Agroforest Syst (2011) 81:1–14
DOI 10.1007/s10457-010-9356-1

Five native tree species and manioc under slash-and-mulch agroforestry in the eastern Amazon of Brazil: plant growth and soil responses

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Received: 13 August 2008 / Accepted: 9 October 2010 / Published online: 16 November 2010

Abstract Throughout the Amazon of Brazil, manioc (*Manihot esculenta*) is a staple crop produced through slash-and-burn agriculture. Nutrient losses during slash-and-burn can be large and nutrient demand by food crops so great that fields are often abandoned after two years. In recent decades, farmers have reduced the fallow phase from 20 to ~5 years, limiting plant nutrient accumulation to sustain crop yields. Improved fallows through simultaneous planting of trees with food crops may accelerate nutrient re-accumulation. In addition, slash-and-mulch technology may prevent loss of nutrients due to burning and mulch decomposition may serve as a slow-release source of nutrients. This study in Pará, Brazil, in a 7-year-old secondary forest following slashing and mulching of the vegetation, involved two main plot treatments (with and without P and K fertilizers) and two sub-plot treatments (with or without a N_2-fixer *Inga edulis*). A mixed-culture of trees and manioc was planted in all plots. P and K fertilizer increased tree mortality due to weed competition but growth of surviving trees in four of the five tree species tested also increased as did biomass production of manioc. In the N_2-fixer treatment trends of greater growth and survival of four of five tree species and manioc biomass were also observed. Fertilization increased the biomass of competing vegetation, but there was a fertilizer by N_2-fixer interaction as *I. edulis* caused a reduction in competing biomass in the fertilized treatment. After one year, fertilization increased decomposition of the mulch such that Ca, Mg, and N contents within the mulch all decreased. In contrast, P and K contents of mulch increased in all treatments. No influence of the N_2-fixer on 0–10 cm soil N contents was observed. Two years after establishment, this agroforestry system succeeded in growing a manioc crop and leaving a well-maintained tree fallow after the crop harvest.

Keywords Mixed culture · Fertilization · Native species · Slash-and-mulch

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Introduction

In the Bragantina region of Northeast Pará, Brazil the staple food crop cassava or manioc, locally known as '*mandioca*' (*Manihot esculenta* Crantz), is produced by practicing swidden-fallow agriculture where forest vegetation is slashed and burned to prepare the land for cultivation. Unfortunately, the highly-weathered soils in this region are low in available nutrients, particularly N, P, and K, which can restrict crop productivity under low-input agriculture. The ash of burned vegetation fertilizes the subsequent crops, which are cultivated for up to two years before farmers abandon the plot to secondary forest succession. Sustainability of swidden-fallow agriculture depends largely upon the length of secondary forest succession in which nutrient accumulation can occur through shallow and deep root uptake (Stanley and Montagnini 1999). Farmers in Northeast Pará are reducing the length of time in fallow vegetation from 20 to <5 years (Gehring et al. 1999), thereby reducing the fallow-cropping period ratio to levels that may be too low to sustain the system (Metzger 2002).

Slash-and-burn farming also reduces the nutrient capital of the system due to element losses through volatilization, oxidation, ash dispersion, erosion, and leaching (Hölscher 1997). Slash-and-mulch technology can eliminate losses from fire through the use of a mulching tractor (Kato et al. 1999), which fells the forest, chops the vegetation, and lays it on the surface. This method adds all of the nutrient components to the surface, which are then potentially available for future plant uptake (Denich et al. 2004). High C:N ratios of this felled material due to a 69–79% contribution from wood biomass and only 8–10% from leaves may initially immobilize nutrients, however, making fertilization necessary for sufficient crop growth. Enrichment plantings with N_2-fixing trees may also serve to decrease C:N ratios and increase nutrient availability.

The use of N_2-fixing and other fast-growing trees may augment fallow re-growth. Use of *Inga edulis*, an N_2-fixing legume, has generated greater biomass than control fallows in this region (Brienza 1999). N_2-fixing trees can also be used during the cropping phase as a source of green manure for manioc and then left to stimulate secondary forest succession, though they can have a negative effect on crops through competition (Sanchez 1995). High productivity and slow foliar decomposition (Zech et al. 1997) has made *I. edulis* a particularly desirable N_2-fixer for agroforestry projects.

In addition to N limitation, phosphorus may also be a major limiting nutrient to plant production in upland soils of the eastern Amazon (Davidson et al. 2004; Gehring et al. 1999). Adding mulch can immobilize P during initial stages of decomposition (Baggie et al. 2004). Whether additions of inorganic P fertilizer can ameliorate any immobilization or even enhance rates of mulch decomposition is unknown. Furthermore, the effects of mulch on weed competition are uncertain (Gallagher et al. 1999).

Fallow management through small inputs of fertilizer and/or planting of selected trees species may contribute to nutrient accumulation in the ensuing secondary forest and enhance ecological values. Moreover, selection of appropriate species can provide owners of small landholdings an opportunity to produce marketable commodities such as cattle fodder, posts and small timber at the end of one or two swidden cycles that would not normally occur on these sites. The objectives of this research were to evaluate the potential of planted tree fallows under slashed and mulched secondary forest in the presence and absence of P and K fertilization and N_2-fixing trees to enhance food crop yield and economic value of the system. The hypotheses tested were (1) P and K fertilization and interplanting of N_2-fixing trees would accelerate mulch decomposition and increase topsoil nutrient contents and (2) that all tree species and manioc would respond positively to P and K fertilizers and interplanting with an N_2-fixer. We report data of the two first years of tree survival and growth, the impact of the system on soil properties, and data from the first manioc harvest.

Materials and methods

Site description

The research site is at the experimental farm of the Universidade Federal Rural da Amazônia (UFRA) in the Municipality of Igarapé Açu (1°07′41″ S, 47°47′15″ W) 110 km East of Belém, Pará, Brazil. This region, known as the Bragantina, is one of the oldest continually inhabited agricultural areas in the Amazon and the landscape is now completely dominated by human activities and secondary forests. Soil great groups in the municipality of Igarapé Açu are predominantly Kandiudults, Kanhapludults, Kandiaquults, and Kanhapluaquults; all represent soils with argillic horizons but are differentiated by drainage. In the Brazilian classification these soils would be in the Argisolos and Gleisolos orders. Igarapé Açu has an average annual temperature of 26°C and annual rainfall of 2500 mm (Kato et al. 1999) with a dry season from July to November.

Species descriptions

The tree species utilized are native to forests of the Bragantina region. *Inga edulis* Mart. (Mimosoideae) is the only demonstrated N_2-fixer among the tested species. *I. edulis* is widely used in agroforestry systems (AFS) in the Americas because it is acid-soil tolerant, has high rates of N_2-fixation, and high N content in its litter. It has high survival and good production in both monoculture and multi-species plantings (Kettler 1997). *Parkia multijuga* Benth. is a Mimosoideae with uncertain nodulating properties (Moreira et al. 1992). It is a strong light-demander, a commercially valuable species, and has a substantial role as a secondary forest tree in Peruvian AFS (Peck and Bishop 1992). *Schizolobium amazonicum* Hub. ex Ducke. (Caesalpinioideae) is a short-lived, non-nodulating, early successional pioneer species (Peña-Claros 2003). It has beneficial commercial timber properties and rapid growth (Yamada and Gholz 2002). *Ceiba pentandra* (L.) Gaertn. (Bombacaceae) is a fast-growing heliophyte (Lorenzi 2002) with high lumber value that has been harvested heavily and is commonly used in paper-pulp production (Pinedo-Vasquez et al. 2001). *Cedrela odorata* Linn. (Meliaceae) is a strong light demander but considered a slow-growing species (Pinedo-Vasquez et al. 2001). *C. odorata* has one of the highest commercial timber values in Brazil (Lorenzi 2002) and is an important species for shading coffee in Central America (Navarro et al. 2004). *Manihot esculenta* Crantz (Euphorbiaceae) is native to South America, and is a staple crop throughout the tropics of the world. Bitter manioc grows well in very acid, nutrient poor soils without external inputs, although yields may begin to decline with consecutive cropping due to K deficiency (Howeler 2002).

Plot establishment

In March of 2005, a one-hectare site of previously cultivated 7-year-old secondary forest was cleared with a TRITUCAP mulching tractor (Denich et al. 2004) that evenly distributed the macerated above-ground biomass over the soil surface. Four experimental blocks that run north–south across the site were established (Fig. 1). Since we expected to observe large differences due to fertilization each block was divided into two main plots, one received fertilization and one did not. These main plots were split into two subplots. One subplot was planted with a species mix that included N_2-fixing species and the other was planted without inclusion of N_2-fixing species. Each subplot measured 24 × 24 m. The main plot fertilization treatments were randomly assigned within each block and then N_2-fixer addition was assigned randomly within the fertilizer or no fertilizer main plots. The main-plot fertilizer treatments consisted of no fertilization (PK−) or phosphorus and potassium fertilization (PK+). Phosphorus, as concentrated super phosphate, was surface applied in a 0.5 m radius around each tree at a rate of 73 g/tree, equivalent to 20 kg ha^{-1} elemental P. Potassium was applied as KCl at a rate of 36 g/tree in a similar manner, a rate equivalent to 25 kg ha^{-1}

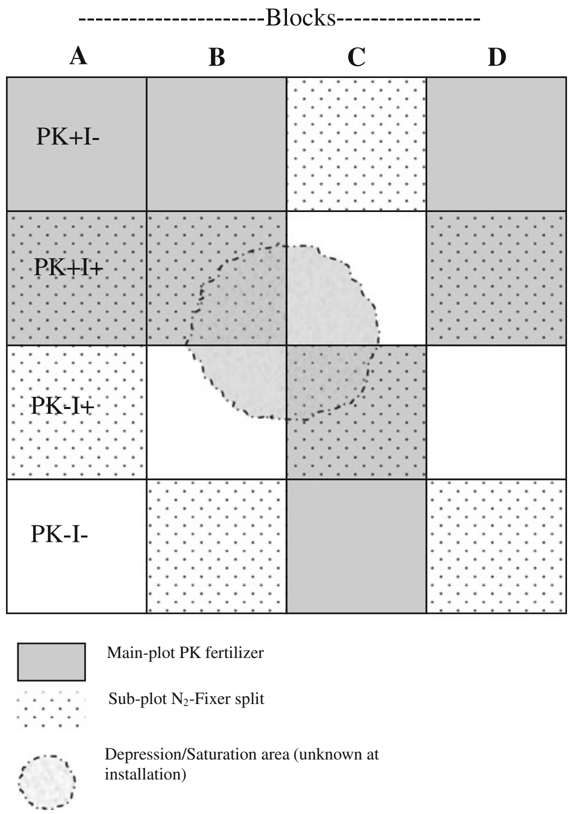

Fig. 1 Experimental design for fertilization and N_2-fixer Agroforestry System trial in the eastern Amazon of Brazil

elemental K. The split-plot treatment consisted of planting *S. amazonicum, C. odorata* and *C. pentandra* together (I−), or in combination with the N_2-fixing species *I. edulis* as well as with the Mimosoideae *P. multijuga* (I+). Species within the Mimosoideae are generally N_2-fixing, but *P. multijuga* has uncertain nodulating properties. To avoid introducing a potential N_2-fixer in the non N_2-fixer plots, we planted this species only in the N_2-fixer plots.

In the topsoil (0–10 and 10–20 cm depth increments), physical and chemical (Table 1) properties across the blocks were quite uniform at establishment with coefficients of variation <20% for all parameters at both depths. On this site, the topsoil was relatively sandy (~70%), moderate in organic matter (1–2%), mildly acidic (~pH 4.3), and of low charge (1–7 $cmol_c\ kg^{-1}$). Soil bulk density was measured on a plot basis at establishment and demonstrated limited variation with a mean value of 1.2 ± 0.1 g cm^{-3}. Initial total N concentrations in 0–10 cm averaged (±SE) 1.1 ± 0.08 g kg^{-1} (Table 1) and were slightly lower at the surface than at 10–20 cm depth (1.4 ± 0.16).

Each split-plot contained six rows of trees with 13 trees per row for a total of 78 trees per 0.06 ha plot (1354 trees ha^{-1}). Within each row, 1.8 m spacing was utilized with 4.0 m between rows of trees. Seedlings were produced at a local nursery (AIMEX) and were 3–5 months in age depending on species at the time of planting. Seedlings were culled to minimize variance in seedling size. In both treatments, species were alternated continuously within rows in a systematic fashion so that two of the same species could not occur together within a row. A 2-m buffer area was established between plots and a 1.5 m buffer was used between blocks.

In July of 2005, bitter manioc was planted at 1×1 m spacing in all treatments, at a planting density of 10,000 stems ha^{-1}. Rows of manioc were planted with 0.5 m spacing on both sides of each row of trees and the nearest row of manioc. Mature manioc plants were cut into 10 cm segments and used as planting stock. Fallow vegetation is traditionally slashed at the beginning of the dry season and burned after drying, while planting of manioc coincides with the onset of the rains in December or January. Planting was not completed until July for this project; however, the thick mulch layer produced by the mulching tractor maintains soil moisture at levels acceptable for manioc growth (Denich et al. 2004).

Table 1 Soil chemical and physical attributes (mean ± 1SE) at two depths at establishment of research study in Igarapé Açu, Pará, Brazil in June, 2005

Depth (cm)	pH_{KCl}[a]	OM[b] (g kg^{-1})	Sand (g kg^{-1})	Clay (g kg^{-1})	N[c] (g kg^{-1})	P[d] (mg kg^{-1})	K[d] ($cmol_c\ kg^{-1}$)	Ca[e] ($cmol_c\ kg^{-1}$)	Mg[e] ($cmol_c\ kg^{-1}$)	Al[d] ($cmol_c\ kg^{-1}$)
0–10	4.3 ± 0.2	18.8 ± 1.4	715 ± 13	105 ± 23	1.11 ± 0.08	4.39 ± 0.66	0.16 ± 0.02	2.87 ± 1.09	0.46 ± 0.08	0.48 ± 0.32
10–20	4.2 ± 0.09	11.1 ± 1.46	668 ± 8	160 ± 16	1.43 ± 0.16	1.68 ± 0.58	0.14 ± 0.03	0.39 ± 0.14	0.18 ± 0.03	0.37 ± 0.16

[a] pH_{KCl}-pH in 1 M KCL

[b] *OM* organic matter

[c] Total Kjeldahl N

[d] Double-acid extractable

[e] KCl extractable

Growth and biomass assessment

The initial size of the nursery-grown seedlings was determined by randomly sampling 10% of the trees before planting for measurement of ground-line diameter (GLD) and height. Then, in March of 2006, July 2006, and July 2007 survival, height, and GLD were recorded for all trees of each species. GLD was measured using digital calipers and height was measured using a 3 m pole or hypsometer. In March 2007, all *I. edulis* that were above 2 m height were pruned at $\sim$1.8 m and pruned material was left on site around the base of the tree.

At the time of planting in June of 2005 there was no appreciable above-ground biomass of weed competition or manioc as the site had recently been mulched and planted. In June 2006 manioc and above-ground weed competition biomass were collected. Each plot was divided into four quadrants and each quadrant was divided into twenty potential sampling sectors. A 1 m^2 sampling frame constructed from PVC tubing was placed within a randomly selected sector within each quadrant. All living vegetation within the vertical plane above the PVC tubing was collected. This procedure was used to collect all competing vegetation that was neither manioc nor planted tree species. During Year 1 tree measurement, all competing vegetation on site above the soil surface was hand-cut and left on site. This was the only time such weeding was preformed.

In March 2007, manioc biomass was re-measured within an 8 $\times$ 8 m sampling plot placed in the center of each treatment plot. All manioc biomass within the vertical plane of the sampling plot was collected and separated into aboveground (leaf and stem) and belowground (tuber) components. All manioc biomass was weighed fresh in the field using a hanging spring balance. Sub-samples were taken to UFRA in Belém and dried in a forced-air oven at 60°C until a constant weight was achieved.

Mulch sampling

In June 2005, the initial mulch layer was sampled to quantify the initial mass and nutrient contents of the mulch. A 25 $\times$ 25 cm frame was placed randomly within each of four quadrants within each plot and all mulched biomass within this frame was collected down to the mineral soil surface. Mulch material was dried to a constant weight in a forced-air oven at 60°C. Mulch material was analyzed at UFRA using total Kjeldahl Nitrogen procedures for N (Bremmer and Mulvaney 1982) and nitric-perchloric acid digest for P, K, Ca, and Mg (Hossner 1996). Phosphorus was measured using molybdate blue chemistry on a manual spectrophotometer; K by flame photometry; and Ca and Mg by atomic absorption spectrophotometry. In June 2006, the same procedures were followed to estimate changes in mulch mass and nutrient content.

Soil sampling

In June 2005, prior to fertilization, soil cores were taken from each of the four quadrants within each plot; soil cores were divided into 0–10 and 10–20 cm depths. The four cores were composited by depth within each plot. All plots of the same block were then further composited by depth for a single block sample (Table 1). Samples were analyzed for total N, extractable P, K, Ca, and Mg, and pH at UFRA while organic material and particle size (i.e., sand, silt, and clay) were analyzed at the Soil Analysis Laboratory of Embrapa Amazônia Oriental in Belém. Soil N was analyzed using total Kjeldahl procedures; P and K were extracted using Mehlich-1; Ca and Mg were extracted with 1 M KCl. Organic matter was by loss on ignition (Nelson and Sommers 1996) and particle size by the hydrometer method (Gee and Bauder 1986). Soil bulk density was also characterized by block using a 5-cm diameter core (Blake and Hartge 1986). In June 2006, in conjunction with mulch sampling, the soils were re-sampled and the same procedures were followed except bulk density was not re-measured and samples were retained separately by plot to estimate changes in nutrient concentrations and contents.

Statistical analysis

Analysis of variance (ANOVA) was used to analyze the study as a two-factor split-plot experiment with four complete blocks. Fertilizer treatment with and without P plus K additions were the main-plot treatments ($n = 4$) and treatments with or without the presence of *I. edulis* and *P. multijuga* were the sub-plot treatments ($n = 4$). Time was also treated as a split-split-plot for tests of repeated measures where appropriate, such as for re-sampling of mulch. Where significant differences were indicated by ANOVA, mean separation was conducted across treatment combinations using Tukey's adjustment.

Results

N_2-fixer treatment

Both *I. edulis* and *P. multijuga* were planted as part of the N_2-fixer treatment. During the 2-year period after planting, abundant nodules were observed on the roots of *I. edulis* but were never observed on *P. multijuga* roots. As such, throughout the results and discussion we often refer to the N_2-fixer treatment as a N_2-fixer or specifically as a response to *I. edulis*.

Tree survival

Mean survival across all species after Year 1 was higher ($P = 0.002$) in unfertilized (PK−) plots than in fertilized (PK+) plots (Table 2). A trend of increased survival ($P = 0.10$) in the N_2-fixer was also observed but there was no Fert × N_2-fixer interaction ($P = 0.16$). After Year 2 results were similar although percent survival had declined in most treatments such that there was a significant effect of year ($P = 0.01$). After Year 2, all-species mean survival was still higher ($P < 0.011$) in unfertilized (PK−) plots and had a similar tendency with an N_2-fixer ($P = 0.10$). The greater all-species mean survival with the N_2-fixer results partly from the good survival of *I. edulis* (Table 2).

Growth responses

Fertilization had a positive effect ($P < 0.01$) on GLD and height growth of all tree species except *P. multijuga* while the presence of *I. edulis* did not have a significant effect on any species (Figs. 2 and 3) and there was no significant interaction. Trends of increased biomass were observed on fertilized plots and in the presence of *I. edulis* for manioc stems and manioc tubers (Fig. 4) beginning in Year 1. Twenty months after planting manioc, the dry weight of manioc leaf + stem production ($P = 0.01$), manioc tuber dry-weight biomass ($P = 0.03$) and total dry-weight biomass ($P = 0.01$) were greater with P plus K fertilization than without (Fig. 4). There was, however, no significant effect of N_2-fixer on total manioc biomass, although there was a significant interaction ($P = 0.039$). Without fertilization, manioc leaf + stem, tuber and total dry-weight biomass

Table 2 Percent survival (mean ± 1 SE) of five species of trees native to the Amazon grown under different treatments 12 and 24 months after planting in June 2005 in Igarapé Açu, Pará, Brazil

Age (months)	Species	Treatment			
		PK−I− (%±1 SE)	PK−I+ (%±1 SE)	PK+I− (%±1 SE)	PK+I+ (%±1 SE)
12	*Inga edulis*		98.8 ± 0.7aA[a]		51.3 ± 6.1bA
	Parkia multijunga		87.9 ± 5.1aA		14.3 ± 5.5bA
	Cadrela odorata	79.8 ± 3.6aA	80.0 ± 4.1aA	6.9 ± 3.4bA	5.3 ± 6.3bA
	Schizolobium amazonicum	63.6 ± 4.4aA	65.8 ± 5.9aA	51.5 ± 3.4aA	43.6 ± 10.3aA
	Ceiba pentandra	97.1 ± 1.4aA	100 ± 0.0aA	37.4 ± 6.7bA	25.0 ± 10.4bA
	All species mean	80.1 ± 3.6aA	91.3 ± 1.6aA	32.0 ± 4.4bA	37.2 ± 4.0bA
24	*Inga edulis*		91.9 ± 3.3aA		44.4 ± 5.9bA
	Parkia multijunga		78.8 ± 7.9aA		11.4 ± 4.1bA
	Cadrela odorata	56.6 ± 8.9aA	57.5 ± 7.5aA	5.9 ± 2.0bA	0.0bA
	Schizolobium amazonicum	29.9 ± 5.8aB	21.0 ± 6.1aB	46.5 ± 13.6aA	43.6 ± 7.7aA
	Ceiba pentandra	82.9 ± 3.9aA	82.9 ± 4.9aA	32.7 ± 6.8bA	20.0 ± 8.2bA
	All species mean	56.3 ± 5.2aB	77.2 ± 3.6bB	27.5 ± 3.2cA	32.1 ± 3.6cA

[a] Lower case letters indicate results for all means comparison within a row for each period

Upper case letters indicate results for means comparison between years within a treatment

Different letters for either comparison indicate $P < 0.05$ for Tukey's honestly significant difference

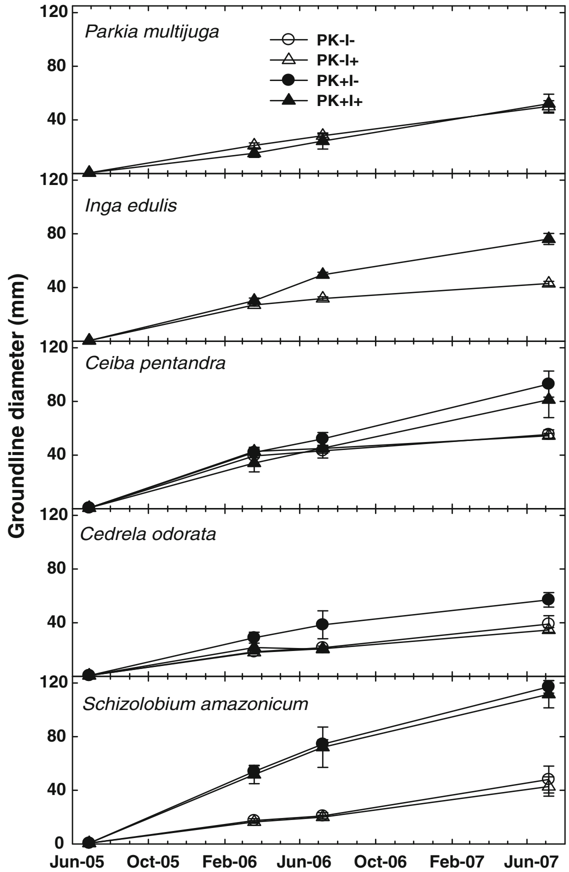

Fig. 2 Ground line diameter of five native tree species measured over a 2-year period at 9, 13, and 25 months after planting in June 2005 in Igarapé Açu, Pará, Brazil. Treatments consist of a factorial combination of fertilization with P and K (PK+) or without fertilizer (PK−) planted with manioc and with 5 native tree species including *I. edulis* (I+) or of 3 native species without *I. edulis* (I−). *Error bars* represent 1 SE

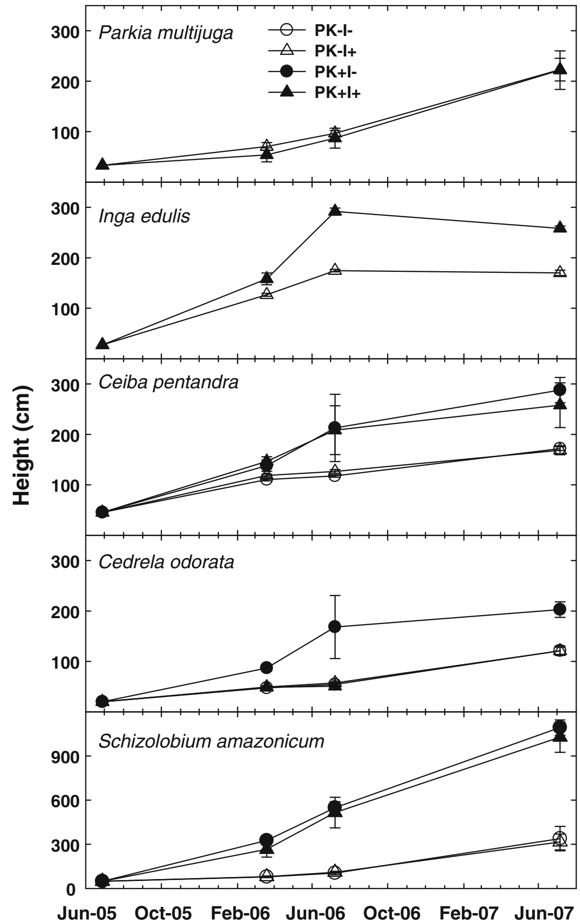

Fig. 3 Height of five native tree species during a 2-year period at 9, 13, and 25 months after planting in June 2005 in Igarapé Açu, Pará, Brazil. Treatments consist of fertilization with P and K (PK+) or without fertilizer (PK−) planted with manioc and with 5 native tree species including *I. edulis* (I+) or of 3 native species without *I. edulis* (I−). *Error bars* represent 1 SE

was increased in the presence of *I. edulis* while with fertilization biomass production was not affected in the presence of *I. edulis* at 20 months (Fig. 4).

Competing weedy biomass increased with fertilization ($P = 0.03$) but there was no effect of the N_2-fixer. There was also no significant fertilization by N_2-fixer interaction (Fig. 5).

Soil response

At time of establishment there was an average of 54 ± 4.8 Mg ha^{-1} of mulch biomass across the site with no significant differences by treatment (Fig. 6). One year after establishment mulch mass had decreased in all plots (i.e., effect for year; $P = 0.004$) with a slight effect for fertilizer ($P = 0.057$) but not *I. edulis* ($P = 0.57$). The PK+I+ treatment had the greatest mass loss on average (i.e., 70%), which exceeded the 36% mass loss in the PK+I− treatment (Fig. 6). There was also a 45% mass loss from the mulch layer of the unfertilized treatments (PK−). The concentration of nutrients in mulch at establishment (Table 3) did not differ among treatments but had, in fact, increased for N, P, and K, and declined for Ca by the end of Year 1 (i.e., effect for year; $P \leq 0.05$). The combination of the mass loss and increased concentration, however, resulted in a non-significant decline ($P = 0.23$) in the content of N and no significant treatment effects after one year (Fig. 7). Phosphorus ($P = 0.009$) and

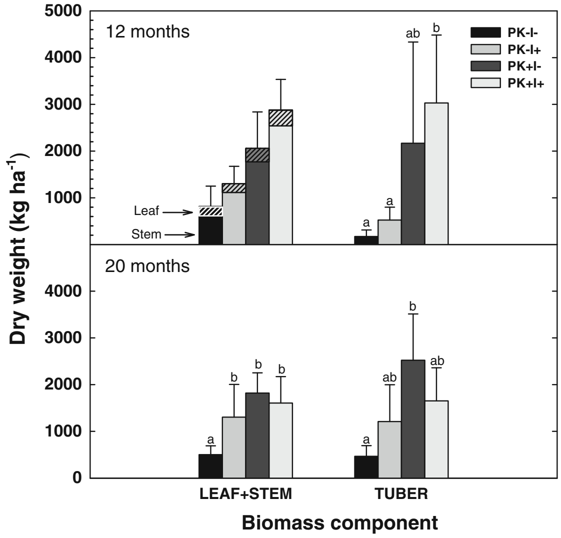

Fig. 4 Manioc dry weight (mean ± SE) 12 and 20 months after planting in July 2005 in Igarapé Açu, Pará, Brazil. Treatments consist of a factorial combination of fertilization with P and K (PK+) or without (PK−) and 5 native tree species with *I. edulis* (I+) or of 3 native tree species without *I. edulis* (I−) {$n = 4$}. *Letters* indicate significant differences for all means comparisons with Tukey's HSD within a period; *absence of letters* indicates no differences were significant

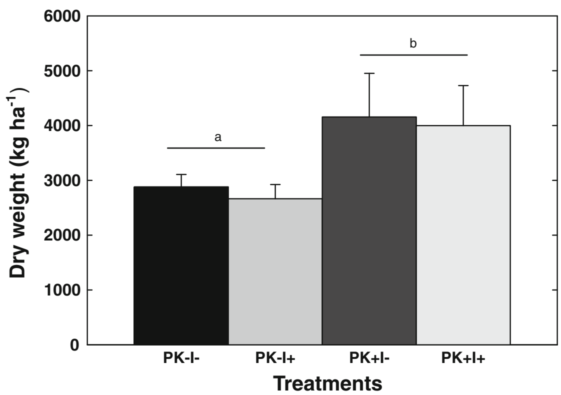

Fig. 5 Dry weight of competing vegetation (mean ± 1SE) one year after planting in June 2005 in Igarapé Açu, Pará, Brazil. Treatments consist of a factorial combination of fertilization with P and K (PK+) or without (PK−) and 5 native tree species with *I. edulis* (I+) or of 3 native tree species without *I. edulis* (I−) {$n = 4$}. *Letters* indicate a significant main fertilizer effect ($P < 0.05$); all means comparison with Tukey's HSD found no significant differences

K ($P = 0.09$) increased in content while Ca ($P = 0.003$) and Mg ($P = 0.01$) contents declined. No effects of treatment were evident for any element at the end of Year 1 (Fig. 7).

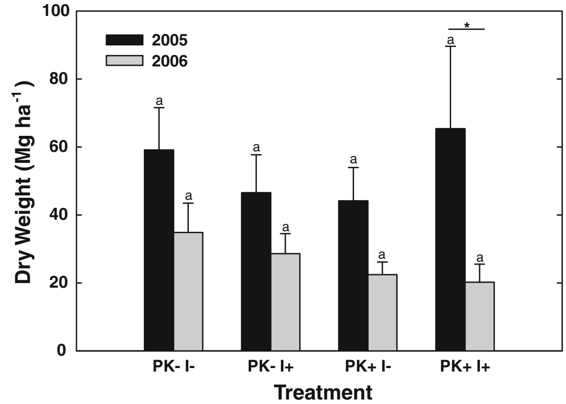

Fig. 6 Mass (mean ± 1SE) of mulch layer by treatment at establishment in June 2005 and after one year in June 2006 in Igarapé Açu, Pará, Brazil. Treatments consist of a factorial combination of fertilization with P and K (PK+) or without (PK−) and 5 native tree species with *I. edulis* (I+) or of 3 native tree species without *I. edulis* (I−) {$n = 4$}. The main effect of year was significant ($P < 0.05$) while fertilization and N_2-fixer were not. *Letters* indicate all mean comparison across treatments within a year and the asterisk indicates a significant difference between years

After one year, total soil N concentrations in the 0–10 cm layer exceeded 10–20 cm concentrations (Table 4). The mean exchangeable K values were 0.084 ± 0.007 mg kg^{-1} in 0–10 cm and 0.055 ± 0.004 mg kg^{-1} in 10–20 cm, which were slightly below those measured in the block composite (Table 1). Responses of Ca, Mg and pH_{KCl} were similar to those at initiation in that variation across blocks or plots was limited and there were no differences ($P > 0.10$) in the 0–10 or 10–20 cm depths after one year between treatments (Table 4).

Biomass nutrient concentrations and contents

There were no significant differences in nutrient concentrations measured for manioc leaves (26 ± 3, 2.9 ± 0.8, 7.5 ± 1.0, 10 ± 2, and 3.3 ± 0.3 g kg^{-1}; mean ± 1SE for N, P, K, Ca, and Mg, respectively), stems (10 ± 3, 3.1 ± 0.6, 5.9 ± 0.6, 6.0 ± 0.3, and 1.6 ± 0.1 g kg^{-1}, respectively) or tubers (4.3 ± 1.3, 2.4 ± 0.3, 5.5 ± 1.5, 2.1 ± 0.8, and 0.8 ± 0.3 g kg^{-1}, respectively) and no differences in nutrient contents for manioc leaves (Fig. 8). In manioc stems, however, K content was slightly greater ($P = 0.09$) with fertilization as was N content ($P = 0.09$) with N_2-fixer. Manioc tubers also responded with greater

Table 3 Nutrient concentration (mean ± SE) of mulch layer at establishment in 2005 and after one year in Igarapé Açu, Pará, Brazil

Year	Treatment	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})
2005	PK−I−	7.2 ± 1.0aA[a]	0 .26 ±0.01aA	0.30 ± 0.04aA	6.8 ± 0.5 aA	0.9 ± 0.1aA
	PK−I+	5.2 ± 0.3aA	0.25 ±0.01aA	0.22 ± 0.04aA	5.8 ± 0.8aA	0.7 ± 0.04aA
	PK+I−	5.3 ± 0.2aA	0.26 ±0.02aA	0.23 ± 0.02aA	5.8 ± 0.5aA	0.8 ± 0.05aA
	PK+I+	5.9 ± 0.9aA	0.26 ±0.03aA	0.23 ± 0.05aA	5.9 ± 1.1aA	0.8 ± 0.1aA
2006	PK−I−	8.7 ± 1.3aA	3.2 ± 0.5aB	2.2 ± 0.7aA	5.5 ± 0.7aA	0.7 ± 0.2aA
	PK−I+	6.9 ± 0.7aA	2.4 ± 0.6aB	1.7 ± 0.5aA	4.9 ± 0.5aA	0.7 ± 0.2aA
	PK+I−	11.9 ± 1.2aB	2.9 ± 0.6aB	1.1 ± 0.1aA	6.5 ± 0.7aA	0.6 ± 0.1aA
	PK+I+	9.9 ± 2.2aA	3.6 ± 0.5aB	1.8 ± 0.4aA	5.5 ± 1.1aA	0.7 ± 0.1aA

[a] Lower case letters indicate results for all means comparison within a column for each year

Upper case letters indicate results for means comparison between years within a treatment

Different letters for either comparison indicate $P < 0.05$ for Tukey's honestly significant difference

Mg content in the presence of the N_2-fixer when fertilized. There were no significant interactions for any manioc component. In competing vegetation, fertilization resulted in a greater concentration of Ca (6.2 ± 1.5 vs 7.2 ± 1.0, $P = 0.05$) and nutrient contents were elevated in competing vegetation by fertilization for K and Ca ($P = 0.05$) and slightly for Mg ($P = 0.09$) (Fig. 9). There were no significant differences in competing vegetation nutrient contents due to the N_2-fixer treatment (Fig. 9).

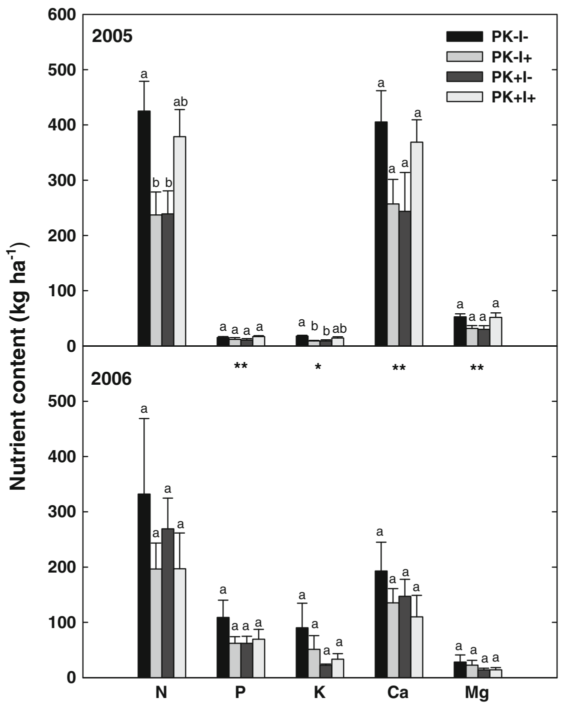

Fig. 7 Nutrient content (mean ± 1SE) of mulch layer at establishment in June 2005 and after one year in June 2006 in Igarapé Açu, Pará, Brazil. Treatments consist of a factorial combination of fertilization with P and K (PK+) or without (PK−) and 5 native tree species with *I. edulis* (I+) or of 3 native tree species without *I. edulis* (I−) {$n = 4$}. There was no main effect of fertilization or N_2-fixer for any element but *asterisks* indicate significant main effects for year at the $P < 0.005$ (**) and $P = 0.09$ (*). *Letters* indicate all means comparison among treatments within a year and element

Discussion

Tree survival

Initially, survival of the trees was highly impacted by fertilization due to a 25% increase in weed competition (Fig. 5). The rapid growth of the competing vegetation increased shading for crop trees, a few of which were shade intolerant. Allelopathic effects or competition for water and nutrients by weeds are also possible (Hoffman and Carroll 1995). Survival of trees in the absence of fertilization was impressive, however, being >60% for all species through Year 1.

Fertilization with K may have also contributed to mortality by stressing immature root systems of seedlings, which can lead to death during the dry season due to reduced drought tolerance (Jacobs et al. 2004). Planting season for crops and trees in the eastern Amazon region generally coincides with the onset of the rainy season in January. In this study, planting did not take place until late June, during the transition from the wet to dry season. In the fertilizer treatment, increased tree growth and thus demand for

Table 4 Soil pH and nutrient concentrations (mean±1SD) in June 2006 one year after establishment of treatments in Igarapé Açu, Pará, Brazil

Treatment	Depth (cm)	pH (KCl)	N[a] (g kg^{-1})	P (mg kg^{-1})	K (cmol$_c$ kg^{-1})	Ca (cmol$_c$ kg^{-1})	Mg (cmol$_c$ kg^{-1})	Al (cmol$_c$ kg^{-1})
PK−I−	0–10	4.3 ± 0.2a[b]	1.8 ± 0.8a	4.6 ± 0.3a	0.08 ± 0.01a	2.2 ± 1.0a	0.34 ± 0.12a	0.35 ± 0.11a
PK−I+		4.4 ± 0.2a	1.5 ± 0.2ab	5.9 ± 2.5a	0.09 ± 0.02a	2.1 ± 0.4a	0.35 ± 0.10a	0.35 ± 0.10a
PK+I−		4.3 ± 0.2a	1.4 ± 0.4b	5.9 ± 3.2a	0.09 ± 0.03a	2.6 ± 1.2a	0.27 ± 0.18a	0.33 ± 0.03a
PK+I+		4.3 ± 0.3a	1.4 ± 0.2b	5.7 ± 3.9a	0.09 ± 0.06a	1.7 ± 0.7a	0.23 ± 0.07a	0.31 ± 0.05a
PK−I−	10–20	4.1 ± 0.2a	1.3 ± 0.6a	1.9 ± 0.8a	0.06 ± 0.01a	0.4 ± 0.3a	0.13 ± 0.06a	0.91 ± 0.74a
PK−I+		4.2 ± 0.3a	1.1 ± 0.1a	2.2 ± 0.8a	0.06 ± 0.01a	0.5 ± 0.1a	0.15 ± 0.05a	0.53 ± 0.09a
PK+I−		4.1 ± 0.1a	1.1 ± 0.2a	1.4 ± 0.8a	0.07 ± 0.04a	0.5 ± 0.3a	0.13 ± 0.07a	0.49 ± 0.07a
PK+I+		4.4 ± 0.5a	1.0 ± 0.0a	3.1 ± 1.2a	0.07 ± 0.01a	0.2 ± 0.0a	0.04 ± 0.05a	0.49 ± 0.04a

[a] Total Kjeldahl Nitrogen, Double-acid extracatable P, or KCl-extractable cations

[b] Lower case letters indicate results for all means comparison within a column and depth. Different letters within a column indicate $P < 0.05$ for Tukey's honestly significant difference

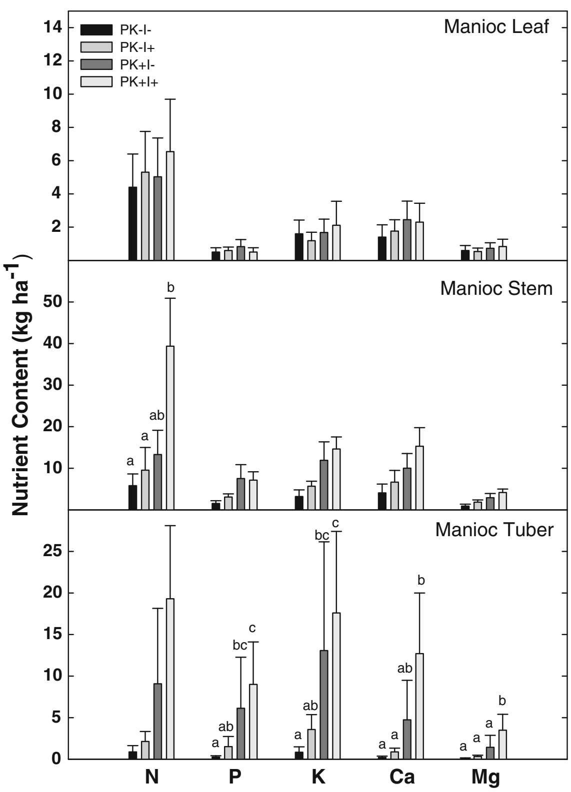

Fig. 8 Manioc nutrient content (mean ± 1SE) one year after establishment in June 2005 in Igarapé Açu, Pará, Brazil. Treatments consist of a factorial combination of fertilization with P and K (PK+) or without (PK−) and 5 native tree species with *I. edulis* (I+) or of 3 native tree species without *I. edulis* (I−) {$n = 4$}. *Letters* indicate significant differences for all means comparisons with Tukey's HSD; *absence of letters* indicates no differences were significant

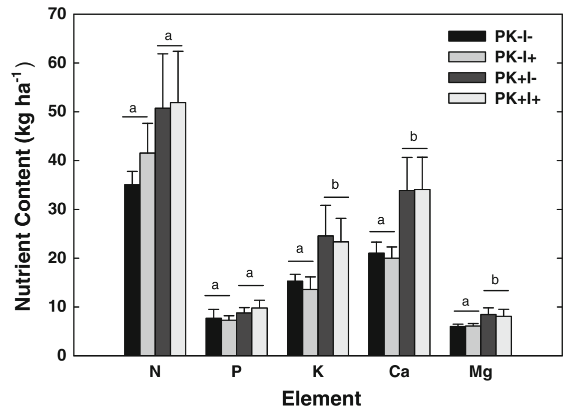

Fig. 9 Nutrient content (mean ± 1SE) of competing vegetation one year after establishment in June 2005 in Igarapé Açu, Pará, Brazil. Treatments consist of a factorial combination of fertilization with P and K (PK+) or without (PK−) and 5 native tree species with *I. edulis* (I+) or of 3 native tree species without *I. edulis* (I−) {$n = 4$}. *Letters* indicate significant differences for the main fertilizer effect. There was no effect of the N_2 Fixer and all means comparisons of treatments with Tukey's HSD also found no significant differences

moisture as well as increased weed competition apparently exceeded plant tolerances.

C. odorata, in particular, had exceptionally low survival in the fertilized treatment, <10% after Year 1 and <5% after Year 2. *Hypsipila grandella* damage was not noted on any *C. odorata* at the site. Davidson et al. (1998) showed similarly low survival of *C. odorata* with fertilization in Perú. *C. odorata* should only be fertilized well after the seedlings are established. In fact, Davidson et al. (1998) showed that among 15 native species planted, including both early and late successional species, fertilization reduced survival.

In contrast to mortality due to drought stress, poor soil drainage on portions of the site (Fig. 1) also decreased tree and manioc survival. A mild depression (<30 cm deep) approximately 25 m in radius, in the middle of the site, was poorly drained and periodically had water at the surface. Unfortunately, the mulch layer obscured this depression during plot establishment and thus a number of blocks and treatment plots were impacted. Survival was very low in this area.

Growth response

In general, height responses of the five species planted compares favorably to results reported elsewhere from the tropical Americas (Alegre et al. 2005; Brienza 1999; Browder and Pedlowski 2000; Camargo et al. 2002; d'Oliveira 2000). *S. amazonicum* was the most responsive to fertilization with 417% greater growth after one year. From Year 1 to 2, fertilized *S. amazonicum* also had the greatest absolute growth difference (+490 cm) and unfertilized *S. amazonicum* had the greatest percent difference (+181%). As such, farmers could expect very vigorous growth from *S. amazonicum.* Height growth of *I. edulis* (67%) and *C. pentandra* (40%) also increased in response to fertilization while *C. odorata* had slower growth, although the slower growth of *C. odorata* should be balanced against its greater regional timber value.

Unlike the trees, total manioc tuber biomass (Fig. 4) was low relative to previous reports that ranged from 1 to 6 Mg ha^{-1} (El-Sharkawy 1993; Howeler and Cadavid 1983; Kato et al. 2005). It is not clear if the presence of competing vegetation (planted trees and "weeds") had an impact on biomass production of manioc as no treatments without trees or weeds were included in the trial. Previously, high manioc production in the Northeast of Brazil not only lacked trees but also had weed control and improved hybrids grown in monoculture (El-Sharkawy 1993; Kato et al. 2005). Brienza (1999), however, reported no loss of manioc tuber growth with the inclusion of N_2-fixing trees at a number of planting densities (e.g., 1 × 1, 1 × 2 and 2 × 2 m).

Despite the generally low manioc tuber productivity at this site, manioc did respond to fertilization with increased manioc plant height but not leaf production (Fig. 4); manioc only carries leaves at its canopy level. The strong tree and manioc growth responses to fertilization indicate that P and/or K is limiting growth at this site. In contrast, the lack of a growth response to the N_2-fixer *I. edulis* suggests that N may not be a limiting nutrient at this site (Gehring et al. 1999). It is also possible that two years was not sufficient time for the N_2-fixing trees to influence N availability either through their roots or through litterfall and thus to increase growth of neighboring plants. Growth responses in I+ sup-plot treatments were not statistically significant at the end of Year 1 but there was a trend of greater growth in the presence of *I. edulis*. The presence of N_2-fixers also increased biomass of manioc stems and tubers in both the fertilized and unfertilized treatments after one year (Fig. 4); a result different from Howeler (2002) that did not report significant differences for manioc tubers between control and NPK fertilization in Colombia until harvest in the third consecutive year of cropping.

Potential benefits of N_2 fixation from *I. edulis* can be offset by competition for other resources such as water or light (Sanchez 1995). After Year 2, *C. odorata* responded negatively to the presence of *I. edulis* even in the presence of fertilization, suffering high mortality and suppressed growth. *C. odorata* is a strong light-demander and may have suffered from the increased shading by *I. edulis* due to its larger canopy with fertilization.

Competing vegetation

A potential benefit of slash-and-mulch technologies is weed suppression. Unfortunately, in this study, the mulch had little effect on competing woody vegetation since sprouts were able to establish under the mulch layer, contrary to earlier results of Rippin et al. (1994). Intense weed competition in the fertilized treatments undoubtedly had a negative impact on growth and survival of planted tree species as well as manioc. Species with slowly decomposing biomass, such as *I. edulis*, have also been reported to achieve greater weed control when compared to other legumes (Salazar et al. 1993). Competition suppression due to *I. edulis* could probably be expected to increase over time as trees age and deposit more biomass on the surface. This research indicates that *I. edulis* may have exerted some control on competition when not fertilized. In the fertilized treatment it appears that the addition of P and K was enough to free competing vegetation from nutrient limitations and competition from the planted trees.

Nutrient cycling

The observed initial N content of mulch (Fig. 6) was similar to a slash and mulch study in a 10 year-old secondary forest in Igarapé Açu that yielded 24 t ha^{-1} of mulched biomass with 332 kg ha^{-1} of N (Kato et al. 1999). In the present study, after one year, N content decreased by $\sim 70 \pm 50$ kg ha^{-1} and fertilization (PK+) appeared to increase N mineralization of the mulch layer. There were, however, no significant treatment effects on the C:N ratio ($P > 0.10$). In fact, assuming C is 50% of biomass, the mean C:N ratio of the mulch at establishment was 88:1 while after 12 months it was 59:1, which in both cases is apparently too high for net N mineralization (Seneviratne 2000).

In an another slash and mulch study in Igarapé Açu, net losses from the mulch layer were 285, 75, 125, and 16 kg ha^{-1} of N, K, Ca, and Mg, respectively; however, P content increased by 11 kg ha^{-1} after 18 months (Sá et al. 1998). In contrast, Kato et al. (1999) working in the same region reported decreases of up to 50% in the mulch layer for Mehlich-1 extractable P over 18 months in the absence of fertilizer. Baggie et al. (2004) observed that fertilizing mulch with P increased P extracted but not release of P from mulch residue. In the current study, observed gains in P and K mulch content in all treatments may have been the result of incorporation of mineral soil P through bioturbation or redistribution of dissolved fertilizer through ponded surface water. Increases in mulch P and K content ranged from 200 to 400% and 50 to 280%, respectively, relative to the amount applied.

Despite some large changes in the mulch layer, only small differences in 0–20 cm soil N among treatments were observed. Response in soil-N to the presence of N_2-fixers has been reported previously (Montagnini and Sancho 1994). Fertilization with P plus K also did not create consistent patterns in soil concentrations of these or other nutrients. The only significant response to fertilization in the main-plot treatment was a decrease in Mg.

Plant growth of manioc and weeds accounted for an uptake of 100, 26, 58, 50, and 13 kg ha^{-1} of N, P, K, Ca, and Mg, respectively. The nutrient loss from mulch could account for this supply of N, Ca, and Mg but mulch was a sink for P and K. The accumulation of N, Ca, and Mg in both trees and manioc generally increased in response to fertilization treatments with manioc also having higher N under the N_2-fixer. Presently, there is conflicting evidence regarding increased N uptake by manioc with fertilization or in the presence of N_2-fixers (Howeler 2002; Carsky and Toukourou 2005). In Colombia, foliar N concentrations of manioc did not respond to NPK fertilization but stems and tubers both had increased N concentrations (Howeler 2002). No increases for N content in stems or tubers between an unfertilized control and 60–16–138 N–P–K fertilization were reported in Benin, Africa (Carsky and Toukourou 2005); however, increases in N content were reported for whole-plant uptake with fertilization. Data presented here indicates that PK fertilization or presence of N_2-fixers may increase N uptake by manioc. Nutrient contents of P, K, Ca and Mg also increased with fertilization and the presence of *I. edulis*. Increased uptake of K in response to K fertilization, which can be limiting to manioc, may have facilitated uptake of other nutrients.

Due to the absence of hand weeding during this study, as likely would have been carried out in a farmer's field, there was a relatively large amount of nutrient accumulation in weeds. Between 40 and 65 kg ha^{-1} $year^{-1}$ of N accumulated in weeds. N concentration and contents of weeds increased in the presence of *I. edulis*. With fertilization, concentration tended to decline, although N contents still increased.

Phosphorus is typically considered to limit growth for agriculture in the eastern Amazon (Gehring et al. 1999) and Davidson et al. (2004) report an increase of 23% in foliar P concentrations with N and P fertilization. In this study there was a decrease of about 10% in foliar P concentrations of weedy vegetation. Accumulation of P in mulch was observed, and although this uptake is difficult to explain, it may limit plant available P. Measured cation contents all increased in response to fertilization with P plus K indicating that fertilization increases the rate at which weedy vegetation accumulates nutrients and could reduce nutrient availability to trees and crops.

Conclusions

Slash and mulch technologies combined with simultaneous AFS for native trees and manioc is an attractive alternative to slash and burn for sustaining soil productivity. In all cases, the cycling of nutrients through the mulch, including the incorporation of inorganic fertilizers during the first planting phase, should help sustain nutrient cycles. Of the native tree species utilized, the N_2-fixer *I. edulis* had high survival in both fertilized and un-fertilized conditions and interplanting with *I. edulis* increased growth of *C. pentandra*, *S. amazonicum,* and manioc. However, *I. edulis* may compete with slower-growing heliophytes such as *C. odorata*, through shading, especially when fertilized, so might require pruning. As demonstrated in other research, one beneficial use of pruned material is to smother weeds and also to provide nutrients as a green manure. *C. pentandra* and *S. amazonicum* also performed well if released from light competition. After two years, several *S. amazonicum* exceeded 15 m in height with fertilization.

The greater growth demonstrated by trees and manioc coupled with elevated mortality of trees and manioc in the fertilized treatment indicate that synchronization of management techniques is needed. It may be advisable to fertilize only after the onset of the rainy season to avoid moisture stress and for trees and manioc to compete effectively against other vegetation. Given that fertilization caused significant increases in both manioc tuber yield and tree growth it may be an attractive allocation of available capital. Also, since only limited vegetation control was performed in this trial reported growth should represent the lowest expected values for a farmer in this region.

For the first two years of this project (Mar-05 to Jul-07) results demonstrated success with secondary forest mulching, establishment of 4 m wide mixed-species tree plantings, and harvest of a crop of manioc after ~20 months (Jul-05 to Mar-07) as well as retention of the two-year-old trees (Jul-05 to Jul-07) after harvest.

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