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Growth, production and carbon sequestration of silvopastoral systems with native timber species in the dry lowlands of Costa Rica

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Abstract The multiple environmental issues of loss of forest cover due to cattle farming combined with pasture degradation leading to low levels of production, consequent extensification and therefore to more deforestation, are serious concerns in Costa Rica. To test the feasibility of countering these by combining a more productive pasture system with indigenous tree species, a silvopastoral experiment was established on a farm in the seasonally dry lowlands of Cañas, Guanacaste Province. A rapidly growing pasture species (*Brachiaria brizantha*) was tested against a traditional pasture dominated by *Hyparrhenia rufa*. Three indigenous tree species were established: *Pithecellobium saman*, *Diphysa robinoides* and *Dalbergia retusa*. Plots were grazed by cattle for 4 or 5 days with one to 2 month intervals between grazing episodes. After 51 months, *D. robinoides* was the fastest growing species, and *P. saman* the slowest, while *B. brizantha* produced three times the above

ground and twice the below ground biomass as *H. rufa*, and trees had no effect upon grass yield. Contrary to competition theory, there was no effect of pasture species upon the two faster growing tree species. The carbon in above and below ground phytomass varied between 3.5 and 12.5 Mg C ha⁻¹ in treeless pasture controls and silvopastoral systems, respectively, and total soil organic carbon (TSOC) in the upper 0.6 m averaged 110 Mg ha⁻¹. *B. brizantha* appeared to stimulate tree root production, which in turn was highly correlated with TSOC, resulting in annual increments in TSOC of up to 9.9 Mg ha⁻¹ year⁻¹. These early results indicate the promising potential of this silvopastoral system for combining cattle production, and increasing tree cover and carbon sequestration.

Keywords Agroforestry · *Brachiaria brizantha* · *Dalbergia retusa* · *Diphysa robinoides* · *Hyparrhenia rufa* · Indigenous tree species · *Pithecellobium saman* · Soil organic carbon

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Introduction

This paper reports research on tree–grass interactions in terms of growth, production, fine root biomass and carbon sequestration in a silvopastoral experiment in a seasonally dry lowland Pacific zone of Cañas, Costa Rica.

Deforestation represents one of the most important problems in the World; around 13 million hectares per year are being lost due to conversion of forest to agricultural lands (FAO 2005). In the Central America region, the total area dedicated to permanent pastures has slowly grown over the last decade ($0.1\% \text{ year}^{-1}$; FAO 2006); to about 10 to 12 million hectare by 2003 (63% of the agricultural area, and 82% in Costa Rica), most being conventionally managed using fire and low inputs. These pastures degrade in time resulting in decreased in productivity. In the dry Chorotega region of Costa Rica, where the municipality of Cañas is located, forests have become fragmented over the last four decades. Between 1960 and 1980, fragmentation was due to forest shrinkage and division mainly attributed to cattle ranching practices; whereas between 1980 and 2000, due to abandonment by farmers, the landscape became a mosaic of secondary forest growth and pastures (Arroyo-Mora et al. 2005).

Silvopastoral systems have been promoted as win-win technologies to enhance productivity and provide environmental services (Gobbi and Ibrahim 2004). Most farmers permit natural regeneration of trees in pastures because it is a cost effective way to introduce trees into the grassland dominated landscape. There is however, a tendency to replace traditional pastures with more aggressive and drought tolerant grass species. In the Cañas area, Esquivel et al. (2003) estimated that introduced, more productive grasses (*Brachiaria brizantha* and *Brachiaria decumbens*) occupy 72% of the pasture areas and 56% of total agricultural area. In such dry and seasonally dry areas, the use of drought tolerant and productive grasses improves the overall productivity of pastoral systems.

It is hypothesised that according to competition theory, more productive pastures would have a negative effect upon tree growth, to the detriment of overall system productivity. Some studies have demonstrated increased growth of tropical grasses under tree canopies at moderate density (Wilson 1998; de Andrade et al. 2004). These responses are mainly attributed to increased fertility or nitrogen availability under the tree canopy. However, high tree density or cover may cause excessive shade and exert a detrimental level of competition on the pasture and therefore reducing its carrying capacity (Wilson 1998). On the other hand, the economic and ecological importance of silvopastoral systems may increase if livestock grazing is also used to

manage the under-storey vegetation (Braziotis and Papanastasis 1995).

There is little information about how compatible the *Brachiaria* grasses are in silvopastoral mixtures with native timber tree species. This information is important for designing and managing silvopastoral systems for sustainable production of multiple outputs (meat, milk and timber) alongside the generation of environmental services such as increased ecological diversity and carbon sequestration. Most studies on traditional systems have focused on inventories of tree species and system composition and structure. Few studies have been conducted which evaluate how the grass component affects the growth and performance of associated native tree species.

In addition to the agricultural production issues arising from combining trees and pastures, over the past decade or so there has been increasing interest in the role of agroforestry, including silvopastoral systems, as a means of sequestering atmospheric carbon to mitigate the effects of this greenhouse gas (Albrecht and Kandji 2003; Montagnini and Nair 2004; Oelbermann et al. 2004). The advantage of agroforestry systems compared to forests is that the land can remain in agricultural use whilst sustaining a greater phytomass than a purely arable or pastoral system.

Materials and methods

Description of experimental site

This study was carried out on the farm Hacienda La Pacifica ($85^{\circ}9'14.5'' \text{ W}$ and $10^{\circ}28'36.8'' \text{ N}$; 50 masl) located 5 km north of Cañas, Guanacaste, Costa Rica. The zone is classified as dry tropical forest (Holdridge 1996). The main climatic conditions are listed in Table 1. During the period of growth measurements (between April 2003 and December 2005) the site received total rainfall of 5800 mm rainfall. The 2003–2004 dry season (December to April) was considerably drier than the 2004–2005 season (59 and 204 mm, respectively).

The soil was classified as a Lithic Ustorthent–Lithic Dystropept complex (Herrick 1993). The experimental field had an average slope of 4%. Initial soil characterization was conducted in treeless *Hyparrhenia rufa* control plots in September 2003, at the

Table 1 Main climatic and soil conditions in the experimental site, Hacienda La Pacífica, Cañas, Costa Rica

<i>Climatic conditions</i>						
Rainfall	1,500 mm year ⁻¹ ; 85% falls between May and November (wet season)					
Temperature	28°C (23–36°C)					
Relative humidity	60% and 85%					
Reference evapotranspiration	1,800 mm year ⁻¹					
Source: IMN (2003)						
<i>Soil conditions</i>						
Texture	Clay (44%)					
Depth (m)	Organic matter content (%)	pH	Ca (g kg ⁻¹)	Mg (g kg ⁻¹)	K (g kg ⁻¹)	P (mg kg ⁻¹)
0–0.2	3.5	6.7	2.60	0.53	0.25	1.02
0.2–0.4	1.9	7.0	2.62	0.52	0.20	0.66
0.4–0.6	1.1	7.1	2.76	0.58	0.14	0.44

point when tree and pasture growth recordings commenced (Table 1). These data are considered to be the baseline treatment against which others were compared.

Establishment of the experiment

The experiment was set up in September 2001 in *H. rufa* (Nees.) Stapf. pastures which had been grazed over the previous 20 years. A randomized complete block design with three replications and a factorial treatment structure with a split plot design was used. Two grass species formed the main plots. These were palisade grass (*B. brizantha* (Hochst. ex A. Rich.) Stapf.; syn. *Urochloa brizantha* (C. Hochst. ex A. Rich.) R. Webster), an introduced, more productive pasture species originally from Africa, and a pasture dominated by *H. rufa*, also originally from Africa but now widely naturalized (Herrick 1993; Baruch and Jackson 2005); with the local name, '*jaragua*'. Both possess the C₄ carboxylation pathway. Three randomized tree treatments (*Pithecellobium saman* (Jacq.) Benth., *Diphyssa robinoides* Benth., *Dalbergia retusa* Hemsl.), with a treeless control, formed the subplots. Main plots had an area of 4,000m²; and the subplot dimensions were 20 × 50 m. The three tree species are indigenous and leguminous and are present in forests at very low densities. All are reported to fix nitrogen (Tilki and Fisher 1998; Wishnie et al. 2007)

The original *jaragua* pasture was removed. The seedbed in the *B. brizantha* main plots were prepared with a tractor, plough and rake, then established by

sowing 4 kg seeds ha⁻¹, while the *H. rufa* plots were established by vegetative propagation. All plots were initially fertilized using a compound fertilizer (12:30:20 N/P/K) at a rate of 180 kg ha⁻¹. Trees were planted in double lines (2 × 2 m) within the pasture plots, leaving a strip of 8 m between lines and were fertilized at 100 g plant⁻¹ with the same fertilizer used for the pastures. No further fertilizers were applied after these initial starter doses. Seedlings were produced on Hacienda La Pacífica, with seeds from CATIE's seed bank and soil material from fertile sites on the same farm. Seedlings were transplanted at 3 months when they had a height of approximately 40 cm. Two subsequent infillings were done (May and October 2002), replacing all dead saplings.

For the first 2 years after establishment, grass was harvested and collected by tractor to avoid grazing and damage to young trees. Grazing of the experimental site started in September 2004 when the trees were completely established. Calves of around 80 kg live weight were used for the first three grazing periods, to minimize tree damage. After that, mature animals were used. A system of flexible grazing was used, with about 4 or 5 days of occupation and an average of 30 and 50 resting days in the rainy and dry seasons, respectively. A mean stocking rate of 2.0 AU¹ ha⁻¹ was used and animals had free access to all experimental plots. Cattle live weight gains

¹ One animal unit (AU)=one cow of approximately 450 kg weight.

were not recorded because it was not possible to separate each sub-plot with fencing.

Variables evaluated

Tree growth The 36 central trees per subplot were measured every 6 months between April 2003 and December 2005 (total height [TH], diameter at 0.3 m height [D30] diameter at breast height [DBH] and crown diameter in two directions: N–S, E–W). Mean quadratic diameter (MQD) at 0.3 m height and at breast height was calculated using Eq. 1, because these tree species usually had more than one stem. In this case, the two thickest trunks were measured.

$$\text{MQD} = \sqrt{(D_1^2 + D_2^2)} \quad (1)$$

Where;

MQD Mean quadratic diameter (m)
 D_1 and D_2 Diameter of the two major trunks (m)

Above ground biomass was estimated with a mixed or multi-species biomass model developed following the approach recommended by Segura et al. (2006). Twenty seven trees were destructively sampled (nine per species) to develop preliminary models for each tree species and statistically compared to evaluate differences in their intercept and slopes.

Forage production and grass residual biomass Sampling positions were located under the tree canopy and at the limit of canopy perpendicular projection in selected trees whose canopy area was similar to the mean canopy dimensions in the subplot. For estimation of system productivity, forage production was measured by cutting the grass down to 0.3 m height. For calculation of carbon sequestration, the residual grass biomass (i.e. more or less stable biomass) was considered to be the biomass between ground level and 0.3 m height. For both variables, two quadrats (0.5 × 0.5 m) per subplot were sampled the day before each evaluated grazing cycle. A sub-sample was taken from each quadrat to determine dry matter content (DM; 48 h at 65°C). A regression analysis was carried out to evaluate the effect of tree cover on grass production for both species.

Fine root biomass Soil cores were collected from two trees per sub-plot and two positions with respect to trees (under canopy, 1 m and intermediate, 2 m from the tree stem, respectively). Sampling was thus restricted to a 5 m wide sampling zone in each sub-plot, and results are reported on that basis. The sampled trees had similar dimensions (diameter at breast height, total height and canopy area) to the mean dimensions of the trees in each subplot. Root cores were collected from three depths (0–0.2, 0.2–0.4 and 0.4–0.6 m), extracted with an engine-powered auger (EFCO TR1540, 50 mm diameter and 0.6 m depth) due to the hardness of the clay soil. The root samples were taken to the laboratory for separation from soil and dead material, and then between components (tree and grass) and stored in a refrigerator (4°C) until analysis. The root separation by species was based on differentiating characteristics such as colour; grass roots being white contrasting with brown roots of trees. When the quantity of roots was high, a subsample of around 40% of the sample was taken for separation; in this case the remnant sample was dried to estimate dry matter. Each sample was oven dried (65°C for 48 h) to quantify fine root biomass by component.

Carbon content in biomass Samples of grass and tree species were collected to estimate the carbon fraction in biomass. From trees, 54 samples were taken comprising five components (stem, small and large branches, leaves and fine roots) from three species with three replications, except for fine roots (six replications). Grass samples were also collected above and below ground for both species. The samples were oven dried (65°C for 48 h) and then pulverised using a ball mill. In the case of woody components such as stem and branches, the samples were fragmented into small pieces using a hand drill before milling. All samples were analyzed by combustion using a CHN auto-analyzer (Thermo Finnigan FLASH EA 1112, Rodano, Milan, Italy) at the CATIE soil laboratory.

Soil nitrogen and organic carbon One combined sample for each stratum (0–0.2, 0.2–0.4 and 0.4–0.6 m) was obtained by mixing ten sub-samples collected in February 2005. Organic carbon and nitrogen was analyzed using a CHN auto-analyzer. Total soil organic carbon (TSOC) for the profile was calculated using organic carbon concentration, soil

depth and bulk density. To estimate soil bulk density, two soil core samples per block from the three horizons studied were collected with a metallic ring (43 mm diameter \times 44 mm height). Accumulation of soil organic carbon was calculated using the sample in September 2003 (Table 1) as a starting point (17 month interval between sampling).

Total carbon in biomass Biomass of structural roots of trees was not measured, and so was estimated using Eq. 2, developed by IPCC (2003) for tropical areas. Carbon in above ground biomass (trees and grasses), fine and structural root biomass were summed to calculate total carbon storage in biomass. Carbon accumulation rates in biomass were calculated over a period of 51 months, corresponding to the age of the trial.

$$\text{Br} = e^{(-1.0587 + 0.88 \times \text{Ln}(\text{Ba}))} \quad R^2 = 0.84 \quad N = 151 \quad (2)$$

Where;

Br Biomass of roots (Mg ha^{-1})
 Ba Above ground biomass (Mg ha^{-1})
 Ln Natural logarithm

Statistical analyses All statistical analyses were carried out using SAS (SAS 1985). Analyses of variance, comparison of simple and mixed means and regression procedures were carried out using GLM, MEANS, LSMEANS, CORR and REG procedures of SAS.

Results

Above ground tree biomass equations

Various models using tree height (TH), tree diameter at 30 cm height (D30), diameter at breast height (DBH, at 130 cm) and crown diameter were assessed, and it was found that use of mean quadratic diameter using D30 explained 92% of the biomass variability. There was no statistical difference between tree species in terms of relationships between total above ground biomass and tree mean quadratic diameter. A single, multi-species biomass model for the three tree species was therefore developed with good adjustment indicators ($R^2 = 0.92$; sum of predicted residual

squares: PRESS = 0.45 and Furnival Index = 1.84; Eq. 3).

$$\text{TB} = 10^{(-1.54 + 2.05 \times \text{Log}(\text{MQD}) + 1.18 \times \text{Log}(\text{th}))} \quad (3)$$

Where;

TB Total above ground biomass (kg tree^{-1})
 MQD Mean quadratic diameter at 0.3 m height (m)
 th Total height (m)
 Log Base-10 logarithm

The intercepts and slopes of individual models from each species were statistically similar ($0.12 < P < 0.82$) indicating similarity between them.

Tree growth

D. robinoides exhibited the highest growth rates. There was a seasonal effect on growth of the tree species, such that growth rates were higher in the rainy than in the dry season (15 vs 0.3 mm month^{-1} for MQD at breast height and 25 vs 75 mm month^{-1} height, respectively; Fig. 1). In the dry season, mean growth of trees was better in association with *B. brizantha* than with *H. rufa* (0.5 vs 0.2 mm month^{-1} for MQD at breast height, respectively). *P. saman* and *D. retusa* were not affected by grass treatments; whereas, *D. robinoides* had a higher growth in combination with *B. brizantha* than with *H. rufa* (1.0 vs 0.3 mm month^{-1} MQD at breast height; Fig. 1b). In the rainy season, however, there was no effect of grass species on growth of trees. Tree above ground biomass gain was different between tree species ($P < 0.01$) and between seasons ($P = 0.04$). Although *P. saman* had the lowest biomass gain, this species was less affected by dry season than *D. retusa* and *D. robinoides* (Fig. 1c).

There was an interaction between grass and tree species with respect to MQD at breast height and total height of tree species. Mean MQD at breast height and height of *D. retusa* was higher in combination with *B. brizantha* compared with *H. rufa* (46 vs 37 mm MQD at breast height; 3.4 vs 2.5 m height) but with *P. saman* these values were higher in mixture with *H. rufa* (27 vs 37 mm MQD at breast height; 2.2 vs 2.7 m height; Fig. 1). These growth parameters for *D. robinoides* were not significantly different between grass species. Tree growth, in terms of biomass

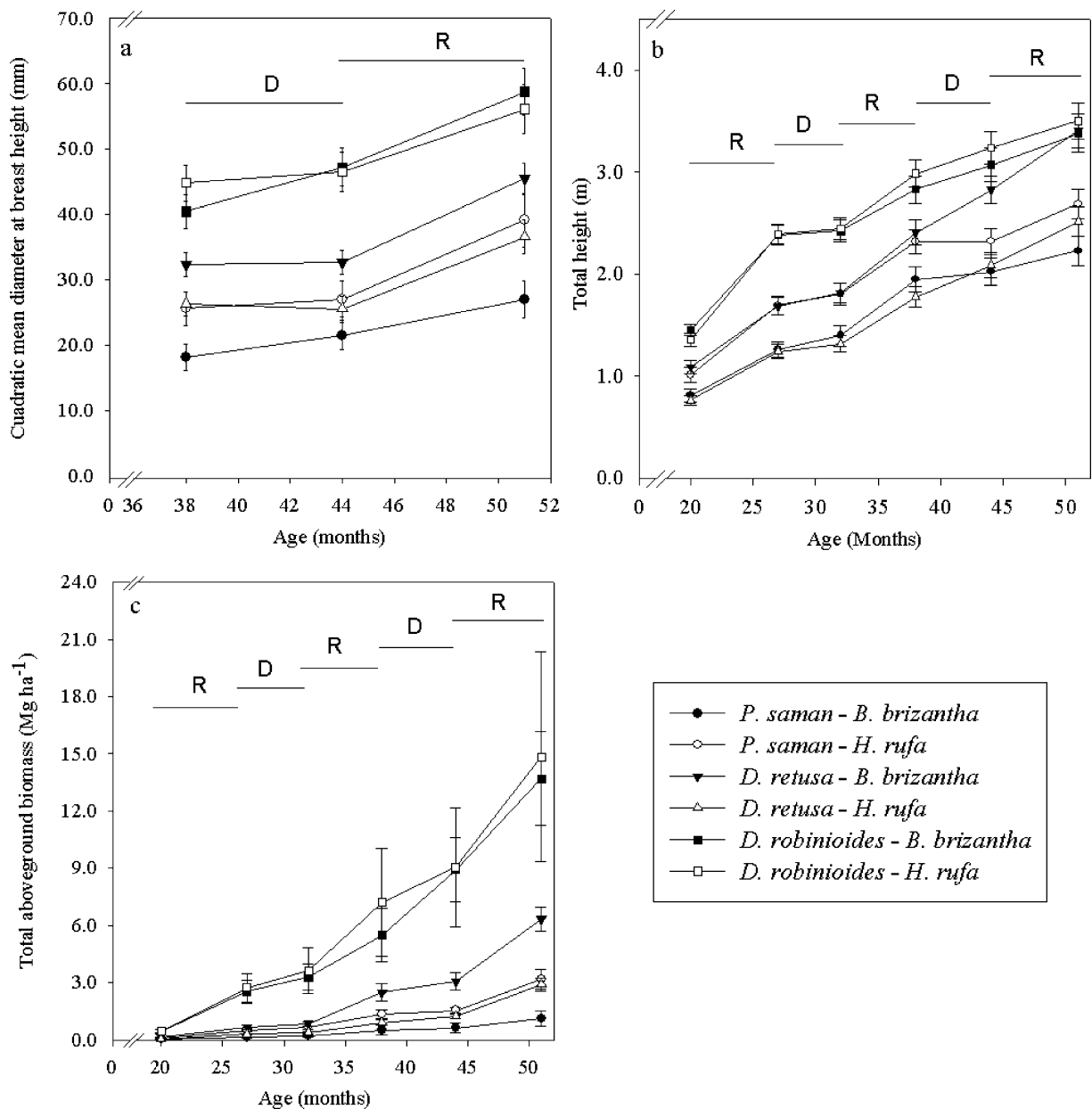


Fig. 1 Performance of three native timber tree species in silvopastoral systems with two contrasting grass species in the dry tropics of Costa Rica. **a** Quadratic mean diameter at breast

height; **b** total height; and **c** total above ground biomass. Error bars correspond to standard error. Dry and rainy seasons are indicated as 'D' and 'R', respectively

accumulation through the whole experiment was not affected by grass species ($P > 0.05$) for trees aged between 20 and 51 months. Tree species differed in growth, ($P < 0.01$). *D. robinoides* having a significantly higher biomass accumulation compared to *D. retusa* and *P. saman* (5.2 vs 1.7 vs 0.8 Mg ha⁻¹ year⁻¹; Fig. 1c).

Forage production

Mean dry matter (DM) production of *B. brizantha* was almost three times that of *H. rufa* (4.0 vs 1.5 g DM m⁻² day⁻¹). Production of DM in *B. brizantha* plots was higher than that of *H. rufa* in both seasons with mean of 2.6 and 1.1 g DM m⁻² day⁻¹,

respectively in the dry seasons and corresponding values of 5.3 and 1.4 g DM m⁻² day⁻¹ for the wet seasons (Fig. 2).

Tree species did not affect production of DM of grasses, with the exception in the rainy-I season, where the grasses under *D. robinoides* and *D. retusa* produced less DM than under *P. saman* and when grown in monoculture (Fig. 2). There was a negative linear relationship between grass productivity of *H. rufa* as tree canopy area as a proportion of sub-plot land area increased (dry matter production [Mg ha⁻¹ year⁻¹] = 7.16–0.09 × tree cover (%); $R^2 = 0.56$; $P = 0.02$). In contrast, *B. brizantha* was not affected by tree canopy area ($R^2 = 0.09$; $P = 0.43$).

Fine root biomass

Seventy percent of the fine roots were recorded in the 0–0.2 m soil layer and only 20% and 10% of fine roots were found in the 0.2–0.4 m and 0.4–0.6 m horizons, respectively (Table 2). Mean fine root biomass of trees was significantly higher ($P < 0.01$) in association with *B. brizantha* than with *H. rufa* (101 vs 54 g m⁻² in the 0–0.6 m horizon). In contrast, fine roots of grasses were not affected by presence of trees. There was no interaction between tree and grass species for root biomass by component ($P > 0.05$). The majority of the fine root biomass was attributable to the tree component. *B. brizantha* being greater than *H. rufa* (167 vs 103 g m⁻² in 0–0.6 m horizon, respectively). Systems

with *P. saman* had slightly higher fine root biomass those with *D. retusa* and *D. robinoides* (153 vs 124 vs 127 g m⁻² in 0–0.6 m depth, respectively; Table 2).

In the control plots (no trees), 89% of total fine root biomass was found in the uppermost 0.4 m. *B. brizantha* had a higher root biomass than *H. rufa* in the 0–0.6 m soil profile (220 vs 153 g m⁻²; Table 1). Although differences in root biomass are evident, the only statistical differences between components were for tree fine root biomass due to very high variability within treatments, a common finding in root sampling in the field.

Carbon content in biomass

Tree species had similar carbon content (mean of 45.0%) in their biomass ($P > 0.05$), whereas carbon concentration in biomass of grasses was differed species ($P < 0.05$); *B. brizantha* being 43.7% and *H. rufa* being 40.7%.

Soil organic carbon

Total soil organic carbon was similar in their distribution in the soil to that observed for fine root biomass (Fig. 3). Across all treatments, the upper 0.6 m of soil stored 110.3 Mg C ha⁻¹ of TSOC. The bulk was found in the first 0.2 m soil depth (mean 56%), and a mean of 25% was found in the 20–40 and 19% in 0.4–0.6 m horizons (60.4, 26.8 and

Fig. 2 Grass forage production (dry matter, 0.3 m and above) of two contrasting grasses under three native timber tree species in silvo-pastoral systems and without trees in the dry tropics of Costa Rica. Error bars correspond to standard error of mean. Rainy I: June 2005; Rainy II: August 2005

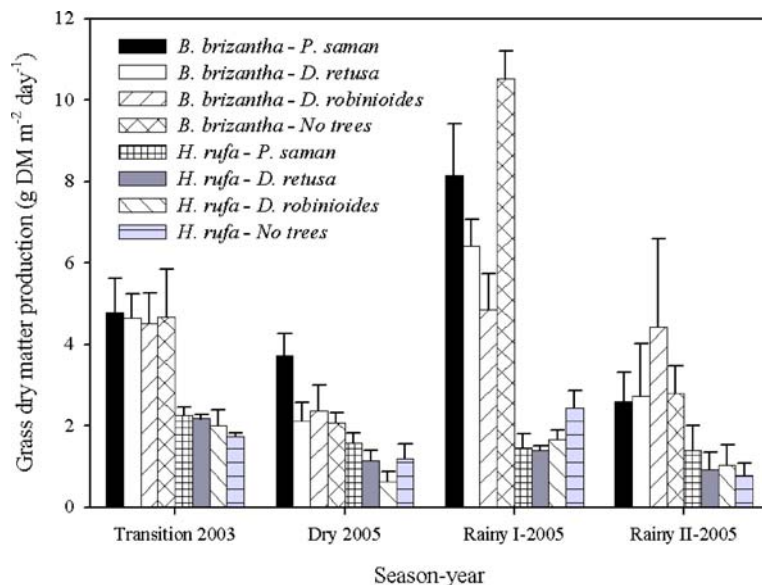


Table 2 Fine root biomass distribution in 6 silvopastoral systems of 2 contrasting grasses (*B. brizantha* and *H. rufa*) under 3 native timber tree species (*P. saman*; *D. retusa* and *D. robinoides*) and 2 monoculture grasses in the dry tropics of Costa Rica

Species		0–0.2m		0.2–0.4m		0.4–0.6m		0–0.6 m	
Grass	Tree	Tree (g DM m ⁻²)	Grass (g DM m ⁻²)	Tree (g DM m ⁻²)	Grass (g DM m ⁻²)	Tree (g DM m ⁻²)	Grass (g DM m ⁻²)	Tree (g DM m ⁻²)	Grass (g DM m ⁻²)
<i>Brachiaria brizantha</i>	<i>Pithecellobium saman</i>	262 (81) a	136 (56) a	101 (56) a	60 (41) a	52 (20) a	11 (2) a	414 (35) a	206 (24) a
	<i>Dalbergia retusa</i>	169 (37) b	140 (32) a	48 (8) a	40 (12) a	25 (4) a	19 (4) a	242 (14) b	199 (13) a
	<i>Diphyssa robinoides</i>	180 (50) b	130 (34) a	50 (6) a	28 (4) a	25 (3) a	27 (12) a	255 (19) b	186 (13) a
	Monoculture (treeless control)	0.00	160 (43) a	0.00	34 (8) a	0.00	26 (8) a	0	220 (28) a
<i>Hyparrhenia rufa</i>	<i>P. saman</i>	97 (35) a	127 (20) a	22 (5) a	29 (6) a	10 (2) a	16 (3) a	129 (13) a	173 (9) a
	<i>D. retusa</i>	133 (42) a	68 (13) a	47 (16) a	23 (6) a	17 (5) a	12 (2) a	198 (16) a	103 (6) a
	<i>D. robinoides</i>	122 (35) a	126 (37) a	26 (5) a	18 (3) a	15 (3) a	13 (3) a	163 (13) a	157 (14) a
	Monoculture (treeless control)	0.00	108 (20) a	0.00	28 (4) a	0.00	17 (2) a	0	153 (15) a

Values correspond to means of 2 core sampling points (1 and 2 m from tree trunk) and are means for 2 sampling periods (July 2004 and July 2005). Values in parenthesis correspond to standard error of the mean. Same letters indicate no statistical differences among components and between species ($P > 0.05$) using LSMEANS procedure in SAS (1985).

21.1 Mg C ha⁻¹ respectively). There were no statistically significant effects of treatment. However, TSOC was increased by 27, 38 and 43% when *D. retusa*, *D. robinoides* and *P. saman* were included in the systems with *B. brizantha*, but no effect of introduction of trees was found in *H. rufa*.

Soil organic carbon content was strongly correlated with nitrogen concentration in soil ($0.71 < r < 0.99$; Table 3). Total carbon and nitrogen were the most highly correlated variables ($r = 0.99$). Nitrogen and carbon parameters were more associated with total

(tree + grass) fine root biomass than the biomass of separate components. Biomass of fine roots of grass species was slightly more closely correlated with soil nitrogen and carbon than that of tree species ($0.60 < r < 0.66$ vs $0.49 < r < 0.58$; Table 3).

Total carbon stock and accumulation rates

The range of total organic carbon (TOC) stocks in biomass was wide, varying between 3.5 (in treeless *H. rufa*) and 12.5 Mg C ha⁻¹ in *B. brizantha* with

Fig. 3 Total soil carbon in six silvopastoral systems of two contrasting grasses (*B. brizantha* and *H. rufa*) grown under three native timber tree species (*P. saman*; *D. retusa* and *D. robinoides*) and two monoculture grasses (NT) in the dry tropics of Costa Rica. Error bars correspond to standard error of mean. Date of sampling: February 2005

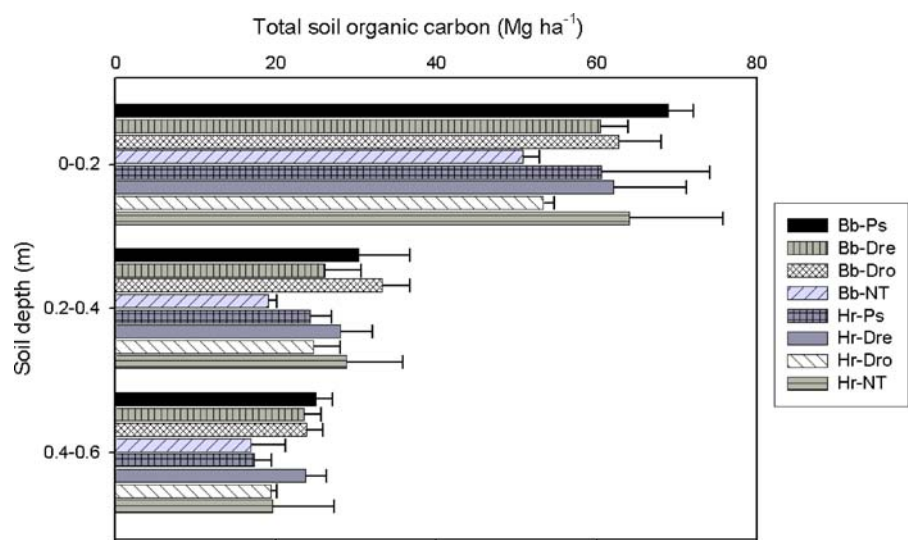


Table 3 Correlation (Pearson coefficient) between carbon, nitrogen and root biomass in silvopastoral systems of 2 contrasting grasses (*Brachiaria brizantha* and *Hyparrhenia rufa*)

		Units	Soil organic carbon	Soil nitrogen	Fine root biomass	
			g 100 g ⁻¹ soil	g 100 g ⁻¹ soil	Tree Mg ha ⁻¹	Grass Mg ha ⁻¹
Soil nitrogen		g 100 g ⁻¹ soil	0.98	–		
Fine root biomass	Tree		0.57	0.54	–	
	Grass	Mg ha ⁻¹	0.66	0.65	0.62	–
	Total		0.67	0.65	0.93	0.86

All Pearson's correlation coefficient are positive and were significant ($P < 0.01$).

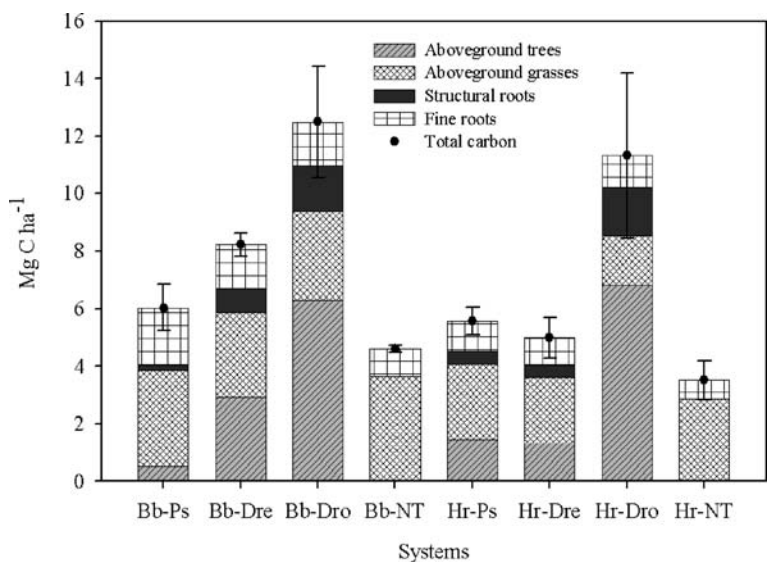
D. robinoides (Fig. 4). Grass species did not affect the TOC in biomass ($P > 0.05$); in contrast, tree species significantly affected TOC ($P < 0.05$). Systems with *D. robinoides* had the highest carbon stock in biomass followed by *D. retusa*, *P. saman* and pastures without trees (11.9 ± 2.2 , 6.6 ± 1.1 , 5.8 ± 0.6 , 4.1 ± 0.5 Mg C ha⁻¹, respectively). While carbon storage in *B. brizantha* and *H. rufa* differed little (Fig. 4), the inclusion of *P. saman*, *D. retusa* and *D. robinoides* increased carbon stock in phytomass by 31%, 78% and 170%, respectively compared to monoculture *B. brizantha* and by 58%, 42% and 222%, respectively with respect to *H. rufa*.

The carbon accumulation rates in biomass of these pasture-based systems over the 51 month period between varied between 0.8 and 2.9 Mg C ha⁻¹ year⁻¹ for monoculture of *H. rufa* and silvopastoral

systems (*B. brizantha* with *D. robinoides*), respectively. The accumulation rates of silvopastoral systems were on average 95% higher than monoculture grasses. Carbon stock accumulation rates were strongly affected by tree component and *D. robinoides* was the most important species for storing carbon in its biomass. Carbon accumulation rates were markedly higher in soil (organic carbon) than in other components, with the exception of *B. brizantha* without trees.

A grass–tree interaction was found in TSOC accumulation ($P < 0.05$). The TSOC accumulation in *H. rufa* was not affected by tree species (on average, 6.6 ± 1.9 Mg C ha⁻¹ over a period of 17 months). In contrast, tree species had a statistically significant effect on TSOC change in *B. brizantha* ($P < 0.05$). TSOC was reduced in treeless *B. brizantha* treatments over the same evaluation period

Fig. 4 Total carbon storage by biomass components in two contrasting grasses (*Bb B. brizantha* and *Hr H. rufa*) grown under three native timber tree species (*Ps P. saman*; *Dre D. retusa* and *Dro D. robinoides*) and without trees (NT) 51 months after establishment of silvopastoral systems in the dry tropics of Costa Rica. Error bars correspond to standard error of total carbon in biomass



($-1.4 \text{ Mg C ha}^{-1} \text{ year}^{-1}$). The silvopastoral system with *P. saman* and *B. brizantha* had the highest accumulation rate of TSOC ($7.4 \text{ Mg C ha}^{-1} \text{ year}^{-1}$).

Discussion

In this experiment, mean annual DM production of *B. brizantha* was 180% higher than that of *H. rufa* (Fig. 2), and this effect was apparent in both wet and dry seasons. This helps explain why farmers have been converting *H. rufa* pastures to *B. brizantha* because this species can support higher carrying capacities and liveweight gains of cattle and is more drought tolerant (Holmann et al. 2004). The concern which gave rise to the experiment reported here was that if *B. brizantha* was so much more productive, would it also be more competitive and so inhibit tree growth in pastures, either by natural regeneration or by deliberate establishment of silvopastoral systems?

Up to the point of cessation of recordings, the experiment showed that this concern was largely unfounded. *D. retusa* grew better in association with *B. brizantha* than with *H. rufa* and *D. robinoides*, the tallest species, was not affected by grass species treatment (Fig. 1). On the other hand, *B. brizantha* decreased the rate of above ground growth of *P. saman*, the smallest species, compared to *H. rufa* treatments. However, below ground growth of *P. saman* as measured by fine roots, was enhanced in association with *B. brizantha* (Table 2).

By the 51 months stage the trees were still small with sparse canopies. On average, *D. robinoides* had the highest percentage crown cover per sub-plot, followed by *D. retusa* then *P. saman* (perpendicular projected ground cover = $30.6 \pm 0.4\%$; $27.8 \pm 0.5\%$ and $9.7 \pm 0.1\%$, respectively; $P < 0.01$; data not presented) and immediately under the crown, between 50% and 66% of photosynthetically active radiation had been captured by the canopy (data not presented). Trees compete with the understorey strata for light, water and nutrients. Both pasture species possess the C_4 carboxylation pathway with associated high radiation use efficiency. However, *B. brizantha* is affected less by shade than other C_4 species due to a degree of tolerance (Wong 1991; de Andrade et al. 2004). In contrast, dry matter production of *H. rufa*, decreased with increased age of tree cover. Only in the early rainy season in 2005 did *B. brizantha*

display reduced growth in association with the two most vigorously growing tree species, *D. retusa* and *D. robinoides* (Fig. 2). Although so far findings indicate a potential for a positive combining ability of *B. brizantha* pasture with indigenous trees, results need to be viewed with caution at this early stage.

Other studies show variable responses of *B. brizantha* in association with trees. Bustamante et al. (1998) found that production of *B. brizantha* was 41% higher in silvopastoral systems with *Erythrina poeppigiana* which was pruned every 6 months compared to production measured in open sunlight; while according to de Andrade et al. (2004), this species exhibited a production increase of between 10% and 42% in rainy and dry seasons when grown under artificial shade of 30%, while under 50% shade production was not significantly reduced. In another study conducted in traditional silvopastoral systems in the dry zone of Cañas, yields of *B. brizantha* pastures were not affected as tree cover increased over the range 0% to 20% (Esquivel et al. unpublished data).

The highest fine root biomass of trees was found in combination with *B. brizantha*, the more vigorously growing species, and may indicate the stimulation of tree root production in a water competitive environment. For example, fine root biomass of *D. retusa* was 22% more with *B. brizantha* than with *H. rufa* in the 0–0.6 m horizon (Table 2). Grass root channels may become available for tree roots after dieback resulting from cutting or grazing of the pasture. The more productive species, *B. brizantha*, may therefore have promoted higher tree root production. In turn, increased nitrogen availability from tree fine root and nodule turnover may have contributed to the greater growth observed in *B. brizantha*. These aspects were not investigated in this study but would make an interesting topic for further investigation.

Introduction of trees into these pasture systems increased the potential for sequestration of carbon compared to treeless pasture controls (Fig. 4) in both woody biomass and as soil organic carbon. In the trees represented in this experiment, the carbon concentrations range of 42.4 to $48.0 \text{ g C } 100 \text{ g}^{-1}$ dry matter was similar to values reported by Segura and Kanninen (2002). Additionally, by February 2003, the mean soil stock of total organic carbon (TSOC) was 110.3 Mg ha^{-1} , similar to values reported for soils under forests by Brown and Lugo (1992) in Amazonia (60 – 115 Mg C ha^{-1}) and

115 Mg ha⁻¹ in tropical lowland dry forests in Senegal (Bationo et al. 2007). Ruiz et al. (2004) reported values for soil carbon stock in 0.6 m depth of 150 Mg C ha⁻¹ for silvopastoral systems with *H. rufa* and 158 Mg C ha⁻¹ in silvopastoral systems with improved grasses (*B. brizantha*, *Panicum maximum* and *Cynodon dactylon*) in Nicaragua. However, trees did not have any effect on TSOC accumulation in the same study. Annual increments in soil organic carbon in the current experiment (2.6 to 7.4 Mg C ha⁻¹ year⁻¹) were much higher than net biomass increments (0.8–2.9 Mg C ha⁻¹ year⁻¹), possibly due to recycling of biomass via leaf litter deposition and root turnover of pastures following grazing and cutting.

In conclusion, this experiment has demonstrated the potential for establishment of indigenous timber tree species in improved, higher productivity grasslands. Up to 4 years old, there was a good combining ability between *B. brizantha* and faster growing tree species. These silvopastoral systems allow the farmer to obtain multiple products from the same area of land; timber, fodder, and grazing whilst increasing soil and phytomass carbon sequestration.

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