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Research paper

Silvicultural potential of two legume species in different planting spacing

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ABSTRACT The objective of this work was to investigate the silvicultural potential of angico (*Anadenanthera peregrina* (L.) Speg.) and paricá (*Schizolobium parahyba* var. *amazonicum (*Huber ex Ducke) Barneby)) in different planting spacings. The study evaluated the three spacings: 3 m x 3 m, 4 m x 4 m and 5 m x 5 m. A forest inventory was carried out eight years after planting in order to characterize the stand in terms of diameter at breast height (dbh), commercial height, total height and survival. Using dbh, height-diameter relationship and commercial volume models were adjusted for each planting spacing. A meta-analysis was conducted to compare the differences between results in the literature for species of the Fabaceae family. In both species, the 3 m x 3 m spacing produced the largest volumes and the 5 m x 5 m spacing the smallest volume. The angico recorded total mean volume ranging from 23.8 to 29.8 m³ per hectare. The paricá had total mean volume between 111.8 and 143.0 m³ per hectare. There was a strong correlation between height and dbh for the species in the meta-analysis. Higher mean height and dbh values were found for paricá when compared to the other Fabaceae species, showing the species' strong suitability for forestry.

KEYWORDS: Volume, height, *Anadenanthera peregrina* (L.) Speg., *Schizolobium parahyba* (Huber ex Ducke) Barneby, Fabaceae.

Introduction

Forests, prevalent across diverse climates ranging from icy regions with short growing seasons to lush tropical areas with ample water resources, constitute a dominant vegetation type worldwide. These ecosystems play a crucial role in providing fuel and wood products, with global wood product consumption experiencing a significant surge from 1950 to 1990. Around 1990, the overall global wood consumption stabilized at approximately 3.5 billion m³ per year, evenly distributed between fuel and industrial products (Sutton 2014, Binkley et al. 2017).

The evolution of forest production through the centuries, for the most part, relies on the development of management technics. The ability to increase hardwood production by manipulating genomic characteristics, planting technics, site quality, fertilization, water regime and planting spacing, among others, have made silviculture a precise tool, emphasized on intensive management (Puettmann et al. 2015).

Intensive management is usually related to increased timber production and financial returns, relying on shorter rotations, favorable terrain and even aged monospecific stands. Despite the impacts that any intensive activity may cause, forest intensive management can also be linked with sustainability and, for example, good practices on carbon storage management. By adjusting fertilization timing and frequency, nutrient demands of the soil and the species, careful soil preparation and genetic material selection, the very welcomed increase in biomass production also results in carbon sequestration (Ameray et al. 2021).

Brazil has been a role model for management in silviculture in the last few years, especially for eucalyptus plantations. From the 1960s to 2023 estimates, the eucalyptus mean production increased from 10 m³ ha^{-1} year^{-1} to 32,7 m³ ha^{-1} year^{-1}, respectively (IBÁ 2023). This is consequence to great investments on clonal propagated plants and adequate management, avoiding losses by drought, diseases and nutritional imbalance (Xavier et al. 2021). Advances in eucalyptus planting and management are prominent, but also shows that tropical silviculture has a lot of ground to be covered.

Brazil is a wide diverse country with numerous species of great potential for silvicultural management (Machado et al. 2018). The challenge is to identify gaps in the silviculture of unusual native species, as there is a lack of research on primary subjects such as forest management and modeling, and a scarcity of information on tree growth, rotation estimates, and the effects of tree competition. This lack of data hampers the comprehensive understanding and sustainable management of these species (Rolim et al. 2019). Modelling tree growth and yield among different tree spacings has been a proved as a consistent tool in the development of forest plantations in Brazil (Scolforo et al. 2019).

Some of the species have been addressed for its known potential in silviculture, such as Fabaceaes angico (*Anadenanthera peregrina* (L.) Speg. *var. peregrina*) and paricá (*Schizolobium parahyba var. amazonicum* (Huber x Ducke) Barneby) (Rolim et al., 2019), among numerous other species. Targeting specific potential species can strongly contribute to the future of silviculture in the tropics. That

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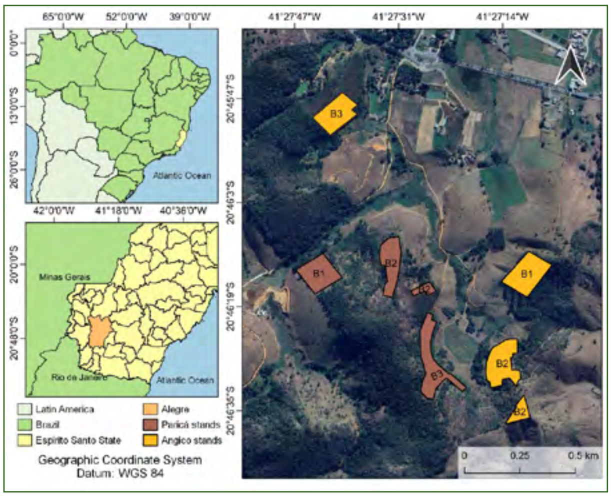
being stated, the objective of this work was to investigate the silvicultural potential of angico and paricá species in different planting spacings.

Methods

The stands of angico (*Anadenanthera peregrina* var. *peregrina*) and paricá (*Schizolobium parahyba* var. *amazonicum*) were planted in a study area belonging to the Federal Institute of Education, Science and Technology of Espírito Santo - IFES (Alegre campus), located in Alegre, Espírito Santo State, Brazil (Fig. 1), accessed at the 47th km of ES-482 highway (Cachoeiro-Alegre).

Figure 1 - Location of the experimental area on the Alegre campus in Alegre, ES, Brazil.



The experimental area on the IFES campus is part of the Floresta Piloto Research Project, an initiative of the Espírito Santo State Government in partnership with the Capixaba Institute for Research, Technical Assistance and Rural Extension - INCAPER, the State Secretariat for Agriculture, Supply, Aquaculture and Fisheries - SEAG, EMBRAPA and other scientific institutions and private enterprise. Its aim is to test and promote sustainable forestry production models, using various species and different planting arrangements, and to generate new technologies through research into the forestry sector.

The area where the experimental plots were located consisted of a pasture with livestock production, with a predominance of grasses of the *Brachiaria* (or *Urochloa*) genus. The region's climate is Aw according to the Koppen classification, with a dry winter and rainy summer and during the evaluation period of this experiment the mean annual temperature was approximately 24°C with mean annual rainfall of 1,200 mm (Alvares et al. 2013).

The area is located in the Itapemirim River basin, with a local altitude ranging from 90 to 280 meters above sea level (Souza et al. 2023). The soil type was classified by a survey carried out by IFES (1984 unpublished data), with revised nomenclature according to EMBRAPA (2018), predominantly eutrophic and dystrophic Red-Yellow Argisols.

For both species, three blocks were set up with nine experimental plots measuring 1,500 m^2 (30 m x 50 m) per block (3 spacing times 3 plots per block), representing three planting spacings: 3 m x 3 m (1,111 trees ha^{-1}), 4 m x 4 m (833 trees ha^{-1}) and 5 m x 5 m (400 trees ha^{-1}).

The angico and paricá plantations were planted in June 2011 and the area was prepared by removing the cattle on site, wire fencing the area and desiccating the brachiaria with glyphosate to control spontaneous species. The seedlings were donated by Vale Nature Reserve nursery in Linhares – ES. They were planted in holes measuring 0.30 m x 0.30 m x 0.30 m and plant height of 0.50 m, with fertilization of 220 grams per plant of the NPK 02-30-06 formulation, containing the micronutrients B (0.2%), Cu (0.2%) and Zn (0.2%). The plantation was maintained for one year by replanting, mowing and manual weeding.

A forest inventory was carried out around eight years after planting in order to characterize the stand in terms of diameter at breast height (dbh) in centimeters, commercial height in meters (Hc) and survival in percentage. Diameter measurements were taken with a graduated tape measure and commercial height (Hc) with a graduated pole measured up to the first tree bifurcation (Hc). The measurements were taken in all the experimental plots where dbh and Hc were taken for all the individuals except for the outermost raws of the plot.

To estimate the total height (Ht) of all the trees, by using a digital clinometer the total heights of the first five trees in each plot were measured, totaling 45 trees per spacing (5 trees per plot times 3 plots per block times 3 blocks). Based on this data, height-diameter relationship models were used to estimate the other total heights. It is worth to point out that measuring only five trees per plot, when adopting the relative height method is sufficient, as it provides greater agility in carrying out the forest inventory, as well as not jeopardizing the quality of the estimates and reducing the total cost (Leite and Andrade 2002).

The basal area (G) was calculated from the individual sectional area at breast height and estimated for one hectare for each spacing (depending on the number of trees per hectare and survival). Using the dbh and Hc data, 10 height-diameter relationship models were adjusted for each planting spacing (Tab. 1).

The models with the best fits were selected based on the adjusted coefficient of determination ($R^2_{adjusted}$) and the residual standard error (S_{yx}) and are shown in Table 2.

To estimate the commercial volume of the trees (Vi), 30 trees were sampled, 10 per spacing, comprising all the diametric classes. The volume of the stemwood with bark (commercial due to the morphology of the species) was calculated using the Smalian method and from the values of dbh, Hc and stemwood volume of the felled trees, regression models were adjusted to predict the individual and total volumes of the stands (Tab. 3). Cubic volume of all frustums using the Smalian's formula based on cross sectional area of both the ends of each frustum, which in the present study was 1 m.

Based on the dbh, *Hc* and stemwood volume values of the 10 trees felled per species and per spacing, the regression model described by Schumacher and Hall was the one with the best fits for the three spacings, based on the adjusted coefficient of determination ($R^2_{adjusted}$) and the residual standard error (S_{yx}) (Tab. 4).

Table 1 - Height-diameter relationship models for equation adjustments in angico (*Anadenanthera peregrina* var. *peregrina*) and paricá (*Schizolobium parahyba* var. *amazonicum*) trees at eight years after planting, in Rive, Alegre, ES.

Authors	Regression models
Linear	$h = \beta_0 + \beta_1 d + \varepsilon$
Trorey	$h = \beta_0 + \beta_1 DBH + \beta_2 d^2 + \varepsilon$
Assmann	$h = \beta_0 + \beta_1 / d + \varepsilon$
Henricksen	$h = \beta_0 + \beta_1 Ln(d) + \varepsilon$
Stoffels	$Ln(h) = \beta_0 + \beta_1 Ln(d) + \varepsilon$
Curtis	$Ln(h) = \beta_0 + \beta_1 / d + \varepsilon$
Petterson	$h = [1/(\beta_0 + \beta_1/d)]^3 + 1.3 + \varepsilon$
Naslund (Prodan)	$h = \frac{d^2}{\beta_0 + \beta_1 d + \beta_2 d^2} + \varepsilon$
Naslund	$h = \left(\frac{d^2}{\beta_0 + \beta_1 d^2} + 1.30\right) + \varepsilon$
Naslund (Prodan)	$h = \left(\frac{d^2}{\beta_0 + \beta_1 d + \beta_2 d^2} + 1.30\right) + \varepsilon$

Where: d = diameter at 1.30 m height from the ground (cm); h = total height (m); Ln = Neperian logarithm; = parameters of the adjusted model (i=0, 1, 2...n) e; = estimation error. SOURCE: Schneider and Schneider (2008).

Table 2 - Adjusted equations and their respective statistics for estimating the Ht of angico (*Anadenanthera peregrina* var. *peregrina*) and paricá (*Schizolobium parahyba* var. *amazonicum*) trees at eight years after planting, in Rive, Alegre, ES.

Spacing	Equation	$R^2_{adjusted}$	S_{yx}%
	Angico (*Anadenanthera peregrina*)		
3 m x 3 m	$h = -5.844 + 2.798$ d -0.1158 d^2	0,97	2,3
4 m x 4 m	$h = 5.535 + 0.4277$ d	0,93	2,4
5 m x 5 m	$h = 9.945 - 0.0918$ d $+ 0.0095\ d^2$	0,91	3,1
	Paricá (*Schizolobium parahyba* var. *amazonicum*)		
3 m x 3 m	$h = -35.574 + 18.72$ Ln(d)	0,88	3,6
4 m x 4 m	$h = -15.59 + 11.54$ Ln(h)	0,82	4,4
5 m x 5 m	Ln(h) $= 1.468 + 0.4917$ Ln(h)	0,85	5,8

Adjusted coefficient of determination ($R^2_{adjusted}$), Standard error of estimate in percentage (S_{yx}%). d = diameter at 1.30 m height from the ground (cm); Hc = commercial height (m); Ln = Neperian logarithm.

Table 3 - Mathematical models for commercial volume equations adjustment in stands of angico (*Anadenanthera peregrina* var. *peregrina*) and paricá (*Schizolobium parahyba* var. *amazonicum*) at eight years after planting, in Rive, Alegre, ES.

Authors	Regression models
Kopezky-Gehrhardt	$v = \beta_0 + \beta_1 . d + \varepsilon$
Hohenadl e Krenn	$v = \beta_0 + \beta_1 . d + \beta_2 d^2 + \varepsilon$
Husch	$ln(v) = \beta_0 + \beta_1 . Ln(d) + \varepsilon$
Brenac	$Ln(v) = \beta_0 + \beta_1 . Ln(d) + \beta_2 . (1/d) + \varepsilon$
Spurr without β_0	$v = \beta_1 . (d^2 Hc) + \varepsilon$
Spurr (combined)	$v = \beta_0 + \beta_1 . (d^2 Hc) + \varepsilon$
Stoate	$v = \beta_0 + \beta_1 . Hc + \beta_2 . d^2 + \beta_3 . (d^2 Hc) + \varepsilon$
Naslund	$v = \beta_0 + \beta_1 . d^2 + \beta_2 . (d^2 Hc) + \beta_3 . (d . Hc^2) + \beta_4 Hc^2 + \varepsilon$
Meyer	$v = \beta_0 + \beta_1 . d + \beta_2 . Hc + \beta_3 . d^2 + \beta_4 (d^2 Hc) + \beta_5 (d . Hc) + \varepsilon$
Schumacher e Hall	$ln(v) = \beta_0 + \beta_1 . Ln(d) + \beta_2 . Ln(Hc) + \varepsilon$
Spurr	$Ln(v) = \beta_0 + \beta_1 . Ln(d^2 Hc) + \varepsilon$

Where: v = estimated commercial volume (m³/tree); d = diameter at 1.30 m height from the ground (cm); Hc = commercial height (m); Ln = Neperian logarithm; = parameters of the adjusted model (i=0, 1, 2...n) e; = estimation error. SOURCE: Schneider Schneider (2008).

Table 4 - Adjusted equations and their respective statistics for estimating the commercial volume of trees (m³/tree) of angico (*Anadenanthera peregrina* var. *peregrina*) and paricá (*Schizolobium parahyba* var. *amazonicum*) at eight years after planting, in Rive, Alegre, ES.

Spacings	Equation	$R^2_{adjusted}$	S_{yx}%
	Angico (*Anadenanthera peregrina*)		
3 m x 3 m	$Ln(V) = -9.032 + 1.884\ Ln(^d) + 0.8479\ Ln(Hc)$	0.99	0.01
4 m x 4 m	$Ln(V) = -9.596 + 2.174\ Ln(^d) + 0.7341\ Ln(Hc)$	0.99	0.02
5 m x 5 m	$Ln(V) = -9.007 + 1.922\ Ln(^d) + 0.7832\ Ln(Hc)$	0.99	0.01
	Paricá (*Schizolobium parahyba* var. *amazonicum*)		
3 m x 3 m	$Ln(V) = -9.374 + 1.730\ Ln(^d) + 1.0006\ Ln(Hc)$	0.99	1.22
4 m x 4 m	$Ln(V) = -7.598 + 2.027\ Ln(^d) + 0.0851\ Ln(Hc)$	0.99	2.19
5 m x 5 m	$Ln(V) = -9.374 + 1.730\ Ln(^d) + 1.0006\ Ln(Hc)$	0.99	1.08

Where: Adjusted coefficient of determination ($R^2_{adjusted}$), Standard Error of Estimate in Percentage (S_{yx}%). d = diameter at 1.30 m height from the ground (cm); Hc = commercial height (m); Ln = Neperian logarithm.

Stands of both species were cubic scaled at eight years of age, the total length of the tree and the stem was measured up to the insertion of the first bifurcation that clearly characterized its subdivision (Hc). This measurement was made using a tape measure. The stem was then subdivided into sections with a maximum length of 1.0 m. The diameter of the stemwood with bark and the thickness of the bark at the beginning and end of each section were measured using a tree caliper and a digital caliper, respectively. A descriptive analysis of the variables measured in both species can be seen in Table 5.

The basal area (G) and commercial volume (Vc) per hectare were estimated taking into account the survival rate and planting spacing (number of trees per hectare at the time of planting).

Treatments' results were subjected to variance homogeneity (Cochran, p<0.05) and error normality (Shapiro-Wilk, p<0.05) analyses. Once the assumptions were met, analysis of variance (ANOVA, F<0.05) was performed based on randomized blocks. Mean test was applied (Tukey, p< 0.05) to compare mean values recorded for survival, dbh, Hc, G, Vi and Vc, whenever recorded values presented significant difference among spacings (F<0.05). Mean tests, variance homogeneity, error normality and analysis of variance were performed in IBM SPSS software.

A meta-analysis was conducted to quantify and compare the differences between results found in the literature for species of the Fabaceae family and the results of this study. The parameters for admission to the study were: age between 5 and 20 years; at least 5 observations found; spacing between 2 m x 2 m and 5 m x 5 m (living area greater than 4 m² and less than 25 m²); species from the Fabaceae family.

Table 5 - Descriptive analysis of diameter at breast height (dbh), commercial height (Hc); total height (Ht), individual commercial volume (Vi) in stands of angico (*Anadenanthera peregrina* var. *peregrina*) and paricá (*Schizolobium parahyba* var. *amazonicum*) at eight years after planting, in Rive, Alegre, ES.

Angico (*Anadenanthera peregrina*)												
	dbh (cm)			Hc (m)			Ht (m)			Vi (m³)		
Spacing	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
3 m x 3 m	7.3	**10.4**	17.5	3.0	**3.7**	5.5	5.5	**7.6**	10.7	0.017	**0.030**	0.107
4 m x 4 m	7.4	**12.2**	18.3	3.0	**3.9**	5.4	5.9	**8.1**	10.6	0.022	**0.043**	0.113
5 m x 5 m	11.8	**14.4**	25.8	2.7	**4.2**	5.8	6.1	**8.5**	11.2	0.035	**0.064**	0.243
CV(%)		20.4			7.8			9.6			12.7	
SD		2.52			0.31			0.85			0.006	
Paricá (*Schizolobium parahyba* var. *amazonicum*)												
	dbh (cm)			Hc (m)			Ht (m)			Vi (m³)		
Spacing	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
3 m x 3 m	11.4	**15.2**	23.3	10.3	**17.1**	20.3	8.2	**11.5**	14.8	0.083	**0.162**	0.305
4 m x 4 m	12.4	**19.9**	24.9	9.4	**17.6**	19.4	7.8	**12.1**	14.6	0.143	**0.275**	0.543
5 m x 5 m	14.3	**21.1**	25.8	10.8	**18.2**	21.1	8.5	**12.5**	15.8	0.178	**0.330**	0.673
CV(%)		30.1			9.6			12.2			17.7	
SD		5.63			1.69			3.47			0.045	

Where: CV = Coefficient of variation; SD = Standard deviation.

After extracting mean values for survival, height and dbh from the publications, a "forest plot" graph was generated showing a comparison between the publications on Fabaceae species and the results of this study, at a 95% confidence interval (p (x – 1,96 × σ x < μ < x + 1,96 × σ x) = 0,95). The calculations and graphs were made in Excel and based on publications on the subject (Cogo 2020).

Results

There was a significant trend for mean growth of diameter at breast height (dbh) and individual tree volume as the planting spacing increased. The dbh values for the angico and paricá species showed significant variations, ranging from 10.4 cm to 14.4 cm, and 15.2 cm to 21.2 cm, respectively. When analyzing the individual volume data, the variation ranged from 0.030 to 0.064 m³ for angico trees and from 0.162 to 0.330 m³ for paricá trees. It is also notable that, for both species, the 3 m x 3 m spacing resulted in lower dbh values, while the 5 m x 5 m spacing favored the largest diameters at breast height (Tab. 6).

Table 6 - Survival (SUV, %), diameter at breast height (dbh, cm), commercial height (Hc, m), basal area (G, m² ha⁻¹), individual commercial volume (Vi, m³) and commercial volume per area (Vc, m³ ha⁻¹) in stands of angico (*Anadenanthera peregrina* var. *peregrina*) and paricá (*Schizolobium parahyba* var. *amazonicum*) at eight years after planting, in Rive, Alegre, ES.

Spacing (m)	SUV (%)	dbh (cm)	Hc (m)	G (m² ha⁻¹)	Vi (m³)	Vc (m³ ha⁻¹)
Angico (*Anadenanthera peregrina*)						
3 m x 3 m	90.4 a	10.4 c	3.7 a	8.5 a	0.030 c	29.8 a
4 m x 4 m	90.0 a	12.2 b	3.9 a	6.6 b	0.043 b	24.0 b
5 m x 5 m	93.2 a	14.4 a	4.2 a	6.1 c	0.064 a	23.8 b
Paricá (*Schizolobium parahyba* var. *amazonicum*)						
3 m x 3 m	76.1 a	15.2 b	17.1 a	15.4 a	0.162 a	137.2 a
4 m x 4 m	83.2 a	19.9 a	17.6 a	16.2 a	0.275 b	143.0 a
5 m x 5 m	84.6 a	21.1 a	18.2 a	11.8 b	0.330 b	111.8 b

Different letters indicate significant differences between the treatments (Tukey's test; $p < 0.05$).

For a better discussion of the results obtained in this study, Table 7 shows the product of the meta-analysis carried out for different tree species of the Fabaceae family. There is a pattern of significance in the comparison of means between the variables in the meta-analysis, although under different treatments and sites, there is a strong correlation between the behavior of height and dbh for the different species.

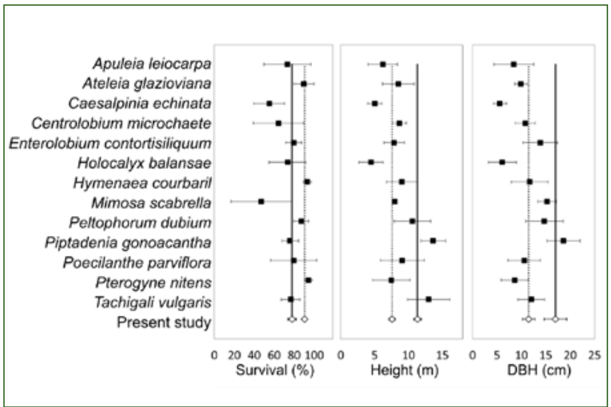
Table 7 - Species, common names, number of observations (n), age, vital area and publications referenced in the collection of meta-analysis data.

Species[1]	Common name	n	Age (years)	Vital área (m²)	REF[3]
Apuleia leiocarpa	Grápia	6	8.7	9.5	1
Ateleia glazioviana	Timbó	7	7.9	7.2	2
Caesalpinia echinata	Pau-Brasil	12	10.3	8.1	1
Centrolobium microchaete	Araribá-Amarelo	5	8.8	11.4	3
Enterolobium contortisiliquum	Timbaúva	23	8.8	8.3	1
Holocalyx balansae	Alecrim	8	9.8	9.0	1
Hymenaea courbaril	Jatobá Verdadeiro	7	12.3	6.3	1
Mimosa scabrella	Bracatinga	6	5.6	9.0	1.4
Peltophorum dubium	Canafístula	16	8.7	9.2	5
Piptadenia gonoacantha	Pau-Jacaré	17	10.3	8.9	1
Poecilanthe parviflora	Coração-De-Negro	5	12.2	9.5	1
Pterogyne nitens	Amendoim	11	9.8	8.8	1
Tachigali vulgaris	Taxi-Branco	13	6.9	8.1	6.7
Anadenanthera peregrina[2]	Angico	9	8.0	16.7	
Schizolobium parahyba[2]	Paricá	9	8.0	16.7	

1 Criteria of inclusion: age between 5 and 20 years; at least 5 observations found; spacing between 2 m x 2 m and 5 m x 5 m (Vital area greater than 4 m² and less than 25 m²); species from the Fabaceae family.
2 Angico e Paricá: number of observations represents one per block per spacing; vital area refers to the mean vital areas for the three spacings.
3 References: 1 = Carvalho (1994); 2 = Carvalho (2002); 3 = Carvalho (2006); 4 = Lisbão Júnior (1981); 5 = Bertolini et al. (2015); 6 = Sousa et al. (2016); 7 = Tonini et al. (2018).

As can be seen in the "forest plot" in Figure 2, each bar is connected to a point representing the mean, with the length of the bar corresponding to the standard error ($p<0.05$) for each species. When the central line touches the bars, there is no significant difference. The comparative analysis of the means of survival, total height and diameter at breast height (dbh) between angico (represented by the dashed central line) and the other Fabaceae species showed that, for the most part, there was no statistically significant difference between the results presented in this study and the meta-analysis. On the other hand, the "forest plot" shows higher mean height and dbh values for the paricá species (represented by the solid central line) when compared to the other Fabaceae species evaluated in the meta-analysis.

Figure 2 - "Forest plot" of a meta-analysis of species from the Fabaceae family compared with the mean results obtained for angico (dashed central line) and paricá (solid central line).



Discussion

The results presented in Table 5 are in line with the work of Miranda et al. (2016). When analyzing the performance of paricá stands at different spacings, they found more significant growth in dbh, height and individual volume at wider spacings compared to smaller spacings.

The planting layout, specifically the spacing adopted, affects the quality and adaptability of the forest species, impacting on the productive capacity of the stand. For this reason, plant spacing is considered a crucial tool that influences the management needed to develop the plantation and, ultimately, the features of the stand until harvest. In this sense, the intensity of competition for resources and the selection of trees to be harvest are determinant, directly influencing tree diameter and forest productivity (Puettmann et al. 2015, Ameray et al. 2021).

In general, using wider planting spacings favors faster growth in the first few years, resulting in trees with larger diameters and individual volumes. However, denser arrangements, in which competition for space, nutrients, water and light is intensified, tend to result in more restricted growth in both diameter and individual volume (Benin et al. 2014). Thus, size-density relationships have long been observed in forests and other ecosystems with monoculture plantations, playing a significant role in agriculture and forestry (Thurm and Pretzsch 2021).

The total heights of angico trees ranged from 3.7 to 4.2 m, while paricá trees showed heights ranging from 17.1 to 18.2 m, with no significant differences between treatments. However, plants tend to engage in competitive interactions when resources are limited, leading to a decline in height and crown size as plant density increases. On the other hand, at wider spacings, although the proportion of the crown decreases with increasing height, competition for light occurs horizontally, not vertically, in the stand. In other words, crown diameter has a more significant influence on competition for light than crown height (Puettmann et al. 2015; Ameray et al. 2021).

In this context, it is coherent to align planting conditions, forest species and the objectives of the planting in order to optimize production. When the aim is to produce wood for processing, denser spacings are more appropriate, in order to maximize physical production (total volume), while wider spacings promote greater viability for the production of sawn or laminated timber (individual volume) (Watzlawick and Benin 2020). According to the authors, it more appropriate to choose intermediate spacings (1,666 to 2,500 plants ha^{-1}) when the forester does not have a specific destination for forestry production (Watzlawick and Benin 2020).

The basal area tended to increase as the planting spacing decreased. Basal area ranged from 6.1 to 8.5 m^2 ha^{-1} and 11.8 to 16.2 m^2 ha^{-1} in the angico and paricá stands, respectively. In both species, the 3 m x 3 m spacing produced the largest basal areas and the 5 m x 5 m spacing produced the smallest basal areas. Similarly, this pattern is repeated in the commercial volume, which increases as the spacing between plants is reduced in both species. The angico stand recorded total mean volume ranging from 23.8 to 29.8 m^3 per hectare. The paricá stand had total mean volume of between 111.8 and 143.0 m^3 per hectare.

The changes between the variables calculated as a function of spacing do not occur in a linear fashion, possibly because they are dependent on genetic and environmental factors, which can lead to an increase in experimental error, making it difficult to observe statistical differences.

A reduction in spacing is generally associated with an increase in basal area (Albaugh et al. 2017). This is due to the greater density of the stand and, in general terms, denser spacing, even if it provides less volume per plant, results in a greater basal area, due to the proximity of the trees and the greater number of individuals per unit area (Sereghetti et al. 2015). However, an excessive increase in the number of trees per hectare causes intense competition between plants for resources such as light, water and nutrients. This can result in higher mortality and lower individual tree growth, leading to higher costs for harvesting, establishing and maintaining the forest (Ribeiro et al. 2017).

The strong correlation between the behavior of height and dbh for the different species found in the meta-analysis is well known. This relationship between the two variables has been studied since 1932 with Trorey's experiments and is the basis for adjusting height-diameter relationship models, such as those in this study, in order to adapt them to the conditions of a given site and reduce inventory costs, enabling better monitoring and forecasting of stand production (Machado et al. 2008).

The higher mean height and dbh values for the paricá species when compared to the other Fabaceae species shows the species' strong suitability for forestry, and it is often targeted as a component in pure or intercropped forest plantations (Cordeiro et al. 2015). The demand for research and use of the species in reforestation results in knowledge in genetic variability and phenotype selection, which culminates in gradually more productive stands (Gomes et al. 2021).

The results obtained in this study demonstrate the silvicultural potential of two leguminous tree species in monospecific stands. Notably, Fabaceae exhibits outstanding performance in mixed stands, positively influencing the diameter growth of other species. By naturally incorporating nitrogen into the system, Fabaceae reduces fertilization costs and shortens planting rotations (Paula et al. 2022).

Therefore, assessing the silvicultural suitability of species with this characteristic is indispensable for research and development in the forestry sector. Integrating individual production with the stand-level gains and biological nitrogen fixation not only offers substantial economic benefits, but also makes a significant contribution to environmental conservation.

Conclusion

The angico recorded total mean volume ranging from 23.8 to 29.8 m³ per hectare. The paricá had total mean volume between 111.8 and 143.0 m³ per hectare.

The best spacing for production per area is 3 m x 3 m, and for individual volume production, with higher added value, it is 5 m x 5 m. However, for parica, from a silvicultural standpoint, we can indicate the spacing of 4 m x 4 m, when there is greater wood production both individually and per area.

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