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ORIGINAL ARTICLE

Improved fallow: growth and nitrogen accumulation of five native tree species in Brazil

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Abstract Small-holding farmers of the Brazilian Amazon often use a rotation of secondary forest, slash-and-burn land-clearing and fallow phase regeneration for agriculture. In recent decades reduction of the fallow phase from ~20 to ~5 years has limited nutrient accumulation by fallow vegetation to sustain future crop growth. Slash-and-mulch and improved fallow schemes, including use of native nitrogen-fixing species, have been investigated to address the issue. In the current study in eastern Amazonia of Brazil, a 7-year old forest site was slash-and-mulched and four treatments applied; no fertilizer and no N-fixer as the control; no fertilizer with N-fixer; P + K fertilizer with no N-fixer; P + K fertilizer with N-fixer. Manioc was planted in all plots at establishment. After manioc harvest and 4 years of fallow, a total of 6 years after planting, use of P + K fertilizer increased tree growth of four of five planted species. In the presence of the N-fixer *I. edulis,* trends of increased growth and survival among these four tree species were observed. After 6 years, fertilization with P + K significantly increased tree volume and biomass. The N-fixer lowered survival of other species yet increased estimated N uptake of planted trees. Use of P + K fertilizer without N-fixer might allow for commercial harvest of *S. amazonicum* at the end of one 7-year crop-fallow cycle without jeopardizing agroecosystem N stocks. Use of P + K fertilizer in the presence of *I. edulis* can increase planted-tree N-content but increases in competition may limit commercial harvest yet may better sustain future food crop growth.

Keywords Agroforestry · Slash-and-mulch · Mixed culture · Tree growth · Fallow growth · Nitrogen uptake · Nitrogen stock · Green bank account

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Introduction

In the Bragantina region of the northern Brazilian state of Pará, land-use has historically been dominated by slash-and-burn agriculture to prepare the land for cultivation. The ash of the burned vegetation serves as fertilizer for the subsequent crops, which are typically cultivated for 1–3 years before declining fertility and weedy competition forces farmers to abandon the plot to secondary forest succession. Sustainability of this system depends largely upon the length of time in fallow vegetation before being cleared and burned again for cropping since enough nutrients must be accumulated in the fallow vegetation to sustain crop growth (Metzger 2002).

The cropping phase of slash-and-burn agriculture is followed by naturally regenerating fallow vegetation that has traditionally occupied the site for 15–25 years. Farmers in the Bragantina region have reduced the fallow phase of the cycle to 3–7 years while continuing to maintain 1–3 years of cropped fields (Gehring et al. 1999). As nutrient stocks are depleted, crop productivity declines and farmers must turn to new lands to sustain their livelihoods or move to urban centers. Management of improved fallows offers the potential to increase the value of secondary forests and farmers' holdings by planting valuable tree species that farmers can harvest after one or successive crop-fallow cycles while sustaining soil fertility through the use of fast growing nitrogen (N)-fixing species.

Trees of early natural forest succession have historically had little commercial timber value (Pinedo-Vasquez et al. 2001). Recent research using improved fallow planting demonstrated that planted timber or biomass species may be harvested as early as 6 years after slashing by smallholding farmers given proper management (Joslin et al. 2011a). Leaving planted but slower growing species for harvest after future crop-fallow cycles may give farmers future revenue opportunities.

To sustain soil productivity, slash-and-mulch technology has been developed to eliminate nutrient losses from burning by chopping vegetation and laying it on the surface with a mulching tractor (Kato et al. 1999). The mulching tractor fells a young forest, adding all of the components to the surface, which become available for future plant uptake. Additionally, unlike burning, the mulching tractor can maneuver around planted trees.

Enrichment plantings of fallow forests using N-fixing legumes, such as *Inga edulis*, can increase N content and generate greater biomass than control fallows (Brienza Jr 1999). Growth increases are inconsistent, however, as no responses in first or second-year tree or manioc growth were observed in a study in the Bragantina region (Joslin et al. 2011b). The use of N-fixing trees, and other fast-growing species, to augment fallow growth by stimulating greater nutrient acquisition, may allow farmers to use shorter fallows or to utilize products from the fallow forest without jeopardizing the nutrient stocks of the system.

This research project was initiated in 2005 with slash-and-mulch clearing, followed by manioc crop harvest in 2007 and left to fallow re-growth. Effects of a planted N-fixing species (*I. edulis*) on the planted non-N-fixing trees were evaluated. The effect of P + K fertilization on the growth and survival of the five tree species was also tested, since phosphorus (P) is a limiting nutrient in the soils of the Bragantina (Gehring et al. 1999). It was hypothesized that all species would respond positively to fertilization and interplanting with an N-fixing tree. Further, it was hypothesized that interplanting of *I. edulis* and commercially valuable tree species with manioc would accelerate the N stock of forest fallow regeneration, compared to interplanting of tree species without the N-fixer. Here, we report the growth and mortality of planted tree species, as well as estimating volume, biomass and N content of trees at Year 6.

Materials and methods

Site description

The research was conducted at the Fazenda Experimental de Igarapé Açu (FEIGA) of the Universidade Federal Rural da Amazônia (UFRA) in the Municipality of Igarapé Açu (1°07′41″ S 47°47′15″ W), approximately 110 km East of Belém, Pará, Brazil. The Bragantina region, as it is known, is one of the oldest continually inhabited agricultural areas in the Amazon (Denich et al. 2004) and the landscape is now dominated by human activities, such as urban, row-crop farms, plantation forests, cattle ranches, and secondary forests.

Soils in the municipality of Igarapé Açu are predominantly Kandiudults (Rego et al. 1993) with a bulk density (BD) of 1.2 g cm^{-3} from 0 to 5 cm and 1.4 g cm^{-3} from 5 to 10 cm (Joslin et al. 2011b). Igarapé Açu has an average annual temperature of 26 °C and annual rainfall of 2500 mm (IBGE 1996; cited in: Kato et al. 2005); the driest months are August–November and the wettest months are January–May.

Species descriptions

The tree species utilized are native to forests of the Bragantina region. *Inga edulis* (Leguminoseae) is the only known planted N-fixer, although N-fixing species may have been naturally recruited in secondary succession. It is a fast-growing, acid soil-tolerant, shade-intolerant species popular in agroforestry systems (AFS) across Latin America as a shade tree and for green manure through leaf trimmings. It is used for farm tools, firewood, charcoal and marketable fruit. *Schizolobium amazonicum* (Leguminoseae) and *Ceiba pentandra* (Bombacaceae) are rapid growing pioneers with soft wood, with viable markets for veneer and plywood, respectively. *Parkia multijuga* (Leguminoseae) and *Cedrela odorata* (Meliaceae) are slower growing tropical hardwoods with high merchantable timber values (See Joslin et al. 2011b for more complete species description). All tree species were planted with the food crop manioc (*Manihot esculenta*), which was harvested after 20 months with growth response reported in Joslin et al. (2011b).

Plot establishment

In March of 2005, a one-hectare study site was selected and cleared. Experimental treatments were applied to the prepared site in June, 2005 and planted with the aforementioned species (Joslin et al. 2011b). Four experimental blocks ($N = 4$) that run north–south across the site were established. Each block was divided into four plots ($n = 16$) that measured 24×24 m. Trees and manioc were planted simultaneously, with trees planted at 4×1.8 m spacing, for a total of 78 trees per plot, while *M. esculenta* was planted at 1×1 m spacing.

A factorial combination of fertilization treatment and N-fixing species additions was assigned to these blocks in a split-plot design. The two main-plot fertilizer treatments consisted of no fertilization (PK−) and fertilization as an application around the base of planted trees of 46 kg P ha^{-1} as P_2O_5 (100 kg of 46 % Simple-Super Phosphate) and 30 kg potassium (K) ha^{-1} applied as KCl (50 kg of 60 % KCl) (PK+). Sub-plot treatments consisted of planting the native species *S. amazonicum*, *C. odorata* and *C. pentandra* together (I−), or in combination with the N-fixing species *I. edulis* as well as *P. multijuga* (I+).

Growth and biomass assessment

Nursery-grown seedlings were randomly selected for measurement of ground-line diameter (GLD) and height so that 10 % of each species was sampled before planting. In March of 2006, July 2006 (Year 1), July 2007 (Year 2) and July 2011 (Year 6), survival, GLD, height and diameter at breast height (DBH), when applicable, were recorded for all species. A 50 cm caliper was used to measure GLD and DBH; height was measured using a height pole for trees up to 2 m tall, a segmented range pole for trees up to 14 m tall and a hypsometer (Hägloff, Sweden) for trees above 14 m. Since nearly all *I. edulis* developed multiple stems above the ground, only the most vigorous and/or longest reaching branch was selected for height measurements. In March 2007, all *I. edulis* were pruned to 1.8 m height, and pruned material was left on site around the base of the tree, but were not pruned again prior to fallow.

Soil sampling

All litter layer material within a 25×25 cm PVC frame was collected from five inter-row locations within each plot and made into a composite sample. Composite samples were dried at 60 °C until a constant weight was achieved. Soil samples were taken for depths of 0–10 and 10–20 cm from the center of each location where the litter layer was sampled using a 2 cm diameter hand auger. Composite samples were made from the five soil samples for each depth in each plot and air-dried in the lab. Litter layer and soil samples were analyzed for C, N, P, K, Ca, and Mg.

Tree volume

For all species except *I. edulis*, tree volume was estimated as a cone (see Yamada and Gholz 2002):

$$V = \left(\pi r^2 * h\right)/3 \quad (1)$$

where, $V =$ volume, $r =$ radius from GLD (cm), and $h =$ tree height (cm).

Given the irregular growth form of *I. edulis*, diameters of up to four stems present at breast height were used to estimate the volume of each stem segment using Eq. 1, even if that stem segment had multiple bifurcations above breast height. Segment volumes were summed to estimate total *I. edulis* volume. Since many *I. edulis* bifurcated below DBH, the height of bifurcation and the diameter were measured at the bifurcation point to create a fustrum volume estimate using:

$$V = (\pi h/3) * \left(R^2 + Rr^2 + r^2\right) \quad (2)$$

where V = volume, h = height, R = radius at ground line and r = radius at bifurcation.

Aboveground biomass estimation

Planted tree aboveground biomass was estimated by multiplying published wood density values (Fearnside 1997) by the volume estimate generated by the method described above, so that:

$$B = V * \rho \quad (3)$$

where, B is biomass, V is volume, and ρ is wood density. Gehring et al. (1999) reported wood:leaf ratio of 5.6:1 for young secondary forests in the Brazilian Amazon, which was used to separate the total biomass estimate into wood and leaf compartments.

Aboveground C and N stock estimates

Aboveground C stock of planted trees was estimated by multiplying the biomass by 0.5 g C g^{-1} dry mass (Fearnside and Laurance 2004). Aboveground N stocks of planted trees were estimated by multiplying the biomass of wood or leaf by reported N concentrations for *I. edulis* in Central Amazonia (Lojka et al. 2005) or the mean of reported values for N in secondary vegetation in the eastern Amazon (Davidson et al. 2004; Johnson et al. 2001). No error estimates were given for N concentrations in *I. edulis* or secondary vegetation from the above reports. Soil C content was estimated by multiplying the C_{org} concentration by the bulk density of each treatment which ranged between 1.18 and 1.26 g cm^{-3} in the 0–5 and 5–10 cm depth increments (Joslin et al. 2013).

Statistical analysis

Analysis of variance (ANOVA) was used to analyze the project as a two-way factorial randomized complete block design. Fertilizer treatment with and without P + K additions were the main plot treatments (N = 4) and treatments with or without the presence of *I. edulis* were the sub-plot treatments.

GLD, DBH and height were tested after using a $\log_{10}$ transformation to normalize the data and for analysis using the SAS (Cary, NC) statistical package. Statistical significance was conferred at the $p = 0.05$ level.

Tree volume, biomass and N-content, as well as litter layer mass, N content, and C:N, were analyzed using the JMP Pro 10 statistical package as described above.

Results

Soil response

O-horizon

No significant differences were found in C content of the O horizon for fertilization ($p = 0.8$) or the presence of *I. edulis* ($p = 0.5$) in Year 6 (Table 1). The organic layer mass remaining at Year 6 was 22–36 % of the mass at establishment ($p < 0.0001$), while 48–88 % of the organic layer mass remained from Year 2 to Year 6 ($p = 0.01$).

Among macronutrient concentrations tested, the only significant responses were greater N concentration in the O-horizon in the presence of *I. edulis* ($p = 0.005$) and an N-fixer × fertilization interaction ($p = 0.04$). However, N content of the organic layer was not different between treatments ($p > 0.7$). The N content of the O-horizon at Year 6 ranged between 37 and 70 % of the N content at establishment (Table 1).

The C:N ratio of the organic layer after Year 6 was not different for any treatment ($p > 0.5$). The C:N ratio for treatments decreased from 88:1 at Year 1 to between 47:1 and 65:1 in the PK+ I+ and PK− I+ treatments, respectively, at Year 6 (Table 1).

Mineral soil

Among soil macronutrients, only P responded significantly ($p = 0.0002$) to treatments, with 37 and 45 % higher concentrations in the 0–10 and 10–20 cm horizons, respectively (Table 2). A trend of increased

Table 1 O Horizon mass, C, N and C:N ratio at establishment, Year 1 and Year 6 in an improved-fallow slash-and-mulch AFS in Igarapé Açu, Pará, Brazil

Year	Treatment[1]	Mass ($Mg\ ha^{-1}$)	C ($Mg\ ha^{-1}$)	N ($kg\ ha^{-1}$)	C:N
2005	PK− I−	59 ± 12 A	30 ± 6	425 ± 54	70
	PK− I+	46 ± 11 A	23 ± 6	237 ± 42	98
	PK+ I−	44 ± 10 A	22 ± 5	239 ± 42	92
	PK+ I+	65 ± 24 A	33 ± 12	379 ± 49	86
2006	PK− I−	35 ± 9 B	17 ± 4	332 ± 137	52a
	PK− I+	29 ± 6 B	14 ± 3	197 ± 47	73b
	PK+ I−	22 ± 6 B	11 ± 3	269 ± 50	42a
	PK+ I+	20 ± 5 B	10 ± 3	197 ± 65	51b
2011	PK− I−	14 ± 2 C	7 ± 1	125 ± 19	54
	PK− I+	12 ± 2 C	6 ± 1	135 ± 28	65
	PK+ I−	14 ± 2 C	7 ± 1	129 ± 21	57
	PK+ I+	13 ± 2 C	6 ± 1	137 ± 19	47

Main plot treatment (N = 4) with (PK+) and without (PK−) P + K fertilizer and sub-plot treatment in the presence (I+) or absence (I−) of N_2-fixing *Inga edulis*. Upper case letters indicate differences between years and lower case letters indicate significant differences ($\alpha = 0.05$) within year

[1] Treatments in a two-way factorial design are indicated by fertilization with P + K (PK+) or without fertilization (PK−) and sub-plot treatment in the presence (I+) or absence (I−) of N-fixing *Inga edulis*

Table 2 Macronutrient and acid cation concentrations (±1SE) of 0–10 and 10–20 cm soil horizons in a slash-and-mulch agroforestry system 6 years after establishment in 2005 in Igarapé Açu, Pará, Brazil

Treatment[1]	Depth (cm)	$C_{organic}$ ($g\ kg^{-1}$)	P ($mg\ dm^{-3}$)	N ($cmol\ dm^{-3}$)	K	Ca	Mg	Al	H + Al
PK− I−	0–10	25.5 (7.7)	4.4 (0.2)Ab	0.8 (0.1)	0.09 (0.01)	2.1 (0.1)	0.6 (0.1)	0.5 (0.0)	6.8 (0.3)
	10–20	14.7 (2.6)	2.7 (0.2)Ac	0.4 (0.1)	0.05 (0.01)	0.6 (0.0)	0.3 (0.1)	0.8 (0.0)	5.6 (0.3)
PK− I+	0–10	19.5 (1.4)	4.3 (0.3)Ab	0.7 (0.1)	0.09 (0.01)	2.1 (0.3)	0.6 (0.1)	0.5 (0.1)	6.9 (0.6)
	10–20	12.4 (0.6)	2.8 (0.2)Ac	0.3 (0.0)	0.04 (0.00)	0.8 (0.1)	0.3 (0.1)	0.7 (0.1)	5.9 (0.2)
PK+ I−	0–10	29.5 (10.7)	6.4 (0.4)Ba	0.5 (0.1)	0.11 (0.02)	1.8 (0.4)	0.8 (0.1)	0.6 (0.0)	7.5 (0.6)
	10–20	21.2 (9.7)	4.1 (0.4)Bb	0.4 (0.2)	0.05 (0.01)	0.7 (0.1)	0.3 (0.1)	0.9 (0.1)	6.4 (0.2)
PK+ I+	0–10	27.8 (9.4)	6.0 (0.5)Ba	0.6 (0.1)	0.07 (0.01)	1.4 (0.4)	0.5 (0.1)	0.8 (0.1)	6.9 (0.5)
	10–20	19.5 (7.2)	3.3 (0.7)Bb	0.6 (0.1)	0.06 (0.01)	0.8 (0.3)	0.2 (0.1)	0.9 (0.1)	6.2 (0.4)

Capital letters indicate significant differences among main-plot treatments (N = 4), and lower case letters represent significant differences among main-plot treatments by depth ($\alpha = 0.05$)

[1] Treatments in a two-way factorial design are indicated by fertilization with P + K (PK+) or without fertilization (PK−) and sub-plot treatment in the presence (I+) or absence (I−) of N-fixing *Inga edulis*

soil N was detected ($p = 0.08$) in the 0–10 cm horizon in PK− treatment, but no trend for N was found in the 10–20 cm horizon. Without P + K fertilization the 10–20 cm horizon had 51 % lower N concentration than the 0–10 cm horizon, yet was only 6 % lower with P + K fertilization.

Growth response

Survival

At Year 6, stand-wide survival of planted trees decreased by 44 % ($p = 0.03$) with P + K fertilization (PK+), but was 26 % greater ($p = 0.10$) in the presence of *I. edulis* (I+), when compared to PK− I−, yet the fertilization × *I. edulis* interaction was not significant ($p = 0.15$; Table 3). Fertilization with P + K reduced survival of *P. multijuga* by 82 % ($p < 0.01$) and of *I. edulis* by 42 % ($p = 0.09$), and reduced survival of *S. amazonicum* by 65 % ($p = 0.035$), *C. pentandra* by 55 % ($p = 0.04$), and 95 % decrease in survival in *C. odorata* ($p = 0.004$), but neither the presence of *I. edulis* ($p > 0.1$) nor the fertilization × *I. edulis* interaction were significant ($p > 0.1$).

GLD and DBH

Responses of GLD growth to P + K fertilization was generally positive (Fig. 1), with *I. edulis* ($p < 0.0001$), *S. amazonicum* ($p = 0.0004$) and *C.pentandra* ($p < 0.0001$) responding significantly, while *C. odorata* ($p = 0.08$) and *P. multijgua* ($p = 0.5$) were less responsive, at Year 6. The fertilizer × time interaction was significant for *I. edulis* ($p < 0.0001$), *S. amazonicum* ($p < 0.0001$), *C.pentandra* ($p < 0.0001$) and *C. odorata* ($p = 0.0003$). The positive contrast of the log-transformed GLD difference between month 72 and 24 indicate that *I. edulis* (0.14; $p < 0.0001$), *S. amazonicum* (0.14; $p < 0.0001$), and *C. pentandra* ($p = 0.0006$) continued to respond positively to P + K fertilization. Although *P. multijgua* did not respond to fertilizer ($p = 0.5$), a positive trend ($p = 0.15$) was detected in the fertilizer × time interaction.

Planted-tree DBH responded positively to fertilization (Table 4), with the exception of *P. multijuga* ($p = 0.2$), while *I. edulis* showed the strongest DBH response to fertilization ($p = 0.0001$), and *C. pentandra* ($p = 0.03$) and *S. amazonicum* ($p = 0.03$) responded strongly as well.

Height

Strong responses to fertilization ($p = 0.004$; Fig. 2), time ($p < 0.0001$) as well as the P + K fertilization × time interaction ($p < 0.0001$) were shown by *I. edulis*. The positive contrast (0.15) between months 72 and 24 indicates that the rate of growth of *I. edulis* continued to respond positively to P + K fertilization. *Parkia multijuga* did not respond to fertilization ($p = 0.5$), although there was a P + K fertilization × time interaction ($p = 0.05$).

Strong responses to P + K fertilization ($p = 0.0003$) as well as P + K fertilization × time

Table 3 Survival (Mean ± 1SE) at Years 1, 2 and 6 after planting in 2005 of five native tree species planted in mixed-culture in Igarapé Açu, Pará, Brazil

Year	Treatment[1]	*I. edulis* Survival (%)	*P. multijuga*	*C. odorata*	*C. pentandra*	*S. amazonicum*	Plot
2006	PK− I−	–	–	79.9 (3.6)	97.0 (1.9)	63.5 (7.3)	79.8 (3.5)
	PK− I+	98.8 (0.7)	88.1 (5.1)	80.0 (4.1)	100 (0.0)	66.1 (5.9)	91.4 (1.6)
	PK+ I−	_	_	12.3 (4.5)	33.8 (9.1)	46.2 (8.5)	30.6 (4.2)
	PK+ I+	51.3 (6.1)	17.8 (8.5)	6.3 (6.3)	25.0 (10.4)	42.0 (10.3)	37.5 (4.1)
2007	PK− I−	_	_	57.1 (8.9)	82.8 (3.9)	29.6 (5.8)	56.3 (5.2)
	PK− I+	91.9 (3.3)	78.1 (7.9)	57.5 (7.5)	83.0 (4.7)	29.4 (7.2)	77.2 (3.6)
	PK+ I−	_	_	6.1 (2.6)	32.6 (5.8)	46.5 (1.6)	28.5 (3.2)
	PK+ I+	44.5 (5.9)	13.5 (6.2)	0.0 (0.0)	17.5 (8.5)	42.8 (7.7)	32.1 (3.6)
2011	PK− I−	_	_	55.0 (9.4)	57.0 (5.6)	12.0 (0.7)	40.7 (4.6)
	PK− I+	73.1 (6.9)	78.1 (8.6)	56.1 (5.0)	62.1 (16.0)	15.8 (7.5)	63.1 (4.7)
	PK+ I−	–	–	5.1 (2.7)	35.5 (11.0)	43.4 (3.9)	27.9 (4.8)
	PK+ I+	42.6 (6.0)	13.5 (5.0)	0.0 (0.0)	17.5 (8.5)	35.3 (5.4)	30.1 (3.8)

Main-plot treatment with (PK+) and without (PK−) P + K fertilization and sub-plot treatment in the presence (I+) or absence (I−) of N-fixing *Inga edulis* (N = 4)

[1] Treatments in a two-way factorial design are indicated by fertilization with P + K (PK+) or without fertilization (PK−) and sub-plot treatment in the presence (I+) or absence (I−) of N-fixing *Inga edulis*

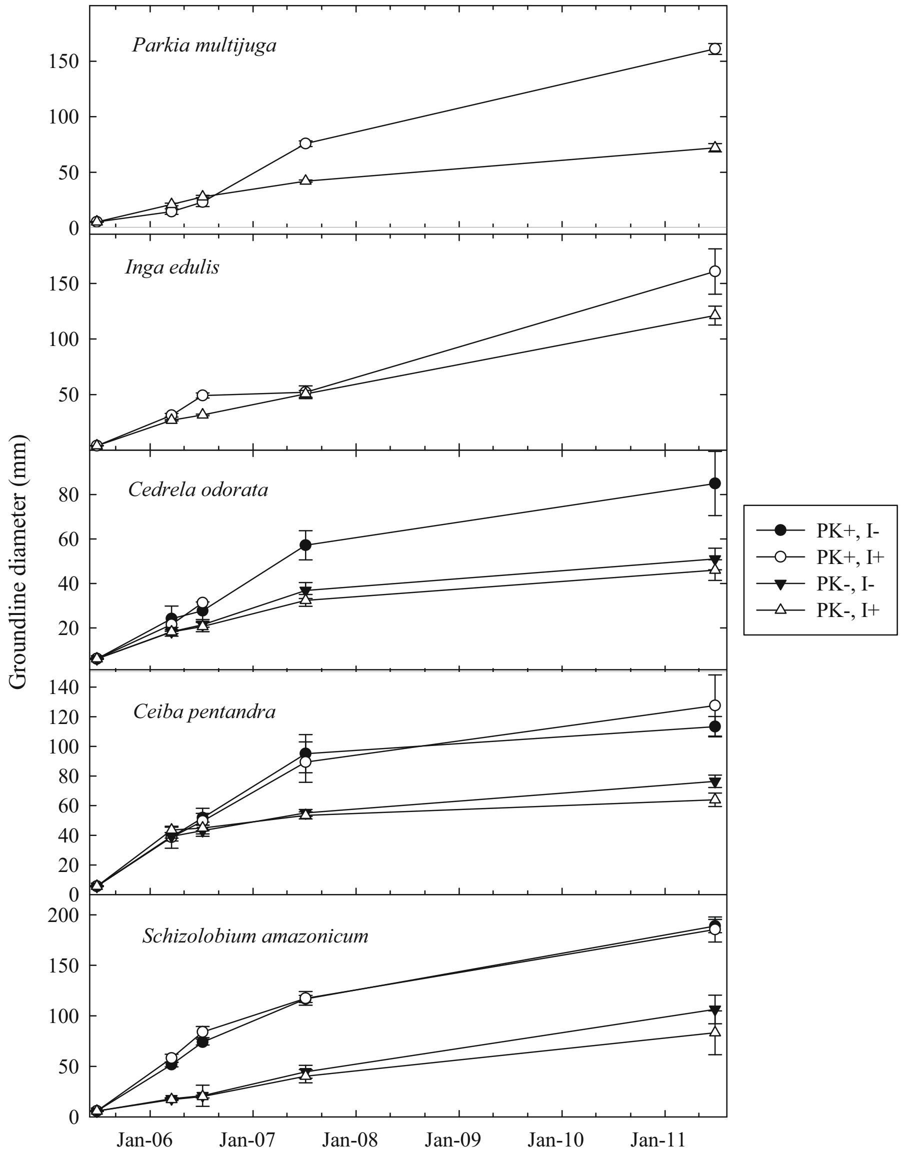

Fig. 1 Ground line diameter (mm) response through Year 6 after planting in 2005 of a slash-and-mulch, improved fallow, mixed-culture agroforestry system in Igarapé Açu, Pará, Brazil. Error bars represent ±1SE (N = 4)

interaction ($p < 0.0001$) were found in *S. amazonicum*. The contrast between months 72 and 24 was negative (−0.08) and not significant ($p = 0.2$), indicating that fertilizer no longer caused a height growth response. *Ceiba pentandra* responded strongly to fertilization ($p < 0.0001$), fertilization × time ($p < 0.0001$), and showed a continuing response to fertilization ($p = 0.0006$). *Cedrela odorata* responded to P + K fertilization ($p = 0.06$), although the rate of height growth did not respond to fertilization after 72 months ($p = 0.4$).

Volume

Fertilization with P + K increased estimated volume for three species, but not *P. multijuga* or *C. odorata*. The presence of *I. edulis* (I+) reduced volume for both *S. amazonicum* and *C. pentandra*, but not *C. odorata* (Table 5). Volume estimates for *S. amazonicum* increased 15-fold with P + K fertilization and 24-fold in the presence of *I. edulis* with fertilization (PK+ I+ vs. PK− I+), while volume estimates for *I. edulis* increased over 3.3-fold and *C. pentandra* increased

Table 4 Diameter at breast height (±1SE) of five native tree species at Year 6 in 2011 planted in a mixed-culture, slash-and-mulch agroforestry system in Eastern Amazonia of Brazil

Treatment[1]	*I. edulis* Diameter at breast height (cm)	*P. multijuga*	*C. odorata*	*C. pentandra*	*S. amazonicum*
PK− I−			2.8 (0.3)	3.5 (0.5)a	8.9 (1.5)a
PK− I+	4.2 (0.3)a	9.7 (0.8)a	2.7 (0.4)	1.6 (0.3)a	8.0 (2.6)a
PK+ I−			4.9 (1.0)	7.2 (0.8)b	17.1 (0.7)b
PK+ I+	9.3 (0.3)b	13.4 (1.3)b	–	10.0 (3.3)b	17.1 (1.2)b

Letters indicate significant differences ($p = 0.05$) for DBH between treatments (N = 4), within species

[1] Treatments in a two-way factorial design are indicated by fertilization with P + K (PK+) or without fertilization (PK−) and sub-plot treatment in the presence (I+) or absence (I−) of N-fixing *Inga edulis*

2.7-fold with P + K fertilization, respectively (Fig. 3).

Biomass

The total biomass of all planted trees was significantly enhanced by P + K fertilization ($p = 0.001$) and the presence of *I. edulis* ($p = 0.0015$; Fig. 4), an increase of over 1100 % compared to control (PK− I−) by Year 6. However, the interaction of the two was not significant ($p = 0.2$). Although 78 % of the estimated biomass in PK+ I+ was generated by *I. edulis*, the presence of *I. edulis* significantly reduced biomass of *C. odorata*, *C. pentandra* and *S. amazonicum*; the biomass impact of *I. edulis* was reduced to 58 % of treatment total without P + K fertilization (PK− I+; Table 6). The control treatment (PK− I−) produced 0.25 Mg ha^{-1} year^{-1} while PK+ I+ produced 3.2 Mg ha^{-1} year^{-1} of planted tree biomass (Table 6). Fertilization in the absence of *I. edulis* (PK+ I−) caused a 13.5-fold increase in biomass for *S. amazonicum* compared to PK− I−, and a 15-fold increase in biomass in the PK+ treatment compared to PK−. Fertilization (PK+) caused 2.9-fold and 3.3-fold increases in biomass for *C. pentandra* and *I. edulis*, respectively, when compared to PK−.

Aboveground C and N content

Fertilization with P + K caused a significant increase in estimated planted tree biomass C stocks ($p = 0.001$; Fig. 5), and the inclusion of *I. edulis* in the mixed-culture planting had a significant effect ($p = 0.0015$) on the estimated sum of above-ground biomass-C, with the same pattern on individual species biomass-C as described for biomass. Soil organic-C stocks did not differ between treatments at the 0–10, 10–20 or 0–20 cm depths (Fig. 5) and the sum of 0–20 cm ranged from 32 to 51 Mg ha^{-1}.

Estimated N content of the aboveground biomass of planted trees ranged from 7.6 ± 2.6 to 141.4 ± 25.3 kg N ha^{-1} in control (PK− I−) to full treatment, respectively (PK+ I+; Table 7), and was greater in the fertilized (PK+) than in the unfertilized (PK−) treatment ($p = 0.0003$) as well as in the presence of *I. edulis* (I+) compared to I− ($p = 0.0003$; Fig. 6). Estimated N content of all species was greater with P + K fertilization, except for *P. multijuga*, and was greater in PK− I+ than PK− I− for all species present (Table 7). Estimated N content was greater in PK+ I− than in PK+ I+ for *S. amazonicum* and *C. pentandra*, but *C. pentandra* was not different between PK+ I+ than either treatment in the PK− main-plot treatment.

Discussion

Organic horizon

Fertilization caused a significant reduction in mulch layer biomass at Year 1 (Joslin et al. 2011b), yet no difference between treatments existed at Year 6 in the main-plot or sub-plot treatments. Observation of the organic layer indicated that very little, if any, of the original mulched forest biomass remained on the soil surface and that most, if not all, of the organic layer on the surface at Year 6 was recently deposited leaf and fine branch material. If this is the case, then nutrients sampled in the Year 6 organic horizon were cycled through post-mulching biomass before deposition on

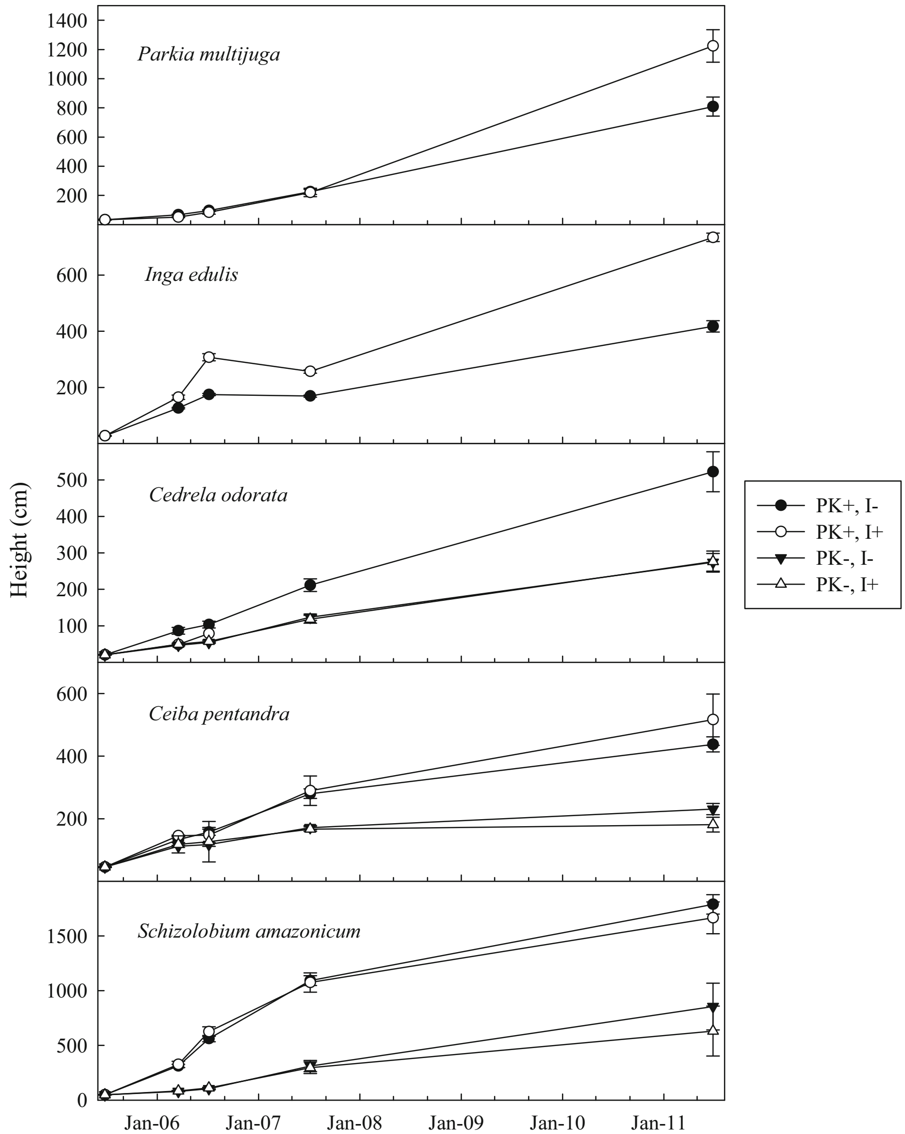

Fig. 2 Height (cm) response at Year 6 after planting in 2005 of a slash-and-mulch, improved fallow, mixed-culture agroforestry system in Igarapé Açu, Pará, Brazil. *Error bars* represent ±1SE (N = 4)

the surface as litter. Higher N concentrations, as well as trends of higher N content, in the presence of *I. edulis* support this observation.

Litter layer mass reported here is higher than AFS in central Amazonia (≤4.9 and ≤7.2 Mg ha^{-1}; Tapia-Coral et al. 2005; Schroth et al. 2002, respectively), although similar to plantation forests in eastern Amazonia (≤11 Mg ha^{-1}; Smith et al. 1998). Litter layer mass reported here is similar to rates of litterfall reported from secondary forests of eastern Amazonia (13.4 Mg ha^{1}; Barlow et al. 2007) and central Amazonia (10.3 Mg ha^{-1}; Cuevas and Medina 1986). Due to high decomposition rates in this region, particularly for species of high foliar nutrient concentrations, such as *I. edulis*, (Gehring et al. 1999), additions of litter to the soil surface between Years 2 and 6 likely served to maintain the mulch layer at a relatively constant mass.

Table 5 Statistical significance of treatments (N = 4) on volume estimates of five native tree species planted in mixed-culture in a slash-and-mulch agroforestry system in Eastern Amazonia of Brazil 6 years after planting

Treatment level	*I. edulis* $p > F$	*P. multijuga*	*C. odorata*	*C. pentandra*	*S. amazonicum*
Fert[1]	0.023	0.217	0.005	0.006	<0.001
Nfix[2]			0.006	0.006	0.003
Nfix × Fert			0.072	0.699	0.007

[1] Nfix represents the sub-plot treatment of the inclusion of the N-fixing *I. edulis* in the mixed-culture, or without

[2] Fert represents the main-plot treatment of P + K fertilization, or without

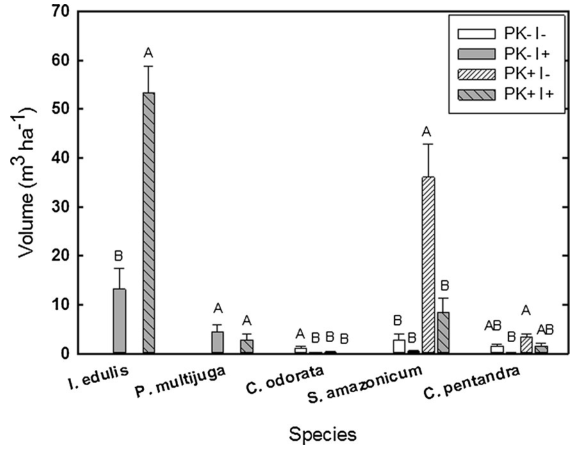

Fig. 3 Volume (m^{-3} ha^{-1}) of five species of native trees planted in a mixed-culture slash-and-mulch agroforestry system in Eastern Amazonia of Brazil at Year 6 after planting in 2005. *Letters* indicate significant differences within species by treatment (N = 4)

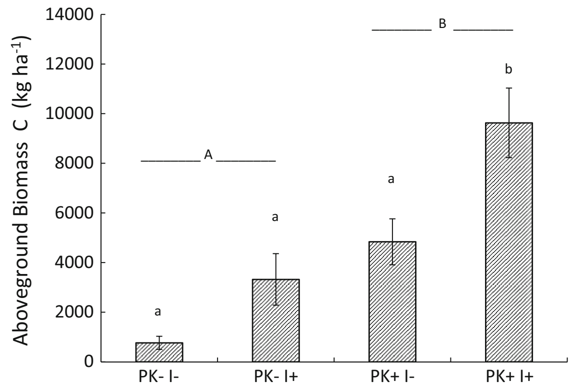

Fig. 4 Above-ground biomass carbon (kg ha^{-1}) of five (5) species of native trees planted in a mixed-culture slash-and-mulch agroforestry system in the Eastern Amazon of Brazil at Year 6 after planting in 2005. Capital letters indicate significant differences among the main-plot treatment with P + K fertilization (PK+) or without (PK−). *Lower case letters* indicate significant differences between treatments (N = 4)

Growth response

Plot-level survival response to the interaction of *I. edulis* and P + K fertilization showed a strong trend of reduced survival, likely to due to increases in competition biomass with fertilization. Competition biomass was measured at the end of Year 1 but was not re-measured at Year 6 (Joslin et al. 2011b). The growth of *I. edulis* itself contributed to reduced survival and growth responses of other planted tree species due to its copious canopy spread that shaded other trees.

Fertilization caused a growth response measured in GLD, DBH and height in most planted species, but the presence of N-fixing *I. edulis* was not associated with a growth response, nor was the interaction of fertilization with *I. edulis* ($p > 0.10$), although the plot-level survival response to the interaction of P + K fertilization with *I. edulis* showed a strong trend of reduced survival. This response was likely to due to increased competition biomass response to fertilization, which was measured after Years 1 and 2 but not at Year 6 (Joslin et al. 2011b). The growth of *I. edulis* itself reduced survival and growth responses of other planted tree species due to its canopy shading other trees.

Ruivo et al. (2010) report growth rates in AFS for *S. amazonicum* after 4 years which are comparable to growth rates reported here, although survival reported here was somewhat higher. Many fertilized *S. amazonicum* died between 2007 and 2011, which had previously been observed as growing vigorously. It is

Table 6 Biomass (Mean ± 1SE) of five native tree species planted in mixed-culture in a slash-and-mulch agroforestry system in Eastern Amazonia at Year 6 after planting in 2005

Species	Treatment[1]				Treatment level[2]		
	PK− I− Biomass (kg ha^{-1})	PK− I+	PK+ I−	PK+ I+	Nfix $p > F$	Fert	Nfix × Fert
I. edulis	–	4707 (1416) A	–	15721 (1557) B		0.023	
P. multijuga	–	1702 (541) A	–	1062 (423) A		0.217	
C. odorata	447 (138) A	94 (34) B	101 (36) B	0 (0) B	0.005	0.006	0.072
C. pentandra	442 (81) AB	56 (8) A	922 (192) B	440 (160) AB	0.006	0.006	0.699
S. amazonicum	641 (306) A	83 (80) A	8652 (1624) B	2036 (664) A	0.003	<0.001	0.007

Letters indicate significant differences between treatments (N = 4) using Tukey's HSD

[1] Treatments in a two-way factorial design are indicated by fertilization with P + K (PK+) or without fertilization (PK−) and sub-plot treatment in the presence (I+) or absence (I−) of N-fixing *Inga edulis*

[2] Treatment Level Nfix represents the sub-plot treatment of the inclusion of the N-fixing *I. edulis* in the mixed-culture, or without; Fert represents the main-plot treatment of P + K fertilization, or without; and Nfix × Fert represents the interaction between the two treatment levels

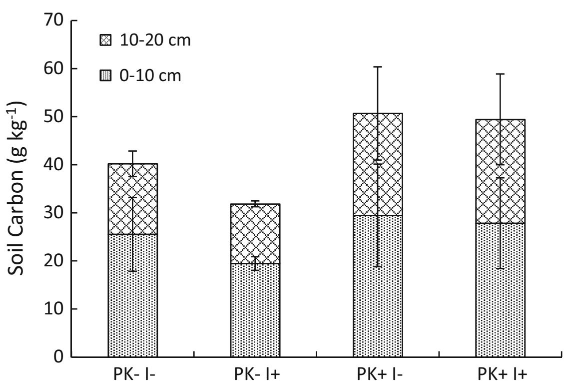

Fig. 5 Soil organic carbon stocks (g kg^{-1}) of soils at 0–10 and 10–20 cm depths in a mixed-culture slash-and-mulch agroforestry system in eastern Amaznonia of Brazil at Year 6 after planting in 2005. No significant differences ($p > 0.3$) were detected between treatments. *Error bars* represent ±1SE (N = 4)

possible that *Quesada gigas*, a root boring insect reported in Pará State (Zanuncio et al. 2004), attacked those individuals. Attack by *Q. gigas* may help to explain why *S. amazonicum* height growth no longer responded to fertilizer at Year 6 whereas GLD growth response continued, since several trees had died back at the top, while continuing to grow at the base.

From field observations, it is likely that attacks by *Hypsipila grandella*, a shoot-boring insect, caused significant (though unmeasured) damage to *C. odorata* (Navarro et al. 2004). Observations indicated that *H. grandella* may have attacked fertilized *C. odorata* at a higher rate, which may have led to increased mortality in fertilized treatment. When combined with the increased mortality caused by shading from *I. edulis*, these attacks may have caused 100 % mortality of *C. odorata* in the PK+ I+ treatment.

Additionally, many *C. pentandra* were attacked by a shoot-boring insect, possibly *Alcides leeuwenii* (Oei-Dharma 1969), which sometimes caused death, but often caused the upper stem to die back and sprout again. As such, many individuals were shorter in 2011 than in 2007.

Many *I. edulis* seedlings were observed underneath the PK+ I+ treatments, although none were observed under the unfertilized treatment. It is likely that the enhanced growth and vigor of fertilized *Inga* allowed them to reach maturity, produce flowers and fruits faster than unfertilized *Inga*.

Volume and biomass response

Estimated volume gains by *S. amazonicum* and *I. edulis* with P + K fertilization were large, yet were accompanied by volume reductions in other species. *Inga edulis* reduced survival and productivity of other species, particularly *C. odorata*. Controlling weedy vegetation and pruning *I. edulis* for green mulch during the cropping phase should be performed to ensure survival and growth of interplanted tree species if producers choose an improved fallow system for timber and/or non-timber forest products.

Table 7 N content (Mean ± 1SE) of five native tree species planted in mixed-culture in a slash-and-mulch agroforestry system in eastern Amazonia of Brazil Year 6 after planting in 2005

Species	Treatment[1]							
	PK− I−		PK− I+		PK+ I−		PK+ I+	
	Wood N (kg ha^{-1})	Leaf	Wood	Leaf	Wood	Leaf	Wood	Leaf
I. edulis			14.4 (4.3)	22.7 (6.8) A			48.0 (4.8)	75.3 (7.5) B
P. multijuga			3.0 (1.1)	12.4 (4.5) A			1.7 (0.7)	3.5 (1.4) A
C. odorata	0.7 (0.2)	1.5 (0.5) A	0.2 (0.1)	0.3 (0.1) B	0.2 (0.1)	0.3 (0.1) B	–	–B
C. pentandra	0.7 (0.1)	1.5 (0.3) AB	0.2 (0.1)	0.7 (0.3) A	1.5 (0.3)	3.1 (0.6) B	0.7 (0.3)	1.5 (0.5) AB
S. amazonicum	1.1 (0.5)	2.1 (1.0) A	0.1 (0.1)	0.6 (0.5) A	14.2 (2.7)	28.9 (5.4) B	3.3 (1.1)	6.8 (2.2) A

The main-plot treatment with P + K fertilization (PK+) or without fertilization (PK−) and the sub-plot treatment of mixed-culture planting with *I. edulis* (I+) or without (I−). Letters indicate significant differences between treatments (N = 4), within species, using Tukey's HSD

[1] Treatments in a two-way factorial design are indicated by fertilization with P + K (PK+) or without fertilization (PK−) and sub-plot treatment in the presence (I+) or absence (I−) of N-fixing *Inga edulis*

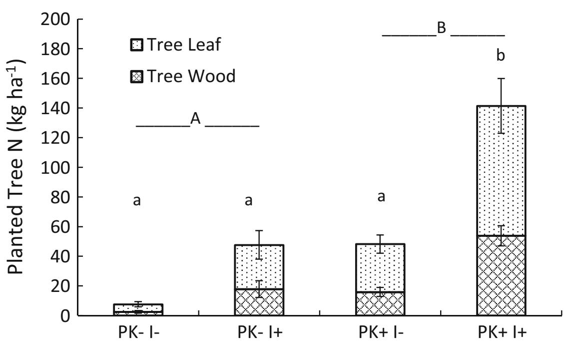

Fig. 6 Nitrogen content (kg ha^{-1}) in the wood and leaf compartments, respectively, of planted trees in a mixed-culture slash-and-mulch agroforestry system in eastern Amazonia of Brazil at Year 6 after planting in 2005. *Capital letters* indicate significant differences in the main-plot treatment with P + K fertilization (PK+), or without (PK−). *Lower case letters* indicate significant differences between treatments. *Error bars* represent ±1SE (N = 4)

Keefe et al. (2009) reported that *S. amazonicum* can be successfully cultivated in mixed-species enrichment plantings with rotation lengths of 30 years, although data presented here indicates that P + K fertilization can reduce the rotation length to <10 years. Keefe et al. (2009) estimated rotation lengths of 90 years for slower-growing, high-value timber species, such as *C. odorata*. Early gains in *C. odorata* were observed through year 6 but cannot be confidently extrapolated to rotation age.

Native hardwood harvests of 60 m^3 ha^{-1} by selective logging were reported from a mature várzea (i.e., floodplain) forest of Amazonia (Schöngart and de Queiroz 2011). Eucalyptus grown in AFS in Minas Gerais, Brazil produced 10–15 m^3 ha^{-1} after 16 months (Ceccon 2007), whereas Gonçalves et al. (2008) found that Eucalyptus plantations across Brazil had yields ranging from 150 to nearly 300 m^3 ha^{-1} after 6 years. Despite its presence in a mixed-culture AFS, timber production reported here may be expected to fall on the low end of the spectrum when compared to plantations in tropical Brazil.

Planted tree biomass reported here spans the range of forest biomass accumulation following various land-uses in Brazil, with a mean of 2.9 Mg ha^{-1} year^{-1} (Omeja et al. 2012). However, we did not measure competing biomass at Year 6, so total biomass in all four treatments is likely higher than estimates for only planted trees.

Aboveground N content

Estimated N content of planted trees in the fertilized treatment (PK+) was 3.4× greater than unfertilized (PK−), and the presence of *I. edulis* caused 2.9× and 6.6× greater N content with and without P + K fertilization, respectively. Although *I. edulis* was 50 % of the original planting density, it accounted for 70 and 80 % of the estimated N content in PK+ and PK− treatments, respectively. Since competing vegetation was not collected, total aboveground biomass-N is not estimated here. The estimated N-content of only the planted trees in the control treatment (PK− I−) is two orders of magnitude less than the reported N content of a 7-year old secondary forest in Eastern Brazil, however, the planted trees in the PK+ I+ treatment contain about 50 % of this reported N content (Denich et al. 2004). Estimated N uptake by planted trees reported here is only a portion of the total aboveground biomass N uptake. Values reported here are similar to N uptake values in secondary forests reported from Brazilian Amazonia, which ranged from 114 to 576 kg ha^{-1}, or 14–72 kg ha^{-1} $year^{-1}$ on an annualized basis (Buschbacher et al. 1988; Denich et al. 2005; Feldpausch et al. 2004; Markewitz et al. 2004).

When manioc (*M. esculenta*) roots were sampled after 20 months they contained between 0.9 and 19.3 kg N ha^{-1} from the control (PK− I−) to the full treatment (PK+ I+), respectively, which would be exported from the site with agricultural harvest (Joslin et al. 2011b). In treatments with *I. edulis* (I+), estimated N uptake in *I. edulis*, to replace N from manioc export, was about 15× and 7× more than N exported in manioc tubers in control (PK− I−) and full treatment (PK+ I+), respectively. In addition, these N inputs would be sufficient to replace the combined N exports from manioc after 20 months and *S. amazonicum* after Year 6, if the trees were harvested as well. Nutrient content of competing vegetation was not sampled at this time, so we cannot estimate whether, in a second rotation, uptake and mulching of competing vegetation alone would replace N from manioc and tree export.

Soils under secondary forests of eastern Amazonia of Brazil can be N-limited or N and P co-limited (Denich et al. 2004, Davidson et al. 2004). Results presented here confirm these observations, since P + K fertilization had a strong effect on growth, as well as estimated volume, biomass and N-content of planted trees. The presence of the N-fixing *I. edulis* contributed to increases in total biomass and N-content of planted trees at Year 6.

Management implications

Data presented here indicate that utilizing mixed-species, improved-fallow plantings may allow producers to include commercially valuable tree species at the time of planting with food crops without jeopardizing crop production. Planted tree species also gain a 2-year advantage on secondary succession growth, which would otherwise suppress planted tree growth and survival.

These data indicate that P + K fertilization in an improved-fallow slash-and-mulch system can allow producers to harvest a merchantable timber species after just one crop-fallow rotation, while leaving slower-growing higher-value trees through subsequent crop-fallow rotations for future timber income. Using tree-crops in this fashion may give low-input farmers additional production and financial options over time.

Losses of N from the agroecosystem from short-rotation slash-and-burn farming can cause a cycle of decreasing soil fertility and declining crop yields (Metzger 2002).Here the data indicate that slash-and-mulch in combination with planting of the N-fixing *I. edulis* in the mixed-culture stimulate N accumulation in excess of losses from crop and tree export. Exporting *I. edulis* stems as charcoal or firewood, as well as logs of *S. amazonicum*, should be a viable option for producers without jeopardizing N stocks for future cropping cycles if the foliage and small branches are left on site as green manure.

Conclusions

Most species grew significantly greater height, DBH, and GLD with P + K fertilizer, and continued to respond to P + K fertilization after 6 years when compared to control, with the exception of *S. amazonicum*, whose growth may have been impacted by a pest. Availability of P + K fertilizer in the soil, and cycling through vegetation and litterfall, continued to stimulate tree growth after 6 years. However, biomass and volume estimates for *S. amazonicum* increased by up to 104-fold and 24-fold, respectively, with P + K fertilization than without.

Inclusion of the N-fixing tree *I. edulis* increased estimated biomass and N-content for planted trees in this mixed-culture AFS after Year 6 by threefold, with the majority of the N stored in the leaves in the plots with *I. edulis*. Use of acid-soil tolerant N-fixers, such as *I. edulis*, with P + K fertilization can be incorporated in short-rotation crop-fallow systems to meet or exceed N demand of both food and tree crops.

Harvesting fast-growing species, such as *S. amazonicum*, after one crop-fallow cycle in a slash-and-mulch AFS should be feasible with the use of P + K fertilization. Including N-fixing species, such as *I. edulis*, should supply sufficient N to maintain system N-stock even with the export of N through harvested timber.

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