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Properties of juvenile wood of *Schizolobium parahyba* var. *amazonicum* (paricá) under different cropping systems

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Abstract *Schizolobium parahyba* var. *amazonicum* (paricá) has been demonstrating good silvicultural performance when cultivated in Agroforestry systems in the Amazon. However, the effects of this cultivation system on wood properties is unknown. The objectives of this research are to understand the effects of the cultivation system on the anatomical characteristics, and physical and mechanical properties of paricá wood. The material used in this study was obtained from an experiment in the southwest region of the state of Pará, Brazil. The treatments included an agroforestry system (AFS) of paricá in consortium with soy (*Glycine max*), in the first year, corn (*Zea mays*) in the second and a monoculture only with the studied species. Our results demonstrated significant differences in soil chemical attributes among treatments: the soil in the AFS showed higher levels of phosphorus (P), calcium (C) and copper (Cu) than the soil of the monoculture system. The wood produced in the AFS is significantly different in relation to the monoculture system: wood density and the resistance to compression parallel to fibers being lower in AFS. Furthermore, the AFS presented significant statistical effects on some anatomical characteristics of the wood. Higher values for tangential diameter of vessel lumina and for ray frequency were found. The alterations in wood properties were mainly related to the high concentration of phosphorus in the AFS soil, which can affect the tree growth rates and cambial activity.

Keywords Agroforestry system · Paricá wood · Density · Mechanical properties · Anatomical features

Introduction

The relationship between the environment and the agricultural systems has been widely discussed in the development plans of governments around the world.

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As for the Amazon region, which holds a hyperdiversity of plants and animals, to find the equilibrium for this relation is a difficult task. The maintenance of environmental services and economic demands has to be conciliated.

The challenges for sustainability in the region includes the expansion of agricultural frontiers, food security, the introduction of bio combustibles and the necessity of socio-environmental services. It is estimated that until 2050, the world population will probably increase to around 9 billion habitants. The food production shall increase 70% until then (FAO 2009). The integration of cultivated agricultural and forestry areas, efficiently managed with conservation practices and adequate soil use, might be a sustainable alternative for the region.

The agroforestry systems (AFS) have been recommend as an environmental, social and economic viable alternative for the recovery of degraded areas and food production. The AFS provide ecological benefits, such as improvements in the nutrient cycling process, soil conservation, biodiversity recovery and carbon sequestration potential (Silva et al. 2011; Abbas et al. 2017; Ajit et al. 2017).

In the Amazon, the paricá, has been cultivated in pure plantations and in AFS. That is due to the species' rapid growth, tolerance to low soil fertility and its facility to be managed, easily done by relatively basic silvicultural practices (Carvalho 2007; Gomes et al. 2010). Paricá wood is mainly used as a raw material for the production of laminates and compensated panels. The wood presents low incidence of defects and trunks with high form factors, which reflects in the increase in yield and quality of plywood (Iwakiri et al. 2011; Modes et al. 2014).

Studies have indicated (Cordeiro et al. 2015; Silva and Sales 2018) high values of average annual increases in height and diameter of paricá in AFS, compared to monocultures. The effect of the site and of the spatial arrangement of the trees on some anatomical and physical properties of wood has already been cited in the scientific literature (Silva et al. 2016; Melo et al. 2018). To our knowledge, there is no information on the extent the adoption of AFS influences the anatomical, physical and mechanical properties of paricá wood, especially the juvenile wood.

Knowing that the factors that influence the tree growth rate also results in variations in wood properties (Zobel 1992), we believe it is relevant to know if the agroforestry sistems affect the phisical-mechanical wood properties and the wood anatomical characteristic. Therefore this study aimed to understand if the cultivation system adopted will effect the anatomical characteristics and physical–mechanical properties of the juvenile wood of paricá.

Materials and methods

Study area

This study was conducted at the Jaspe farm (160 m above sea level, 4°0′58″S and 47°52′32″W) in Ulianópolis, in the southeast of the state of Pará, Brazil (Fig. 1). The original vegetation of the area is classified as dense tropical submontane forest. The climate is mesothermic and humid of the Aw type (Köppen classification). The annual average temperature is 27 °C with relative humidity oscillating between 42 and 92%. The average annual rainfall is 2000 mm, with a rainy season from December to May. The most common soil is a yellow latosol with clayey texture, the terrain is even to gently undulated (Veloso et al. 1991; SUDAM 1993; IBGE 2004; EMBRAPA 2013).

Experiment description

The agroforestry system (AFS) and the monoculture (MN) evaluated in this experiment were composed of paricá trees. In the agroforestry system, the species was in consortium with soy [*Glycine max* (L.) Merr.], in the first year, and with corn (*Zea mays* L.), in the second. Both AFS and MN were implanted in January of 2015 (Martorano et al. 2016). As for the installation of the AFS and MN, the soil was prepared to receive the seeds, with harrowing, application of 2.000 kg ha^{-1} of dolomitic limestone (PRNT 95%) to raise the soil saturation by bases to 60%, and pre-planting desiccation with glyphosate (2 kg ha^{-1}). The spacing for both AFS and MN was 5 × 2 m via direct sowing, with density of 1.000 trees per ha^{-1}.

In the AFS, soy and corn were cultivated in the paricá inter-row. The soy sowing was done at a spacing of 0.45×0.08 m^2, and corn at 0.70×0.23 m^2. The basal dressing was conducted together with the soy planting, by applying

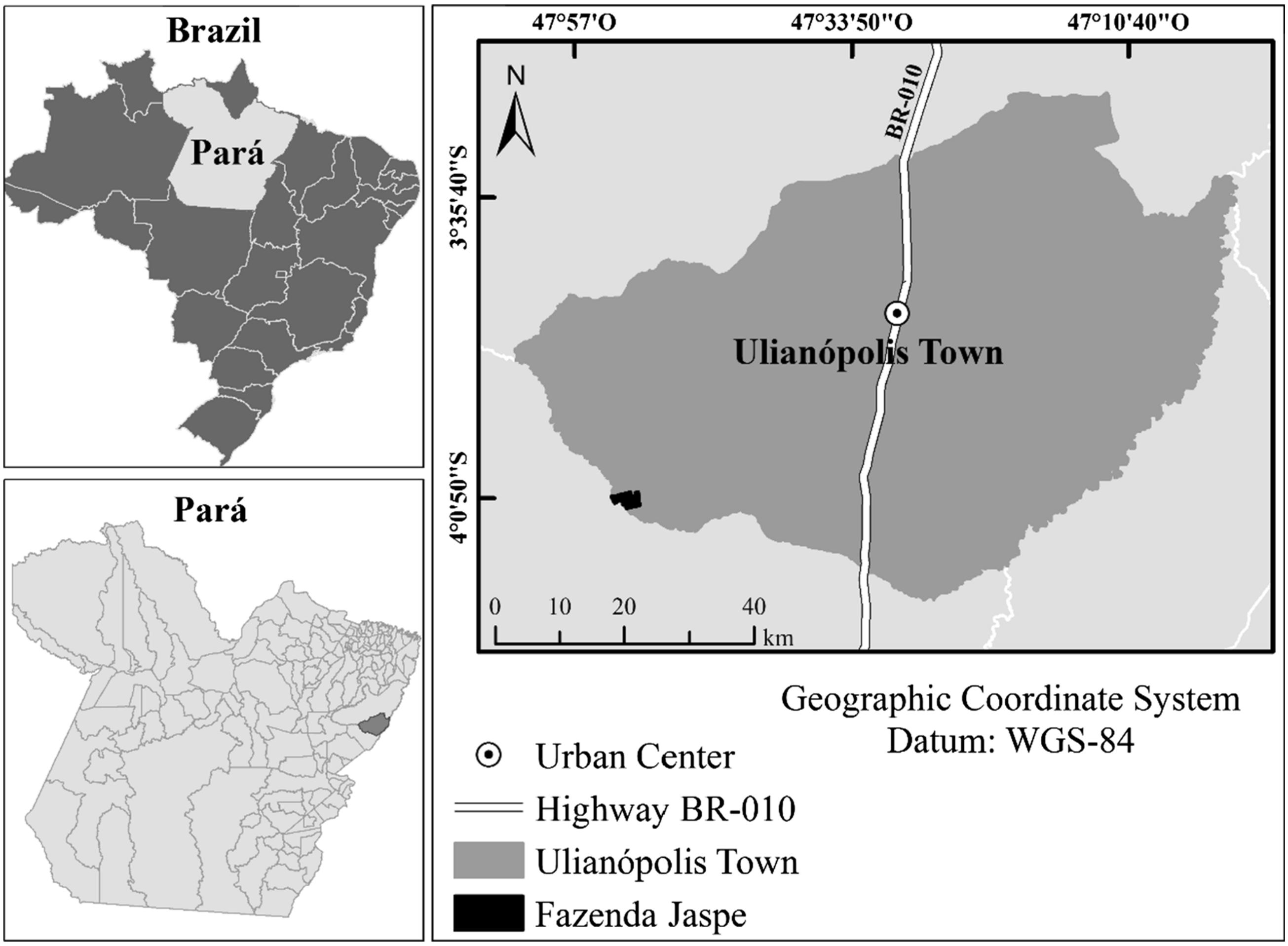

Fig. 1 Location of the study area, Jaspe farm, town of Ulioanópolis, Pará, Brazil

400 kg ha^{-1} of NPK in the formulation 02-25-20 in the planting line. After 30 days, a 7 L ha^{-1} foliar top-dressing of macro and micronutrients was applied.

As for the corn planting, the soil received preparation as well. It was plowed and harrowed in the paricá inter row. The corn seeds were sown simultaneously with the application of 200 kg ha^{-1} of NPK in the formulation 10-50-00, in the planting line. The top-dressing was made after 30 days of planting, with 200 kg ha^{-1} of NPK in the formulation of 20-00-20, also next to the planting line. The phytosanitary control of the annual cultures was conducted according to what is technically recommended for the culture, with periodic application of insecticides, herbicides and fungicides. The harvesting was mechancal.

We defined two treatments combing soil management practices used in the implantation and for the conducting of the species, 1 hectare being destined to each treatment:

- *Agroforestry system (AFS)* Subsoiling + basal dressing + top-dressing + inoculation + consortium with soy/corn;
- *Monoculture (MN)* Without subsoiling + without basal dressing + without top-dressing + without inoculation + without a consortium with soy or corn.

The subsoiling was conducted in the planting line with a subsoiler implement with a unique stem, regulated to reach the maximum depth of 50 cm. The basal dressing was done together with the subsoiling, by applying 300 kg ha^{-1} of NPK in the formulation 10-30-10, in the planting line with the aid of the implement coupled to the subsoiler.

Concurrently to the planting, 30 g hole^{-1} of a biological input was manually applied, 10 cm distant from the pit. The cultivation and the concentration of the biological input followed according to Siviero (2008). 60 days after planting top-dressing was undertaken, with application of 200 g hole^{-1} of ammonium sulfate ($(NH_4)_2SO_4$), in a lateral hole, distant 20 cm from the principal hole.

For each treatment 5 parcels of 400 m^2 of area were installed, containing 40 trees each parcel. The parcel allocation was systematic. Measurements of diameter at 1.3 m in height (DBH), total height (TH) and commercial height (CH) of all trees in each plot were performed at 3 years of age.

Tree sampling

The paricá wood used for this research was taken from a 3 year-old cultivation. We collected 20 trees, selected randomly among the five parcels described before, free from bifurcation, tortuosity, inclination or evidence of any of these phenomena, in the two different cultivation system (AFS and MN), totaling 40 trees (Table 1).

A wood sample, in a disk shape 43 cm thick, was taken at breast height (1.30 m above the soil) from each tree. From each disk we obtained diametrical samples for the determination of the apparent density, at 12% moisture content, through the method of x-ray microdensitometry (Fig. 2). Subsamples were obtained for the analysis of wood anatomy, basic wood density and for mechanical compression tests parallel to the fiber and static bending. Due to the small diameter of the tree trunks, the subsamples were obtained from the disk circumference, always in the most external position, near the cambium—I and II (Fig. 2).

The subsamples obtained for the anatomical analysis were sectioned in a slide microtome, in the three anatomical planes of study for woody material (cross-section, tangential longitudinal and radial longitudinal), with thickness ranging from 15 to 20 µm. The histological cuts were bleached with sodium hypochlorite (60%), washed with distilled water and stained with safranin 1% (Johansen 1940). After these steps, the cuts were fixed on permanent slides, with synthetic resin. For the measurement of the dissociated anatomical elements, we used the macerating method, proposed by Franklin (1945), modified by Kraus and Arduin (1997). The macerated material was stained with aqueous safranin 1% and placed on semi-permanent slides, with glycerin 50% (Strasburger 1924). The anatomical analysis were made according to recommendations suggested by the IAWA Committee (1989), making 30 measurements for each evaluated anatomical parameter. Counts or

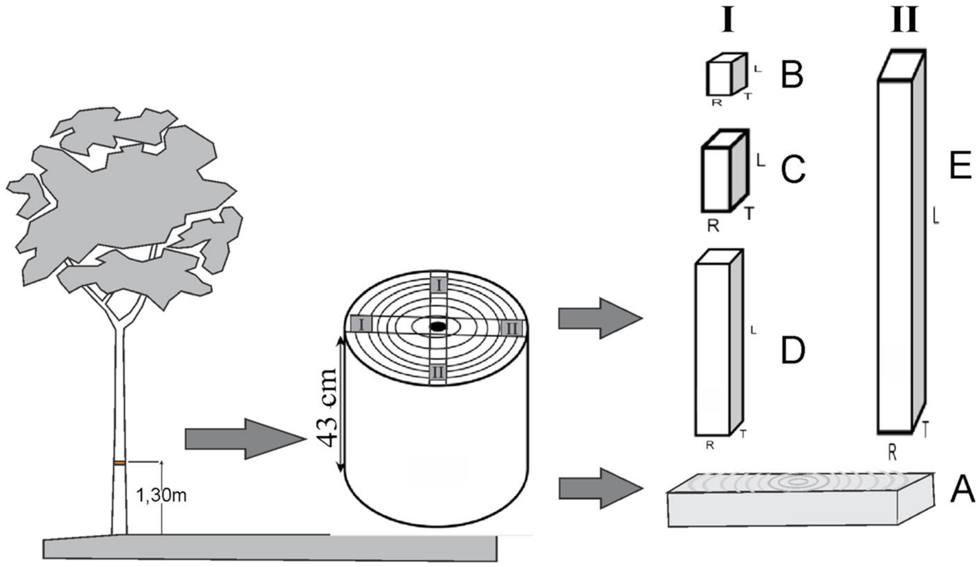

Fig. 2 Draft scheme representing the disk removal and preparation of subsamples. A = apparent density (12%) by X-ray microdensitometry, wood sample of 20 mm thickness. B = subsamples for the anatomical analysis (25 mm^3). C = subsamples for basic density with dimensions of 25 (R) × 25 (T) × 30 (L) mm^2. D = subsamples for testing the parallel compression to fibers, with dimensions of 25 (R) × 25 (T) × 100 (L) mm^2. E = subsamples for testing the static bending with dimensions of 25 (R) × 25 (T) × 410 (L) mm^2. *R* radial, *T* transversal, *L* longitudinal

measurements were made for: vessel frequency (mm^{-2}), tangential diameter of vessel lumina (µm), vessel element length (µm), ray frequency (mm^{-1}), ray width (µm), ray height (µm), fiber length (µm), fiber diameter (µm), fiber lumina diameter (µm), fiber wall thickness (µm). All anatomical measurements were made by using a ZEISS Primo Star HAL/LED light microscope, coupled to a Opton microscopio digital camera and software to analyze the images (Image-Pro Express 6.0).

The basic density was determined by following the proceedings specified in the NBR 7190 (ABNT 1997), from the subsamples free from defects and perfectly oriented.

The apparent density was determined through the x-ray microdensitometry method. The samples were obtained by cutting a 2 mm thick portion of the cross section sample obtained at breast height and conditioned at 21 °C and 65% relative humidity (RH) until reaching approximately 12% humidity. The apparent density profile along the tree trunk was obtained in a microdensitometer, model QTRS-01X Data Analyzer and Scanner (Quintek Measurement Systems—QMS). Individual values of wood density every 5 mm along the sample were read.

The parallel fiber compression test was conducted to determine the compressive strength ($f_{c,0}$) and the modulus of elasticity (E_{c0}). In the static bending test the modulus of rupture MOR (f_M) and the modulus of elasticity MOE (E_{M0}) were determined The tests were conducted in a universal testing machine, model EMIC DL3000, following the specifications in the ASTM D143-14 norm (2014). All samples were previously stored in a climatic chamber at 21 °C and 65% RH until reaching constant mass.

Soil sample collection and processing

As for the chemical characterization of the soil, four simple samples were collected to compose a complete sample for each tree (totaling 40 soil samples), which were taken approximately 5 cm from the base of the trees, in the north, south, east and west directions, and a depth of 0–10 cm. The soil samples were air dried and sieved through 2 mm meshes and taken for soil chemical attributes determination. The levels of Ca^{2+}, Mg^{2+} and K^+ were quantified. The available phosphorus (P) was extracted with Mehlich 1, while the total nitrogen (N) was determined in an elemental analyzer. The concentration of micronutrients B, Cu, Fe, Zn in the soil was also determined. The procedures followed methodology recomended by the Brazilian Agricultural Research Corporation (EMBRAPA 2009).

Data analysis

The results of the chemical analysis of the soil and of the anatomical and physical–mechanical properties of the wood were statistically compared aiming to identify significant variations as an effect of the adopted cultivation system. The data was analyzed by using generalized linear models—GLM—for repeated measurements. The evaluated properties that showed continuous values were adjusted to the GLM by assuming a Gaussian distribution (when the sample presented normal distribution according to the Shapiro–Wilk test at significance level of 0.05 for residue normality) or Gama distribution (in cases where the variables failed to pass the Shapiro–Wilk normality test).

Specifically, the anatomical parameters that had produced discreet values (vessel and ray frequency) were adjusted to the Poisson distribution. The measurements were compared by model contrast through the LS Means test, for multiple comparison. All GLMs were submitted to a residual analysis, as a way to evaluate the adequacy of the error distribution (Crawley 2002). The statistical analysis was made by using the software R, version 3.0.1 (R Development Core Team 2013).

Results and discussion

Soil chemical attributes

In terms of macronutrients, the evaluated treatments differ ($p < 0.05$) only between the P, Ca and Mg. As for the micronutrients, with the exception of Cu, no effects of the cultivation system were noted ($p > 0.05$) (Table 2).

Generally, the AFS has promoted significant gains in soil nutrients in comparison to the paricá MN. The AFS presented significantly higher levels of P (42.4%), Ca (28.8%), Mg (22.6%) and Cu (17.5%) when compared to the soil of the monoculture (Table 2).

Table 1 Dendrometric and basic silvicultural characteristics of trees of *S. parahyba* var. *amazonicum* (average values and standard deviation) in both cultivation systems

	No ha^{-1}	S (m^2)	TH (m)	CH (m)	DBH (cm)
MN	1000	5.0 × 2.0	13.15 ± 1.24	11.26 ± 1.51	11.05 ± 2.35
AFS	1000	5.0 × 2.0	13.47 ± 1.00	11.26 ± 1.00	11.33 ± 2.62

No ha^{-1} number of trees per hectare, *S* spacing, *TH* total height, *CH* commercial height, *DBH* diameter at breast height, *MN* monoculture of paricá, *AFS* agroforestry system with paricá + soy + corn

Table 2 Effects of the cultivation system on the chemical attributes of soil samples under AFS and MN with *S. parahyba* var. *amazonicum*, in the soil layer of 0–10 cm deep

Chemical attributes	Average value (kg ha^{-1})	Standard deviation	Standard error	F/χ^2	*p* value
Nitrogen (N)					
MN	2532.0^a	363.29	81.23	2.9072	0.0963
AFS	2724.5^a	350.63	78.40		
Phosphorus (P)					
MN	17.89^a	8.97	2.00	1.1549*	0.0285
AFS	25.48^b	12.17	2.95		
Potassium (K)					
MN	89.04^a	16.95	3.79	0.0146*	0.5252
AFS	92.51^a	17.58	3.93		
Sulphur (S)					
MN	9.31^a	1.82	0.40	0.1788*	0.1986
AFS	8.15^a	3.44	0.76		
Calcium (Ca)					
MN	506.41^a	216.16	48.33	0.6376*	0.0236
AFS	652.10^b	168.75	37.73		
Magnesium (Mg)					
MN	152.92^a	46.30	10.35	0.4136*	0.0291
AFS	187.44^b	53.72	12.01		
Boron (B)					
MN	0.55^a	0.15	0.03	3.0692	0.0878
AFS	0.47^a	0.12	0.02		
Copper (Cu)					
MN	1.66^a	0.37	0.08	0.2589*	0.0149
AFS	1.95^b	0.36	0.08		
Iron (Fe)					
MN	123.80^a	45.96	10.27	0.8334	0.3670
AFS	134.60^a	26.19	5.85		
Zinc (Zn)					
MN	0.87^a	0.43	0.09	0.466*	0.0912
AFS	1.08^a	0.30	0.06		

MN = paricá monoculture; AFS = agroforestry system of paricá + soy + corn. Average values with different letters between lines indicates statistical differences ($p < 0.05$). F = indicates values where the GLMs were made by Fisher–Snedecor F distribution. χ^2 = represents the values (*) in which the GLMs were made by Chi square distribution

The highest levels of P, Ca, Mg and Cu found in the AFS soil are a likely consequence of the fertilization effects and, together with subsoiling soil preparation, may influence plant growth, especially in the early years. It is worth mentioning that subsoiling has proven its efficiency as to soil physical and water properties by breaking up the deeper compacted layers, promoting better water and nutrient absorption and favoring root development and plant growth (Paul and Weber 2016).

The high P concentration observed in the AFS in this experiment was also reported for AFS of willow tree (*Salix* spp.) in consortium with bean (*Phaseolus vulgaris* L.) and potato (*Solanum tuberosum* L.), compared to the soil where the cultures were cultivated alone (Wilton et al. 2017). According to the authors, the adoption of the AFS with woody species, especially in consortium with agricultural cultures, are important for the food supply and enrichment of the chemical characteristics of the soil, providing important ecosystem services.

Rodrigues et al. (2016), contrary to what was observed in this study, verified high levels of N in the soil of an AFS of paricá (*S. parahyba* var. *amazonicum*) × puerária (*Pueraria phaseoloides*) comparred to the monoculture of paricá.

Martorano et al. (2016) noticed significant increase in the growth rates of paricá and soy productivity in the AFS's first year, in the same experimental area as this research, when compared to the monoculture of both cultures. The authors did not evaluate the soil chemical attributes, but they related these results to the symbiosis characteristics of these species with proteobacteria of the family Rhizoniaceae (Baral et al. 2016) that improves and maintain the soil fertility, by supplying fixed N.

For this research, we collected soil and wood samples from trees with 3 years of age, after the installation of the experiment and the corn harvesting. The high nutritional demand of agricultural cultures of short cycle, such as soy and corn (Lacerda et al. 2015) may have affected availability of some soil nutrients. The availability of N, which is most demanded for the development of the species, could already be metabolized and assimilated in the composition of tissues and organs of these vegetables (stem, leaves, grains, etc.).

Zhang et al. (2017) studying the consortium of wheat, barley and corn, comparred to their respective monocultures, noticed that the maximum accumulated absorption of N, P and K (kg ha^{-1}) was higher in the consortium system when compared to the monocultures. They also noticed that maximum accumulated N and P, (but not K), absorption for the corn crop in consortium, was significantly high than the absorption of the same nutrients in monocultures of corn. Furthermore, for the consortium, it was observed that the absorption of those nutrients rapidly increased after harvesting the wheat and barley crops.

Density and mechanical properties of the wood

The basic and apparent density and resistance to compression parallel to fibers ($f_{c,0}$) showed significant differences ($p < 0.05$) between the evaluated treatments. Regardless, there was no significant effect ($p > 0.05$) for the modulus of elasticity in the parallel compression (E_{c0}) and for the modulus of rupture (f_M) and modulus of elasticity (E_{M0}) in static bending (Table 3).

The wood from AFS treatment was 8.3%, 5.8% and 10% lower in basic density, apparent density and MOR, respectively, than wood from MN. Despite the slight reduction in the percentage among the average values, the properties statically differed between the treatments (Table 3).

In AFS, alterations in the soil chemical and physical attributes are expected. They are the main factors that influence the growth characteristics of the cultures integrated into the system (Sisi et al. 2012; Rodrigues et al. 2016; Pinto et al. 2017; Wilton et al. 2017). Thus, the soil chemical differences found in this study are useful to explain some of the variations observed in the properties of the wood between treatments. Given that spacing between trees and age are similar between treatments, the MN and AFS systems differed only by the presence of the integrated culture and soil fertilization.

In general, soil fertilization positively affects the growth rate of the trees (Caione et al. 2012; Martorano et al. 2016). Nonetheless, this effect is seen as negative or simply does not influence the wood basic density (Barbosa et al. 2014; Castro et al. 2017; Assis et al. 2018).

Thomas et al. (2006) observed that phosphorus limitation increase the density of *Eucalyptus grandis* wood. Notwithstanding, in dosages over 70 mg kg^{-1} there were no significant effects. In this research, we

Table 3 Effects of the cultivation system on the basic density and mechanical properties of *S. parahyba* var. *amazonicum* wood

	Average value	Standard deviation	Standard error	F/χ^2	*p* value
Density					
Basic density (g cm^{-3})					
MN	0.264^{b}	0.0317	0.0026	0.3343*	3.12 e^{-06}
AFS	0.246^{a}	0.0315	0.0027		
Apparent density (g cm^{-3})					
MN	0.518^{b}	0.0453	0.0101	0.0367*	0.009
AFS	0.488^{a}	0.0287	0.0063		
Parallel compression to the fibers					
Compressive strength (MPa)					
MN	25.37^{b}	3.342	0.7473	5.617	0.0229
AFS	23.06^{a}	2.808	0.6279		
Modulus of elasticity (MPa)					
MN	2048.1^{a}	644.9	144.20	1.870	0.1795
AFS	1824.8^{a}	341.9	76.45		
Static bending					
Modulus of rupture (MPa)					
MN	30.36^{a}	9.882	1.804	0.2388*	0.0993
AFS	34.41^{a}	9.138	1.641		
Modulus of elasticity (MPa)					
MN	5031.7^{a}	843.7	188.65	0.0026	0.9599
AFS	5016.8^{a}	1035.5	225.95		

MN = paricá monoculture; AFS = agroforestry system of paricá + soy + corn. Average values with different letters between lines indicates statistical differences ($p < 0.05$). F = indicates values where the GLMs were made by Fisher–Snedecor F distribution. χ^2 = represents the values (*) in which the GLMs were made by Chi square distribution

noticed that, among macronutrients with significant differences between the soils of MN and AFS, P had more accentuated proportion, with concentration 42% higher in the AFS soil.

Phosphorus has an importance similar to that of N for the vegetal metabolism, because it is a limiting nutrient for the biomass production in terrestrial ecosystems, including natural forests (Fisher et al. 2012) and forest plantations (Truax et al. 2012). It has been recently proven that the growth and development of *Eucalyptus globulus* was improved with increasing the supply of P in the soil. There was an increase of the content of ribulose-1,5-biphosphate carboxylase oxygenase (Rubisco), higher liquid photosynthesis, higher internal conductance for CO^2, higher carboxylation rate in the photosynthesis, higher electron transport and higher triose phosphate usage (Warren 2011). This background highlights the importance of P, besides the N, as the fundamental nutrients for plant development (Netzer et al. 2018).

Martorano et al. (2016) points out for the same experiment, with 2-year-old paricá trees in the MN, the trees were 2.76 m high and had 2.95 cm of diameter, while in the AFS, they were 3.21 m high with 4.20 cm of diameter. Thus, the higher basic density value observed in the MN may be related to the lower P concentration in the soil, because the supply of P may limitate the cambial activity and the production of new cells. In this way a better proportion of photoassimilates becomes available for cell wall thickening, leading to an increase in the wood basic density (Thomas et al. 2006).

The properties of resistance and rigidity of the wood are of particular interest for the timber industry, especially because they influence the quality of the sawn timber, and hence the value of the final product. The basic density is related as one of properties that better predicts the other wood properties, mainly when related to the values of the strength and modulus of elasticity of wood, those being commonly and positively influenced by wood density (Uetimane and Ali 2011; Hein and Brancheriau 2018). Therefore, the increase in the resistance to compression parallel to fibers, seen in woods of the MN can be explained by the higher wood basic density values in this treatment.

The modulus of elasticity was also higher in the MN when compared to AFS, however, the elevated variability between trees could have contributed to the non-significant differences between treatments. Therefore, we can conclude that by the high values of basic density, strength and MOE in the compression parallel to fiber observed for the woods in MN, this treatment is that one which most produces woods of higher resistance and mechanical rigidity.

Anatomical characteristics of the woods

The effect of the cultivation system was statistically significant ($p < 0.05$) only for the tangential diameter of vessel lumina and for the ray frequency (Table 4).

The alterations in the dimension and quantity of cells that compose the wood has been frequently described, mainly in relation to fertilizers of greater presence in commercial plantings, such as NPK. Those

Table 4 Effects of the cultivation system on anatomical parameters of the wood of *S. parahyba* var. *amazonicum* between MN and AFS

Anatomical characteristics	Average Values	Standard deviation	Standard error	F/χ_2	*p* value
Fiber length (μm)					
MN	1045.15^a	61.65	13.78	0.5452	0.4648
AFS	1030.52^a	63.61	14.22		
Fibre diameter (μm)					
MN	29.88^a	3.37	0.75	0.0065	0.6763
AFS	29.79^a	3.06	0.68		
Fibre lumina (μm)					
MN	24.26^a	3.70	0.82	0.0025	0.9604
AFS	24.21^a	3.64	0.81		
Fibre wall thickness (μm)					
MN	2.80^a	0.34	0.07	0.0093	0.9235
AFS	2.79^a	0.40	0.09		
Vessel frequency (mm^{-2})					
MN	2.99^a	0.84	0.15	0.4341*	0.51
AFS	2.64^a	0.49	0.10		
Tangential diameter of vessel lumina (μm)					
MN	170.66^a	11.82	2.64	7.5881	0.0089
AFS	158.85^b	15.09	3.37		
Vessel element length (μm)					
MN	320.58^a	35.18	7.86	0.3157	0.5775
AFS	313.6^a	42.91	9.59		
Ray frequency (mm^{-1})					
MN	6.43^a	1.42	0.31	5.7370	0.0216
AFS	5.55^b	0.86	0.19		
Ray height (μm)					
MN	292.25^a	33.12	7.40	3.8497	0.0571
AFS	274.61^a	22.80	5.09		
Ray width (μm)					
MN	37.58^a	3.61	0.80	0.0048*	0.673
AFS	38.42^a	8.18	1.83		

MN = paricá monoculture; AFS = agroforestry system of paricá + soy + corn. Average values with different letters between lines indicates statistical differences ($p < 0.05$). F = indicates values where the GLMs were made by Fisher–Snedecor F distribution. χ^2 = represents the values (*) in which the GLMs were made by Chi square distribution fertilizers change the growth rate condition of the trees and can influence the wood quality. However, the effects of fertilization on wood quality, especially of hardwoods, are difficult to predict. Some researches points towards increases, others point to the decrease in the quality of the wood instead. This all depends on the quantity and on which fertilizer is being used (Barbosa et al. 2014; Freitas et al. 2015; Assis et al. 2018). We have seen that, in general, the anatomical characteristics of *S. parahyba* var. *amazonicum* were little affected by the cultivation system. High statistical values were observed only for the tangential diameter of vessel lumina and ray frequency, both for woods in the MN (Fig. 3).

The tangential diameter of vessel lumina was significantly affected by the cultivation system, showing greater diameter in the MN and lower in the AFS (170.66 µm and 158.85 µm, respectively). Taghiyari and Efhami (2011) noticed that in a AFS of *Populus nigra* var. *betulifolia* with alfalfa (*Medicago sativa*), a N-fixer species frequently used for improving the physical quality of the soils, influenced and increased the vessel diameter (from 62.23 to 66.91 µm) and the vessel lumina area percentage as well (from 27.93 to 35.28%) in comparison with the monoculture of *Populus nigra* var. *betulifolia.* Sette et al. (2014) observed that trees cultivated in soils with high K concentration produced woods with vessels of greater tangential diameter.

The alterations in the dimension and quantity of vessels in the wood during the tree growing season has effects on the hydraulic conductivity and reflects biomechanical aspects. Schuldt et al. (2013) and Zhao (2016) explains that during growth the tree adjusts its anatomical structure, changing for example, the dimension and vessel frequency, as an alternative to maximize the hydraulic conductivity, thus minimizing the xylem vulnerability and ensuring trunk mechanical security. Carlquist (1966) was one of the firsts to prove that a wider vessel diameter and vessel frequency are anatomical patterns associated with the water conduction efficiency expected to occur in species inserted in environments with good availability of water in the soil.

As for the wood of angiosperms, the tangential diameter of vessel lumina impacts more on the trunk

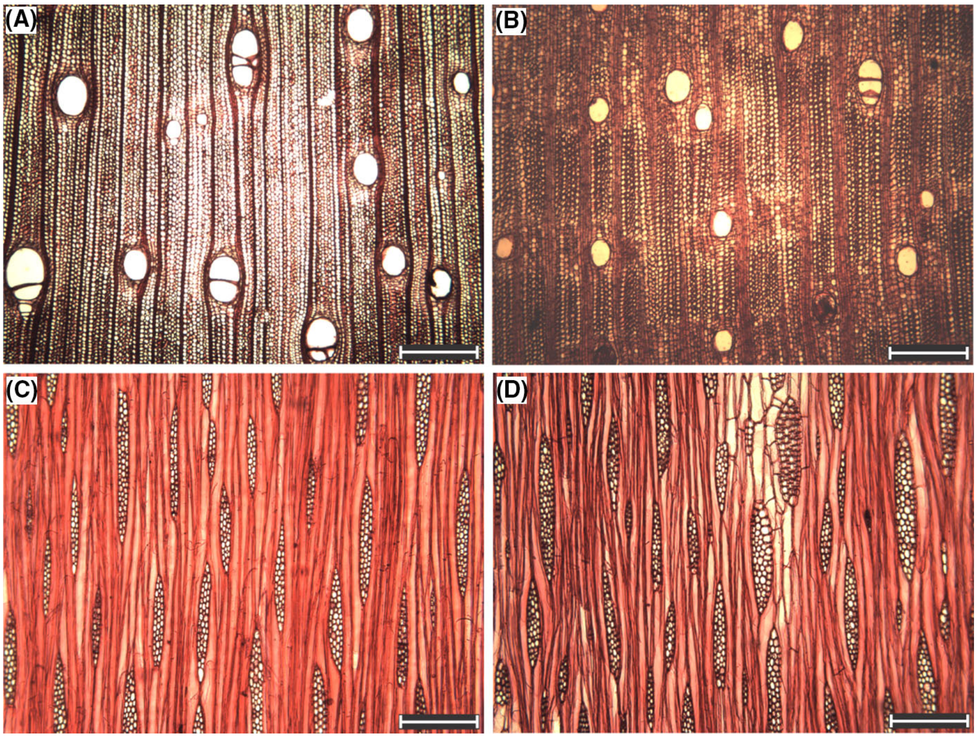

Fig. 3 Light field microscopy for the species *S. parahyba* var. *amazonicum*. Cross section of the MN (**a**) and of the AFS (**b**) evidencing the greater tangential diameter of vessel lumina in the wood of paricá under the monoculture. Longitudinal tangential sections of the MN (**c**) and AFS (**d**), showing higher ray frequency in the wood of paricá under the monoculture. Scale bar: 500 µm (**a**, **b**); 200 µm (**c**, **d**)

hydraulic conductivity, because it is proportional to the vessel ray raised to the fourth power, which indicates that, even with a little increase in the vessel ray, it promotes an increase in the sap transportation capacity (Zimmerman 1983; February and Manders 1999).

The presence of vessels of wider diameter in woods of the MN denotes efficiency in the water transportation in the trunk, perhaps because of the absence of competition with other cultures. The adopted cultivation system can influence the degree of hydraulic conductivity in the tree trunks too. Factors such as the interaction between the cultures or the responses to variations in the wood characteristics due to fertilization can influence the hydraulic architecture of the stem.

What has not been found are studies that specifically addresses the effects of the adopted cultivation system in forest plantations on the characteristics of cell rays in the wood. Research that approaches the degree of influence of soil fertilization on wood quality, commonly restricts itself to the study of the dimension and quantity of fibers and vessels.

This caveat, however, does not reduce the importance of studying these cells for the determination of the quality of hardwoods. Besides their already known functions of reserve, transformation of nutritive substances and radial transportation of water, sugar and other nutrients in the trunk (O'brien et al. 2014; Plavcová and Jansen 2015), the importance of the rays on trunk biomechanical characteristics has been recently demonstrated.

Rahman et al. (2005) recorded positive and statistically significant interaction between width and ray quantity; and density and resistance in parallel radial compression in woods of *Tecntona grandis*. Zheng and Martinez-Cabrera (2013) suggests that greater quantity of radial tissues that evolved to the greater mechanical support of the trunk. We have seen that the trees from the MN produced wood of higher basic density and higher resistance to compression parallel to fibers. The presence of more frequent rays in the wood coming from the MN confirms the knowledge that a higher proportion of rays is associated to a higher density and mechanical resistance in the trunk (Burgert and Eckstein 2001; Rahman et al. 2005; Zheng and Martinez-Cabrera 2013).

Conclusion

The agroforestry system produced vessels of lower tangential diameter and fewer of rays in the juvenile wood of trees of the species *S. parahyba* var. *amazonicum* coming from the AFS. This wood had also presented lower values of basic density and mechanical resistance of compression parallel to the fibers, when compared to the monoculture system.

The main changes observed in the properties of the paricá wood, mainly physical and mechanical, are correlated to a higher concentration of P in the AFS soil, which can affect tree growth and cambial activity.

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