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# Phosphorus Fertilization Increases Biomass and Nutrient Accumulation Under Improved Fallow Management in a Slash-and-Mulch System in Eastern Amazonia, Brazil

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**ABSTRACT:** Improvement of fallow vegetation can have a positive impact on the productivity of slash-and-mulch systems in eastern Amazonia. Phosphorus fertilization can increase biomass and nutrient stocks in the fallow phase, thereby improving nutrient cycling and crop productivity. Here, we compared biomass and nutrient stocks under three fallow management strategies: (1) natural fallow (regrowth vegetation) - NF; (2) NF vegetation improved with leguminous trees (*Sclerolobium paniculatum* Vogel and *Inga edulis* Mart.) - IF; and (3) NF vegetation improved with leguminous trees plus phosphorus fertilization - $IF_{+P}$. We quantified above- and belowground biomass and N, P, K, Ca, and Mg stocks after 23 months of fallow. The $IF_{+P}$ increased aboveground (leaf + branch + stem + liana) biomass and N, P, Ca, and Mg stocks, compared to NF. Similarly, total (aboveground + belowground) biomass and N and P stocks were higher for $IF_{+P}$ than for NF. The differences in aboveground biomass between NF and improved fallow managements were attributed exclusively to the contribution of the tree species enriching fallow vegetation. Phosphorus application increased the aboveground biomass accumulation of the species for fallow improvement. Improving the fallow vegetation with P-fertilized, fast-growing, N-fixing species represents an efficient management strategy to accelerate the reestablishment of biomass and nutrient stocks in slash-and-mulch systems in Amazonia.

**Keywords:** aboveground biomass, fine roots, *Inga edulis*, low-input agriculture, *Sclerolobium paniculatum*.

## INTRODUCTION

Shifting cultivation, also known as slash-and-burn agriculture, is being used by about 600,000 smallholder families in Amazonia (Walker et al., 1998). This low-input farming system (Singh and Lal, 2005) is characterized by repeated cultivation-fallow cycles, with the use of fire for land preparation. The duration of the cultivation period is mainly determined by a gradual reduction in soil fertility. The primary role of fallow vegetation, also called second-growth forest, is to accumulate biomass and nutrients to sustain subsequent crops (Schroth and Lehmann, 2003). This is particularly relevant because most smallholder farmers cannot afford external inputs such as fertilizers and lime. The development and adoption of techniques that improve biomass accumulation and nutrient cycling during fallow periods are therefore needed for the sustainability of shifting cultivation systems.

Slash-and-burn usually increases the short-term availability of base cations and the pH (Béliveau et al., 2015), but soil fertility gradually diminishes afterwards (Sommer et al., 2004). Fine soil particles are lost in the first year of cultivation after slashing and burning in Central Amazonia, suggesting rapid impacts on soil erosion (Béliveau et al., 2015). Recovery of soil fertility in shifting cultivation often requires long fallow periods (usually 7-10 years) and depends on the reestablishment of biomass vegetation. A shorter fallow period and intensified cultivation period (Metzger et al., 1998; Vielhauer et al., 2001) result in lower biomass and nutrient accumulation (Sommer et al., 2004; Zarin et al., 2005). This scenario leads to reduced productivity during the cultivation period and consequently stimulates the further exploitation of forest remnants.

Strategies to increase the sustainability of shifting cultivation would be to avoid burning for land preparation and/or increase biomass and nutrient accumulation by improved fallow vegetation. Chop-and-mulch, a fire-free technique for land preparation (Denich et al., 2004), conserves nutrients, improves soil quality, and reduces carbon dioxide-equivalent emissions from the soil to the atmosphere in comparison to slash-and-burn, as shown by studies conducted in eastern Amazonia (Sommer et al., 2004; Davidson et al., 2008; Comte et al., 2012; Reichert et al., 2015, 2016;). However, chop-and-mulch has not always increased soil carbon stocks (Perrin et al., 2014). A recent study in eastern Amazon that compared the effects of slash-and-burn and chop-and-mulch systems concluded that mulching increases soil phosphorus availability (Farias et al., 2016). However, these authors did not consider that P fertilizer was added to the chop-and-mulch area in the first (Davidson et al., 2008) as well as in the subsequent crop-fallow cycles (O. Kato, personal communication). Chop-and-mulch areas have to be fertilized to overcome nutrient immobilization after soil tillage (Kato et al., 1999). Thus, the conclusion of Farias et al. (2016) is not valid because in their experiment the effects of plant strategies to acquire P could not be separated from the contribution of fertilizer-P. In fact, further investigation is needed to understand the effects of chop-and-mulch systems on P cycling in the eastern Amazon.

Studies in the Amazon and other tropical regions have demonstrated that the inclusion of fast-growing, nitrogen-fixing leguminous trees among the fallow vegetation species improves the biomass and nutrient accumulation, contributing to the recovery of soil fertility (Szott and Palm, 1996; Brienza Jr, 1999; Barrios and Cobo, 2004; Basamba et al., 2007). However, surprisingly little is known about nutrient recovery in response to this improved fallow technique in eastern Amazonia. We hypothesized that associating fallow improvement with P fertilization would increase biomass and nutrient stocks during the fallow period. Phosphorus is known to be limiting to crop production, particularly in tropical soils, due to the fixation of this nutrient on iron and aluminum sesquioxides (Szott et al., 1999). In eastern Amazonia, nutrient-enrichment experiments have shown that P is the most limiting soil nutrient during periods of natural fallow (Gehring et al., 1999; Davidson et al., 2004) and cropping in slash-and-burn and chop-and-mulch systems; comparable experiments on improved fallow systems are not available for this region.

Soil pH controls P availability, but few studies have evaluated the impacts of soil pH adjustment by liming on soil P availability in chop-and-mulch systems in eastern Amazonia. A previous study showed that corn yield did not respond to lime (surface applied) in a slash-and-mulch system in the northern Brazilian Amazon (Costa, 2012). Lime incorporation, which is the most efficient form of soil pH adjustment, would eliminate the mulch layer, which is one of the key elements of chop-and-mulch systems. According to Joslin et al. (2016), the use of tree species tolerant to acid soils (e.g., *Inga edulis*) associated with P fertilization in an improved fallow management met the demands of both food and tree crops of slash-and-mulch systems in eastern Amazonia. This represents a viable low-input approach that does not necessarily rely on lime input. A better understanding of the role of soil P availability in crop growth and nutrient accumulation in improved fallow management may help to improve low-input, fallow-based agricultural systems.

This study aimed to evaluate the effects of P fertilization on above- and below-ground biomass and nutrient accumulation of fast-growing, nitrogen-fixing leguminous trees in an improved fallow management of a slash-and-mulch system in eastern Amazonia.

## MATERIALS AND METHODS

### Study site

This study was conducted on a smallholder farm (1° 00’ 4” S, 47° 38’ 3” W) near the village São João, municipality of Marapanim, in the northeast of the state of Pará, Brazil. Northeastern Pará is part of the Bragantina Region, which is one of the first agricultural frontiers in the Brazilian Amazon.

The climate is Ami, according to Köppen’s classification system. The annual rainfall is 2,506 ± 212 mm (mean ± standard deviation), with a wet season from January to June (1,968 ± 175 mm) and a dry season from September to November (164 ± 67 mm). The mean annual temperature is 26 °C, with little seasonal variation.

The soil in the study area was classified as *Argissolo Vermelho-Amarelo* (Udult), sandy (760-880 g $kg^{-1}$ sand in the 0.00-0.50 m layer), acidic, and characterized by low plant-available P and low cation exchange capacity (Sommer et al., 2004). Some soil chemical and physical properties of the experimental area in June 2007 are presented in table 1. Ultisols represent 53 % of the soils in the watershed where our study site is located (Silva et al., 2013).

In May 2006, a fragment of approximately 0.5 ha of 8-year-old second-growth forest was mechanically chopped and mulched according to Denich et al. (2004), with a forestry mulcher (AHWI FM600). One month after land preparation, the smallholder farmer planted cassava (*Manihot esculenta* cv. cearense) at 1 × 1 m spacing. In June 2007, close to the end of the cassava cycle and the beginning of the fallow period, we planted seedlings of *Inga edulis* Mart (mean height = 0.28 m, n = 40) and *Sclerolobium paniculatum* Vogel (mean height = 0.35 m, n = 40), which are both nitrogen-fixing Fabaceae species,

**Table 1.** Some initial soil chemical and physical properties of the experimental area, in June 2007

| Depth | pH($H_2O$) | $Al^{3+}$ | H+Al | Coarse sand | Fine sand | Silt | Clay |
|---|---|---|---|---|---|---|---|
| m | | cmol$_c$ $dm^{-3}$ | | g $kg^{-1}$ | | | |
| 0.00-0.10 | 5.3 | 0.1 | 5.8 | 544 | 335 | 62 | 60 |
| 0.10-0.20 | 4.8 | 0.6 | 6.6 | 447 | 396 | 57 | 100 |
| 0.20-0.30 | 4.7 | 0.8 | 7.1 | 429 | 383 | 88 | 100 |
| 0.30-0.50 | 4.6 | 1.0 | 6.3 | 381 | 379 | 80 | 160 |

pH in water at a ratio of 1:2.5 v/v; $H^+$ and $Al^{3+}$ extracted with KCl 1 mol $L^{-1}$; particle-size distribution determined by the Pipette method (Ruiz, 2005). Source: Rangel-Vasconcelos et al. (2016).

in eight experimental plots at 2 × 2 m spacing between cassava rows; the two species were planted alternately in the row. These species performed well in a previous trial of fast-growing species for fallow improvement in eastern Amazonia (Brienza Jr, 1999). In four plots, we applied 200 g of partially acidulated phosphate rock (total $P_2O_5$ ≈ 33 %; citric acid-soluble $P_2O_5$ ≈ 11 %) in the planting holes of the *I. edulis* and *S. paniculatum* seedlings (equivalent to a fertilization rate of 165 kg $ha^{-1}$ $P_2O_5$). Four additional plots with spontaneous (natural) fallow were used as control. Although soil P availability is controlled by soil pH, the soil pH was not adjusted in our experiment because: (a) the P release from phosphate rock is higher at increased soil acidity (Rajan et al., 1991), (b) of an absence of aluminum toxicity, and (c) of operational difficulties. This experimental approach was also consistent with our objective to evaluate the potential of trees to improve P cycling in low-input agriculture (Joslin et al., 2016).

The plots measured 10 × 12 m (total = 12), with an evaluated area of 48 $m^2$ in the center. The treatment plots (improved fallow - IF, fertilized improved fallow - $IF_{+P}$, and natural fallow - NF) were arranged in a randomized complete block design with four replicates.

During the cultivation period, the improved fallow plots were managed according to the farmer's criteria, with manual weeding below the crown of the planted trees; the control plots were not managed. In October 2007, cassava was harvested and the planted trees were felled by hand. The tree biomass, litter, fine roots, and adjacent soil were sampled 23 months after planting (May 2009).

## Aboveground biomass, litter, and root sampling and chemical analyses

In April 2008, we collected young, fully expanded, healthy leaves from the mid-canopy of *I. edulis* and *S. paniculatum* trees. We sampled one leaf from each 4-6 trees per species per plot and determined the P content (Murphy and Riley, 1962) separately for each species.

In May 2009, we used a destructive method to quantify the aboveground biomass accumulated over the previous 23 months. Four trees (66.7 % of the total number of planted trees) of each planted leguminous species were randomly selected per plot. To sample the spontaneous species, which included both herbaceous and gramineous species, we randomly defined a 12 $m^2$ area within the subplot. We divided the aboveground plant material into four components (stem, branches, leaves, and lianas) and determined the fresh weight of each component in the field. Approximately 0.5 kg of each component was subsampled to determine the fresh weight in the field and dry weight in the laboratory (65 °C). The sample dry weight was then calculated from the fresh and dry weights of the subsample, for both planted trees and spontaneous species.

We collected forest-floor litter in nine randomly chosen areas (0.5 × 0.5 m) of the evaluated area. For the IF and $IF_{+P}$ plots, we collected three samples between the lines of the planted tree species, three samples from under the *S. paniculatum*, and three samples from under the *I. edulis* canopy. The litter samples were air-dried, and adhering soil particles and roots were gently removed with forceps and soft brushes. We then separated the material into four compartments - leaves, branches, residual mulch (from the previous fallow period), and cassava residue (mostly stem) - which were subsequently oven-dried and weighed.

To quantify root biomass, we randomly collected five soil core samples per plot (ø = 11.5 cm; depth = 13 cm). The soil cores were immediately refrigerated and maintained at 4 °C until processing. The soil cores were gently disaggregated in tap water, and the roots manually separated into two diameter classes (≤2 mm and 2.1-5.0 mm), hereafter referred to as fine and coarse roots, respectively. The root samples were then oven-dried at 65 °C to constant weight.

We determined the N, P, K, Ca, and Mg content of each biomass component (stem, leaves, branches, and roots) and litter fraction (leaves, branches, residual mulch, and cassava residue), as described by Carmo et al. (2000). The nutrient content of the biomass components was analyzed separately for each planted species (*I. edulis* and *S. paniculatum*) and for spontaneous vegetation.

The aboveground biomass, litter, and root samples were ground in a Willey mill and stored for chemical analyses. We used sulfuric acid and peroxide digestion at 270 °C for N digestion, and 2:1 nitroperchloric solution (nitric acid 65 % and perchloric acid 70 %) for P, K, Ca, and Mg digestion. The N and P concentrations were determined by the Kjeldahl method and ultraviolet-visible spectroscopy, respectively. The K concentration was determined by flame atomic emission spectroscopy, whereas Ca and Mg concentrations were determined with atomic absorption spectroscopy. Nutrient stocks were calculated using the nutrient concentration and dry mass data.

### Soil sampling and analytical procedures

Soil was sampled in June 2007, prior to the experiment, and in May 2009, at the end of the experiment. In each plot, we collected six individual samples that were combined to provide one composite sample per soil layer (0.00-0.10, 0.10-0.20, 0.20-0.30, and 0.30-0.50 m).

In the laboratory, all samples were air-dried, sieved (<2 mm), and ground for chemical analyses (Claessen, 1997). The $Ca^{2+}$ and $Mg^{2+}$ were extracted with KCl 1 mol $L^{-1}$ and analyzed using atomic absorption spectroscopy; $K^+$ was extracted with HCl 0.05 mol $L^{-1}$ and analyzed using flame atomic emission spectroscopy. Phosphorus (P) content was extracted with Mehlich-I solution and quantified by a spectrophotometric method. Total C and N contents were determined by dry combustion, using a LECO CNS-2000 elemental analyzer (Leco Corp., St. Joseph, MI).

### Statistical analysis

We tested the effects of fallow management strategies on the aboveground biomass, root, and litter variables using a one-way Anova. We also used a one-way Anova to test wether the natural fallow biomass was changed by improved fallow managments. We tested the effects of sampling period (pre-fallow and post-fallow), fallow management, and the interaction between sampling period and fallow management on the soil chemical variables using a two-way Anova. We used SAS version 9.1 (Statistical Analysis Systems Institute Inc., 2004) for two-way Anova and Sigma Plot version 11.0 (Systat Software, San Jose, CA) for one-way Anova.

## RESULTS

Leaf P contents increased with P fertilization in both *I. edulis* (IF = 0.71 ± 0.06 g $kg^{-1}$; $IF_{+P}$ = 0.81 ± 0.04 g $kg^{-1}$; P-value = 0.059) and *S. paniculatum* (IF = 0.48 ± 0.04 g $kg^{-1}$; $IF_{+P}$ = 0.58 ± 0.04 g $kg^{-1}$; P-value = 0.081). Fallow management strategies and the interaction between fallow strategies and the 23-month period did not alter soil nutrients, whereas the content of soil C, N, P, and K were affected by time. In the post-fallow period, C contents were lowest in the layer 0.30-0.50 m, of N in all layers, of P in 0.20-0.30 m, and of K in the layers 0.20-0.30 and 0.30-0.50 m (Table 2).

The aboveground biomass of the planted tree species in improved fallow was 6.2 Mg $ha^{-1}$ in IF (*I. edulis* = 0.7 ± 0.2; *S. paniculatum* = 5.5 ± 1.1 Mg $ha^{-1}$), and 10.1 Mg $ha^{-1}$ in $IF_{+P}$ (*I. edulis* = 1.5 ± 0.3; *S. paniculatum* = 8.6 ± 1.2 Mg $ha^{-1}$), corresponding to 38 and 46 % of the total aboveground biomass of these treatments (IF = 16.5 ± 2.0; $IF_{+P}$ = 21.7 ± 1.4 Mg $ha^{-1}$) (Table 3), respectively. The biomass of the spontaneous species in the improved fallow treatments did not differ from the biomass of the natural fallow treatment.

Leaf, branch, and stem biomass and P stocks were higher in $IF_{+P}$ than in NF, and intermediate in IF (Table 3). The stem Ca stocks were higher in $IF_{+P}$ than in IF or NF (Table 3). The total

**Table 2.** Total carbon, total nitrogen, available phosphorus, potassium, calcium, and magnesium in soil at the start and at the end of 23 months of natural fallow (NF), improved fallow (IF), and improved fallow with P fertilization ($IF_{+P}$) in Marapanim, eastern Amazonia

| Soil layer | Start | | | | End | | | |
|---|---|---|---|---|---|---|---|---|
| | NF | IF | $IF_{+P}$ | Mean | NF | IF | $IF_{+P}$ | Mean |
| m | | | | | | | | |
| Total C (mg kg$^{-1}$) | | | | | | | | |
| 0.00-0.10 | 15.9 (2.0) Aa | 13.0 (2.3) Aa | 13.4 (0.6) Aa | 14.2 (1.0) A | 13.5 (1.1) Aa | 14.0 (1.1) Aa | 14.8 (2.0) Aa | 14.1 (1.0) A |
| 0.10-0.20 | 8.3 (0.6) Aa | 9.4 (0.6) Aa | 9.5 (0.5) Aa | 9.0 (0.4) A | 8.1 (0.7) Aa | 8.0 (0.4) Aa | 8.5 (0.7) Aa | 8.2 (0.4) A |
| 0.20-0.30 | 6.6 (0.7) Aa | 7.4 (0.5) Aa | 7.2 (0.1) Aa | 7.0 (0.3) A | 7.0 (0.5) Aa | 6.6 (0.3) Aa | 6.8 (0.3) Aa | 6.8 (0.3) A |
| 0.30-0.50 | 7.2 (0.5) Aa | 6.9 (0.4) Aa | 7.6 (0.6) Aa | 7.2 (0.3) A | 5.8 (0.5) Aa | 5.5 (0.3) Aa | 5.8 (0.2) Aa | 5.7 (0.2) B |
| Total N (mg kg$^{-1}$) | | | | | | | | |
| 0.00-0.10 | 1.1 (0.1) Aa | 1.2 (0.1) Aa | 1.1 (0.2) Aa | 1.1 (0.1) A | 0.8 (0.1) Aa | 1.0 (0.1) Aa | 1.0 (0.1) Aa | 0.9 (0.1) B |
| 0.10-0.20 | 0.7 (0.2) Aa | 1.0 (0.01) Aa | 1.1 (0.02) Aa | 0.9 (0.1) A | 0.5 (0.2) Aa | 0.6 (0.02) Aa | 0.7 (0.1) Aa | 0.6 (0.1) B |
| 0.20-0.30 | 0.6 (0.2) Aa | 0.9 (0.03) Aa | 0.9 (0.01) Aa | 0.7 (0.1) A | 0.4 (0.1) Aa | 0.6 (0.03) Aa | 0.6 (0.1) Aa | 0.5 (0.1) B |
| 0.30-0.50 | 0.5 (0.2) Aa | 0.8 (0.1) Aa | 0.9 (0.1) Aa | 0.7 (0.1) A | 0.3 (0.1) Aa | 0.5 (0.02) Aa | 0.5 (0.1) Aa | 0.4 (0.1) B |
| P (mg dm$^{-3}$) | | | | | | | | |
| 0.00-0.10 | 4.4 (0.3) Aa | 3.8 (0.8) Aa | 3.8 (0.5) Aa | 4.0 (0.3) A | 3.3 (0.2) Aa | 2.9 (0.2) Aa | 4.3 (0.9) Aa | 3.5 (0.3) A |
| 0.10-0.20 | 2.7 (0.6) Aa | 3.0 (0.6) Aa | 2.4 (0.3) Aa | 2.7 (0.2) A | 2.3 (0.6) Aa | 2.4 (0.8) Aa | 2.0 (0.4) Aa | 2.2 (0.3) A |
| 0.20-0.30 | 1.8 (0.3) Aa | 1.8 (0.3) Aa | 2.0 (0.4) Aa | 1.8 (0.2) A | 1.3 (0.3) Aa | 1.1 (0.1) Aa | 1.1 (0.1) Aa | 1.2 (0.1) B |
| 0.30-0.50 | 1.0 (0.0) Aa | 1.3 (0.3) Aa | 1.8 (0.5) Aa | 1.3 (0.2) A | 1.0 (0.0) Aa | 1.1 (0.1) Aa | 1.1 (0.1) Aa | 1.1 (0.1) A |
| K (mg dm$^{-3}$) | | | | | | | | |
| 0.00-0.10 | 27.0 (3.3) Aa | 33.50 (6.1) Aa | 31.0 (2.7) Aa | 31.2 (2.5) A | 29.0 (1.7) Aa | 34.8 (3.3) Aa | 27.5 (1.9) Aa | 30.3 (1.6) A |
| 0.10-0.20 | 19.7 (1.8) Aa | 29.3 (5.2) Aa | 19.0 (4.6) Aa | 22.7 (2.7) A | 18.5 (1.3) Aa | 20.5 (5.1) Aa | 18.3 (1.0) Aa | 19.1 (1.6) A |
| 0.20-0.30 | 18.0 (1.0) Aa | 19.0 (1.7) Aa | 20.0 (0.6) Aa | 19.30 (0.6) A | 14.5 (1.0) Aa | 16.3 (1.1) Aa | 14.5 (1.1) Aa | 15.1 (0.6) B |
| 0.30-0.50 | 17.5 (0.5) Aa | 17.5 (1.3) Aa | 18.5 (1.0) Aa | 17.8 (0.5) A | 13.3 (1.4) Aa | 14.3 (0.3) Aa | 13.1 (0.3) Aa | 13.5 (0.5) B |
| $Ca^{2+}$ ($cmol_c$ dm$^{-3}$) | | | | | | | | |
| 0.00-0.10 | 2.2 (0.2) Aa | 2.1 (0.6) Aa | 1.7 (0.2) Aa | 2.0 (0.2) A | 2.0 (0.1) Aa | 2.4 (0.2) Aa | 2.3 (0.3) Aa | 2.2 (0.1) A |
| 0.10-0.20 | 0.7 (0.1) Aa | 1.1 (0.2) Aa | 0.6 (0.1) Aa | 0.8 (0.1) A | 1.1 (0.2) Aa | 2.0 (0.8) Aa | 0.8 (0.1) Aa | 1.3 (0.3) A |
| 0.20-0.30 | 0.6 (0.1) Aa | 0.5 (0.03) Aa | 0.5 (0.03) Aa | 0.5 (0.04) A | 0.7 (0.1) Aa | 0.7 (0.1) Aa | 0.5 (0.02) Aa | 0.5 (0.04) A |
| 0.30-0.50 | 0.5 (0.1) Aa | 0.4 (0.03) Aa | 0.4 (0.03) Aa | 0.4 (0.04) A | 0.6 (0.1) Aa | 0.4 (0.1) Aa | 0.4 (0.04) Aa | 0.4 (0.1) A |
| $Mg^{2+}$ ($cmol_c$ dm$^{-3}$) | | | | | | | | |
| 0.00-0.10 | 0.5 (0.2) Aa | 0.6 (0.1) Aa | 0.6 (0.03) Aa | 0.5 (0.1) A | 0.6 (0.1) Aa | 3.3 (2.7) Aa | 0.6 (0.1) Aa | 1.3 (0.9) A |
| 0.10-0.20 | 0.3 (0.1) Aa | 0.3 (0.1) Aa | 0.2 (0.1) Aa | 0.3 (0.1) A | 0.5 (0.1) Aa | 0.6 (1.0) Aa | 0.5 (0.1) Aa | 0.1 (0.3) A |
| 0.20-0.30 | 0.3 (0.04) Aa | 0.3 (0.02) Aa | 0.03 (0.04) Aa | 0.3 (0.02) A | 0.3 (0.04) Aa | 0.3 (0.02) Aa | 0.3 (0.02) Aa | 0.3 (0.02) A |
| 0.30-0.50 | 0.2 (0.03) Aa | 0.2 (0.03) Aa | 0.2 (0.03) Aa | 0.2 (0.01) A | 0.3 (0.1) Aa | 0.3 (0.04) Aa | 0.3 (0.03) Aa | 0.3 (0.02) A |

Total C and N determined by dry combustion; $Ca^{2+}$ and $Mg^{2+}$ extracted with KCl 1 mol L$^{-1}$; K extracted with HCl 0.05 mol L$^{-1}$; P extracted with Mehlich-1 solution. Standard errors in parentheses. For each soil layer, means followed by the same letter (uppercase compares start and end values for each fallow management and the mean; lowercase compares fallow managements within periods) did not differ at a significance level of 5 % (Tukey's test).

aboveground biomass and total N, P, Ca, and Mg stocks were higher in $IF_{+P}$ than in NF. The N, Ca, and Mg stocks in IF did not differ from the stocks in $IF_{+P}$ or NF (Table 3).

In the $IF_{+P}$ treatment, the values of woody + non-woody litter N stocks were 12 and 67 % higher than in IF and NF, respectively (Table 4). Similarly, the total litter Mg stock values in the $IF_{+P}$ treatment were 25 and 28 % higher than the IF and NF values, respectively (Table 4). The litter mass and P, K, and Ca stocks were not altered by the fallow management strategies (Table 4).

The fine, coarse, and fine + coarse root dry mass and stocks of N, K, Ca, and Mg were not altered by the fallow management strategies (Table 5). The P stocks in the fine roots in $IF_{+P}$ were lower than in NF, whereas the P stock in the coarse roots was higher in $IF_{+P}$. The total (fine + coarse) root dry mass and nutrient stocks did not differ among fallow strategies.

**Table 3.** Dry mass and nutrient stocks in the aboveground vegetation after 23 months of natural fallow (NF), improved fallow (IF), and improved fallow with P fertilization ($IF_{+P}$) in Marapanim, eastern Amazonia

| | NF | IF | $IF_{+P}$ |
|---|---|---|---|
| Dry mass (Mg $ha^{-1}$) | | | |
| Leaf | 3.24 (0.32) b | 6.00 (0.52) a | 7.61 (0.59) a |
| Branch | 1.83 (0.11) b | 2.41 (0.45) ab | 3.80 (3.80) a |
| Stem | 4.76 (0.59) b | 6.61 (0.91) ab | 8.63 (8.63) a |
| Liana | 1.38 (0.28) a | 1.47 (0.15) a | 1.64 (0.17) a |
| Total | 11.2 (0.3) b | 16.5 (2.0) b | 21.7 (1.4) a |
| N (kg $ha^{-1}$) | | | |
| Leaf | 27.2 (4.2) a | 64.7 (9.5) a | 79.0 (15.5) a |
| Branch | 15.4 (2.4) a | 22.6 (6.6) a | 33.7 (4.0) a |
| Stem | 49.1 (15.3) a | 54.3 (9.9) a | 70.4 (8.8) a |
| Liana | 11.0 (1.3) a | 14.2 (1.9) a | 14.1(2.7) a |
| Total | 102.8 (8.5) b | 155.9 (12.2) ab | 197.2 (15.3) a |
| P (kg $ha^{-1}$) | | | |
| Leaf | 3.2 (0.2) b | 5.2 (0.7) ab | 7.1 (1.1) a |
| Branch | 1.0 (0.1) b | 1.4 (0.4) ab | 2.0 (0.4) a |
| Stem | 1.7 (0.3) b | 2.7 (0.7) ab | 4.0 (0.5) a |
| Liana | 0.8 (0.1) a | 1.0 (0.1) a | 1.1 (0.2) a |
| Total | 6.7 (0.03) c | 10.3 (1.5) b | 14.3 (1.6) a |
| K (kg $ha^{-1}$) | | | |
| Leaf | 21.8 (3.3) a | 33.5 (6.2) a | 31.9 (4.9) a |
| Branch | 9.9 (2.2) a | 13.8 (3.6) a | 19.3 (2.8) a |
| Stem | 17.5 (4.7) a | 23.7 (3.1) a | 26.3 (2.2) a |
| Liana | 5.9 (1.0) a | 7.2 (0.6) a | 9.1 (1.8) a |
| Total | 55.0 (6.8) a | 78.1 (10.3) a | 86.6 (9.6) a |
| Ca (kg $ha^{-1}$) | | | |
| Leaf | 25.4 (1.5) a | 31.4 (4.1) a | 45.5 (5.2) a |
| Branch | 6.8 (1.4) a | 10.8 (2.6) a | 14.5 (1.8) a |
| Stem | 16.3 (16.3) b | 18.3 (3.0) b | 24.1 (1.6) a |
| Liana | 6.5 (1.1) a | 8.1 (1.2) a | 8.8 (1.8) a |
| Total | 55.1 (4.1) b | 68.5 (7.4) ab | 93.0 (6.2) a |
| Mg (kg $ha^{-1}$) | | | |
| Leaf | 10.5 (0.5) a | 10.4 (1.2) a | 13.6 (1.6) a |
| Branch | 2.3 (0.1) a | 2.4 (0.4) a | 3.6 (0.6) a |
| Stem | 3.7 (0.1) a | 4.4 (0.5) a | 8.9 (2.9) a |
| Liana | 1.4 (0.1) a | 1.9 (0.3) a | 1.6 (0.5) a |
| Total | 17.9 (6.9) b | 19.1 (1.5) ab | 27.7 (3.3) a |

N extracted with sulfuric acid and peroxide; P, K, Ca, and Mg extracted with nitroperchloric solution. Standard errors in parentheses. Different letters in the same row indicate that treatment means differ significantly for a biomass compartment at a significance level of 5 % (Tukey's test).

The total biomass (aboveground biomass + litter + fine and coarse roots), N, and P stocks were higher in $IF_{+P}$ compared to NF, whereas the IF values did not differ from the other fallow strategies, except for the P stock (Figure 1). The K, Ca, and Mg stocks did not vary among fallow strategies (Figure 1), but tended to increase under improved fallow managment (except for Mg).

**Table 4.** Dry mass and nutrient stocks in the litter layer after 23 months of natural fallow (NF), improved fallow (IF), and improved fallow with P fertilization ($IF_{+P}$) in Marapanim, eastern Amazonia

| | NF | IF | $IF_{+P}$ |
|---|---|---|---|
| Dry mass (Mg ha$^{-1}$) | | | |
| Leaves | 1.8 (0.1) a | 2.4 (0.3) a | 2.5 (0.2) a |
| Branches | 0.3 (0.04) a | 0.4 (0.1) a | 0.5 (0.5) a |
| Residual mulch | 0.3 (0.1) a | 0.2 (0.1) a | 0.6 (0.2) a |
| Cassava residues | 0.3 (0.1) a | 0.2 (0.1) a | 0.3 (0.1) a |
| Leaves + Branches | 2.0 (0.1) a | 2.8 (0.4) a | 3.0 (0.2) a |
| Total | 2.7 (0.2) a | 3.2 (0.5) a | 3.9 (0.3) a |
| N (kg ha$^{-1}$) | | | |
| Leaves | 22.6 (1.9) a | 34.6 (4.7) a | 37.4 (3.9) a |
| Branches | 3.3 (0.8) a | 4.0 (0.8) a | 5.8 (5.8) a |
| Residual mulch | 3.7 (0.7) a | 2.6 (0.9) a | 6.6 (2.1) a |
| Cassava residues | 4.3 (1.2) a | 2.3 (1.3) a | 3.9 (1.3) a |
| Leaves + Branches | 25.8 (1.7) b | 38.6 (5.2) b | 43.2 (4.1) a |
| Total | 33.8 (0.3) a | 43.5 (0.1) a | 53.7 (0.8) a |
| P (kg ha$^{-1}$) | | | |
| Leaves | 0.8 (0.1) a | 0.91 (0.1) a | 0.96 (0.1) a |
| Branches | 0.1 (0.02) a | 0.09 (0.03) a | 0.12 (0.03) a |
| Residual mulch | 0.1 (0.03) a | 0.07 (0.02) a | 0.12 (0.01) a |
| Cassava residues | 0.1 (0.04) a | 0.06 (0.03) a | 0.14 (0.04) a |
| Leaves + Branches | 0.9 (0.1) a | 1.0 (0.1) a | 1.10 (0.1) a |
| Total | 1.1 (0.3) a | 1.1 (0.1) a | 1.34 (0.8) a |
| K (kg ha$^{-1}$) | | | |
| Leaves | 1.5 (0.2) a | 2.0 (0.3) a | 2.1 (0.2) a |
| Branches | 0.2 (0.2) a | 0.3 (0.1) a | 0.4 (0.1) a |
| Residual mulch | 0.2 (0.1) a | 0.2 (0.1) a | 0.4 (1.1) a |
| Cassava residues | 0.2 (0.1) a | 0.1 (0.1) a | 0.4 (0.1) a |
| Leaves + Branches | 1.7 (0.2) a | 2.3 (0.3) a | 2.5 (0.2) a |
| Total | 2.2 (0.03) a | 2.6 (0.03) a | 3.3 (0.04) a |
| Ca (kg ha$^{-1}$) | | | |
| Leaves | 25.7 (5.0) a | 25.8 (3.7) a | 24.7 (6.9) a |
| Branches | 2.5 (0.6) a | 2.3 (0.8) a | 2.6 (0.4) a |
| Residual mulch | 2.3 (0.8) a | 1.2 (0.3) a | 2.8 (0.9) a |
| Cassava residues | 3.5 (0.9) a | 1.5 (0.7) a | 2.1 (0.9) a |
| Leaves + Branches | 28.3 (0.6) a | 28.0 (0.3) a | 27.3 (0.6) a |
| Total | 34.1 (0.4) a | 30.7 (0.2) a | 32.1 (0.4) a |
| Mg (kg ha$^{-1}$) | | | |
| Leaves | 1.8 (0.4) a | 2.1 (0.53) a | 2.2 (0.51) a |
| Branches | 0.2 (0.03) a | 0.3 (0.07) a | 0.3 (0.10) a |
| Residual mulch | 0.2 (0.1) a | 0.1 (0.03) a | 0.3 (0.07) a |
| Cassava residues | 0.3 (0.13) a | 0.1 (0.04) a | 0.3 (0.19) a |
| Leaves + Branches | 2.0 (0.38) a | 2.3 (0.59) a | 2.6 (0.53) a |
| Total | 2.5 (0.03) b | 2.6 (0.02) b | 3.2 (0.02) a |

N extracted with sulfuric acid and peroxide; P, K, Ca, and Mg extracted with nitroperchloric solution. Standard errors in parentheses. Different letters in the same row indicate that treatment means differ significantly for a biomass compartment at a significance level of 5 % (Tukey's test).

**Table 5.** Dry mass and nutrient stocks in fine roots (ø ≤ 2 mm) and coarse roots (ø 2.1 to 5 mm) after 23 months of natural fallow (NF), improved fallow (IF), and improved fallow with P fertilization ($IF_{+P}$) in Marapanim, eastern Amazonia

| | NF | IF | $IF_{+P}$ |
|---|---|---|---|
| Dry mass (Mg ha$^{-1}$) | | | |
| Fine root | 3.5 (0.3) a | 3.3 (0.5) a | 2.6 (0.2) a |
| Coarse root | 0.6 (0.2) a | 0.6 (0.2) a | 0.9 (0.2) a |
| Total | 4.1 (0.4) a | 3.8 (0.7) a | 3.4 (0.4) a |
| N (kg ha$^{-1}$) | | | |
| Fine root | 55.4 (8.2) a | 57.0 (7.9) a | 40.3 (2.3) a |
| Coarse root | 7.6 (2.3) a | 6.7 (2.5) a | 9.2 (1.4) a |
| Total | 63.0 (10.1) a | 63.7 (10.3) a | 49.0 (3.7) a |
| P (kg ha$^{-1}$) | | | |
| Fine root | 2.4 (0.5) a | 2.2 (0.4) ab | 1.5 (0.1) b |
| Coarse root | 0.2 (0.03) ab | 0.2 (0.1) b | 0.3 (0.05) a |
| Total | 2.8 (0.5) a | 2.4 (0.4) a | 1.8 (0.2) a |
| P (kg ha$^{-1}$) | | | |
| Fine root | 1.4 (0.2) a | 1.5 (0.3) a | 1.0 (0.2) a |
| Coarse root | 0.3 (0.1) a | 0.3 (0.1) a | 0.5 (0.2) a |
| Total | 1.7 (0.3) a | 1.8 (0.4) a | 1.5 (0.3) a |
| Ca (kg ha$^{-1}$) | | | |
| Fine root | 24.8 (2.3) | 25.4 (3.9) | 18.6 (1.8) |
| Coarse root | 3.4 (0.9) | 5.5 (2.2) | 5.7 (1.5) |
| Total | 28.2 (2.6) | 30.9 (6.1) | 2 4.3 (3.1) |
| Mg (kg ha$^{-1}$) | | | |
| Fine root | 1.6 (0.2) a | 1.6 (0.2) a | 1.2 (0.1) a |
| Coarse root | 0.2 (0.04) a | 0.2 (0.1) a | 0.3 (0.1) a |
| Total | 1.8 (0.2) a | 1.8 (0.2) a | 1.5 (0.2) a |

N extracted with sulfuric acid and peroxide; P, K, Ca, and Mg extracted with nitroperchloric solution. Standard error shown in parentheses. Letters in the same row indicate significant difference between treatments for a biomass compartment at a significance level of 5 % (Tukey`s test).

## DISCUSSION

The lack of detectable changes in soil P content over the experimental period may be related to (a) a rapid immobilization of P by the plants and/or microorganisms and (b) P chemisorption by iron and aluminum sesquioxides (Sanchez, 1976; Novais et al., 2007). Yet, there was a trend of greater leaf P content of both species (*Inga edulis* and *Sclerolobium paniculatum*) in response to P fertilization. A methodological artifact may also have affected our capacity to detect changes in soil P content: instead of sampling the fertilized spots (localized sampling), we collected random samples (non-localized sampling) at the end of experiment. Because of the low mobility of P in soil, it is very likely that any increase in soil P content would be detectable close to the fertilized spots only. However, the lack of a fertilization effect on soil P content may also be related to nutrient cycling. If we assume that fertilizer-P cycled through the trees (e.g., through litterfall) in the improved fallow management would contribute to the soil P pool over the experimental period (23 months), then non-localized soil sampling would have been adequate to capture a potential effect of fertilization. We suggest that future studies in this area evaluate other pools and processes of the P cycle to better understand the effects of P fertilization on improved fallow systems.

Consistent with another study on improved fallow management in a slash-and-mulch system in eastern Amazonia (Joslin et al., 2011), no changes on soil N, K, Ca, and Mg were observed with fallow improvement, despite changes in aboveground biomass nutrient stocks. According to Joslin et al. (2011), *I. edulis* did not influence the soil N content either.

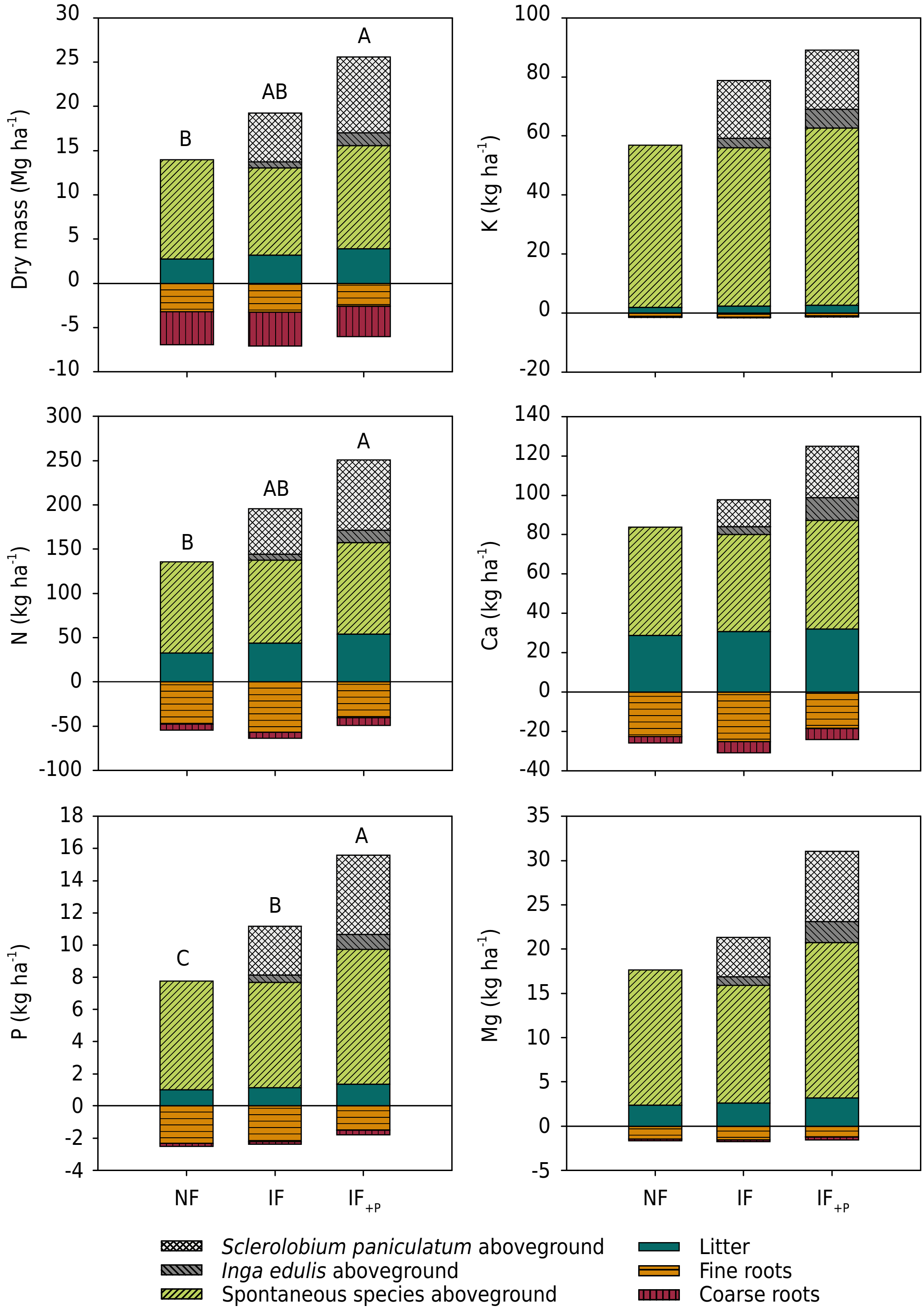


**Figure 1.** Biomass and nutrient stocks in the aboveground, litter, and root compartments after 23 months of natural fallow (NF), improved fallow (IF), and improved fallow with P fertilization ($IF_{+P}$) in Marapanim, eastern Amazonia. Different letters indicate that treatment means differ significantly at a significance level of 5 % (Tukey's test).

Aboveground biomass and nutrient stock estimates for both the natural and improved fallow treatments are within the ranges reported by other studies developed in the eastern Amazon (Denich, 1991; Brienza Jr, 1999). In general, our results showed aboveground biomass and nutrient stock increases over NF due to fallow improvement, although not significant for some nutrients. At the study site, further increases in both biomass and nutrient stocks were observed when fallow improvement was applied in conjunction with P fertilization. Thus, we suggest that P fertilization may have favored biomass accumulation through direct and/or indirect effects. The direct effect is related to the fact that P fertilization generally results in increased growth, as tropical soils have low P availability. The indirect effect of P may be related to the role of this nutrient in providing energy for the biological nitrogen fixation processes of *I. edulis* and *S. paniculatum*, which, in turn, may have increased N availability and, consequently, growth. In fact, N fixers may have a higher requirement for P than non-fixers (Vitousek et al., 2002). Consistent with our results, in another experiment of improved fallow in a slash-and-mulch system carried out in eastern Amazonia, P plus K fertilization increased diameter at breast height, height, and aboveground biomass and N stock of planted *I. edulis* trees (Joslin et al., 2016).

The aboveground biomass increases were exclusively attributable to the contribution of the tree species biomass in improved fallow management, as the natural fallow biomass did not vary with fallow improvement. Thus, the plant spacing used in this study did not suppress natural fallow species growth, as previously shown by Brienza Jr (1999). This issue is especially important regarding the adoption of fallow improvement strategies. In this respect, *S. paniculatum* accumulated a 6 to 8 times higher biomass than *I. edulis* during the fallow period, suggesting that the former species is more appropriate for the objective of improving fallow vegetation.

The use of N-fixing trees for fallow improvement increases N stocks in the system (Szott et al., 1999). In fact, large amounts of N (100-200 kg $ha^{-1}$) can accumulate in the improved fallow vegetation and return through litterfall to the surface soil layers (Sanchez, 1999). However, in our study, litter N stock values increased only in the $IF_{+P}$ treatment, suggesting that P limited N fixation by the species used for fallow improvement. In general, our litter mass and nutrient stock values are consistent with the few available estimates for natural or improved fallow sites in the Amazon (Brienza Jr, 1999; Tapia-Coral et al., 2005).

Although $IF_{+P}$ increased P accumulation in leaves (Table 3), the P stock in non-woody litter, composed mainly of leaves, did not vary with P fertilization (Table 4). Because nutrient transfer through litter depends on resorption efficiency during leaf senescence, the absence of a fertilization effect on the non-woody litter P stock may be linked to conservative mechanisms (e.g., nutrient resorption) that minimize the loss of P with leaf abscission (Güsewell, 2004). Previous reports indicate that 0-95 % of leaf P is resorbed before abscission (Aerts and Chapin, 2000). Secondary forest trees in eastern Amazonia retranslocate about 50 % or more of foliar-P before leaf abscission (Hayashi et al., 2012).

Root biomass values are consistent with the data reported for regrowth (Sousa and Gehring, 2010) and old-growth (Smith et al., 2002) forest sites in Amazonia. The lower P stock under $IF_{+P}$ may result from reduced fine root growth with higher P availability. However, the coarse roots showed a different pattern, with a higher P stock under fertilization. Under nutrient-limited conditions, as those usually observed in tropical ecosystems (Sanchez, 1976), fine root mass and growth are expected to be higher, reflecting greater photosynthate allocation to belowground structures (Kozlowski and Pallardy, 2002), consistent with the resource allocation theory. The reduced fine root biomass in $IF_{+P}$ is consistent with this theory. However, some studies have reported different results, with limited fine root growth and mass under lower soil nutrient availability (McGrath et al., 2001; Lima et al., 2010), suggesting that the relationship between nutrient availability and fine root biomass is complex and requires further investigation.

A comparison of the total dry mass and nutrients accumulated during the fallow period with estimates of nutrients extracted during the cultivation period can provide an estimate of the potential capacity of the fallow vegetation to support the nutritional demands of the crop. Previous studies conducted close to the study area showed that corn (*Zea mays*) cultivars extracted 10.1 to 20.5 kg $ha^{-1}$ N and 1.0 to 2.4 kg $ha^{-1}$ P without fertilization and 41.1 to 57.5 kg $ha^{-1}$ N and 7.8 to 14.1 kg $ha^{-1}$ P with fertilization (Kato et al., 1999). Thus, the N and P stocks of the $IF_{+P}$ treatment would be sufficient to support subsequent corn cultivation, although we recognize that the synchrony between nutrient release from the mulch layer and nutrient uptake during the crop phase is an important additional aspect to be considered in this analysis (Barrios and Cobo, 2004).

Our results demonstrate that fallow improvement with P-fertilized, fast-growing, and N-fixing species represents an efficient management strategy to accelerate the reestablishment of biomass and nutrient stocks in a shifting cultivation system. However, future investigations are needed to better understand the impacts of this management on productivity of subsequent crops and the socioeconomic viability of the whole system.

## CONCLUSIONS

The introduction of fast-growing, leguminous trees increased the biomass and nutrient accumulation during the fallow period and did not suppress the spontaneous fallow species in eastern Amazonia. Additionally, phosphorus application stimulated the growth of the planted tree species and, therefore, increased aboveground biomass and nitrogen, phosphorus, and calcium stocks of the improved fallow system. Our findings show that planting P-fertilized, fast-growing, leguminous trees is an ecologically viable form to accelerate the reestablishment of biomass and nutrient stocks during the fallow period in slash-and-mulch systems in eastern Amazonia.

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