less in soil beneath AGR species the study sites had in common (Lehmann et al., 2001c). Fertilization in these other studies was greater than fertilization in this study. Greater time after establishment, the use of more agroforestry tree species, greater fertilization, and the possibility of some of the soils having been Ultisols are likely reasons that the aforementioned P fractions were greater in our systems compared to those of McGrath et al. (2001b).

Bicarbonate organic P was affected by tree species, i.e., Brazil nut increased bicarbonate organic P (Table 3). Brazil nut had considerably more above ground biomass (372.4 ± 22.0 kg plant dry matter) than any of the other species studied (McCaffery, 2002). This may be indicative of considerably greater below ground biomass, which could be more efficient in taking up and recycling this P fraction.

AP was greater in soils beneath Brazil nut and pupunha than SEC soil, and was greater in AGR soil than PAS soil and SEC soil (Table 4). This suggests that P additions and the use of AGR species and management was beneficial to maintaining AP. Additionally, it suggests that Brazil nut and pupunha may have a mechanism to 'mine' P better than the other AGR species.

Air drying soils from England and Wales increased bicarbonate inorganic and organic P, compared to field-moist soils (Turner and Haygarth, 2003). Although errors in this study may have been caused by air-drying, we suspect error will likely be consistent, making values comparable across species within this study. Additionally, the soils in the study in England and Wales were of a different mineralogy in a temperate climate, which may influence the transferability of air drying errors of soil bicarbonate inorganic and organic P (Turner and Haygarth, 2003).

Fertilization had the greatest impact on producing differences in soil P in the hydroxide organic P fraction (Table 3), which more or less mirror P fertilization differences. Tiessen *et al.* (1992) also found that fertilizer applied P to an Oxisol in Northeastern Brazil was incorporated into hydroxide organic P. Tree species effects were limited only to áraça-boi, which is inexplicable.

MAP was greater in soil beneath all individual AGR species and PAS soil than in SEC soil (Table 4). This suggests that moderate fertilization is key in maintaining MAP. MAP is likely in equilibrium with AP and RP, contributing to plant nutrition and P cycling.

We expected that all species would have had more total soil P (Table 3) beneath AGR species than in SEC soil due to fertilization of AGR species. However, soil P concentrations in soil underneath pupunha did not increase. It is likely that more of the fertilizer P applied to pupunha was removed through harvest of heart of palm and pupunha fruits than was replenished by fertilization. Fertilizer P applied to the other species was also removed through fruits, nuts, wood, etc., but may not have exceeded P additions.

The total P values for soils of AGR, PAS, and SEC of 83.6, 68.2, and 42.5 mg P kg^{-1} soil, respectively were comparable with total soil P values of other studies in Central Amazônia (Lehmann et al., 2001b; 2001c), and were considerably lower than soils of other regions in Brazil (141 to 388 mg P kg^{-1} soil) (Lehmann et al., 2001b), which were considerably less than other worldwide soils (two soils from Africa contained 874 to 1426 mg P kg^{-1} soil) (Solomon et al., 2002).

Organic P was greater in AGR soil, except cupuaçu, than in SEC soil which can be explained by fertilization. Cupuaçu did not follow this pattern due to its capability to immobilize P. McGrath *et al.* (2000a) found cupuaçu litter to immobilize P for a period of one year in a litterbag experiment.

Soil nutrient concentrations in land-use systems and agroforestry species

It is interesting that soil beneath Brazil nut and pupunha had more Ca than SEC soil, considering Brazil nut received no lime and pupunha received very little (Table 5). This may be indicative of a tree specific effect that increased soil AP beneath pupunha and Brazil nut. PAS soil did not contain more Ca than soil beneath the other AGR species probably because of Ca uptake by the pasture grass or litter cycling of Ca in the other AGR species. Other differences in soil acidity, Al, and Ca were most likely due to differences in lime additions to different plants and land-use systems.

Mg was greater in soil beneath Brazil nut and pupunha and PAS soil than SEC soil, which is likely an additional result of lime amendments (Table 5). Soil beneath pupunha additionally contained more Mg than soil beneath cupuaçu. This may be related to the foliar C:N ratio, which is higher for cupuaçu than pupunha (Lehmann et al., 2001a), which could reduce decomposition and Mg release from litter.

Fertilization affected soil K. All species that received some fertilization contained more than SEC, where there was no fertilization.

Conclusion

Low-input fertilization and agricultural management through the use of native agroforestry tree species increased available soil P and other soil nutrients. Pupunha and Brazil nut increased soil AP, whereas áraça-boi, cupuaçu, PAS, and SEC did not. Pupunha and Brazil nut are suggested for use in designing perennial tree crop systems in Central Amazônia where sufficient soil P availability is of concern. We also suggest further research of the physiology of these species in order to better understand how they increase AP, so other species with similar physiology may be tested for use in maintaining AP in soils of central Amazônia.

Fertilization increased MAP, which is important in maintaining long-term P availability. Therefore, in addition to establishing agroforestry systems in central Amazônia with pupunha and Brazil nut tree species, among other native perennial tree crops, it is important to apply or maintain low-level fertilization to at least account for nutrients removed in harvests.

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