Performance of Wood Native Species to Southern Brazil in Successional Agroforestry Systems

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Abstract

Agroforestry systems (AFS) are viable alternatives for sustainable agricultural management, balancing economic, social, and environmental benefits. This study evaluated the performance of 26 native tree species from the Atlantic Forest biome planted in an AFS and identified the 10 most suitable for replication in southern Brazil. The experimental system was established in June 2015 at UTFPR Dois Vizinhos, covering 830 m². Measurements included total height, stem height, crown diameter, and diameter at breast height, from which morphometric and silvicultural indicators were calculated. After 72 months, the best-performing species were *Citharexylum myrianthum* (Tucaneiro), *Enterolobium contortisiliquum* (Timbaúva), *Solanum mauritianum* (Fumeiro-bravo), *Luehea divaricata* (Açoita-cavalo), *Schinus terebinthifolius* (Aroeira), *Drimys brasiliensis* (Casca-de-anta), *Albizia niopoides* (Farinha-seca), *Astronium graveolens* (Guaritá), *Handroanthus impetiginosus* (Ipê-roxo), and *Cedrela fissilis* (Cedro). These species formed an upper canopy layer averaging 8.9 m, with lower branches at 1.7 m in *Handroanthus impetiginosus*. Taller species showed elongated, elliptical canopies, while shorter ones had rounder crowns. The vertical stratification observed reflects successional processes, demonstrating how AFS can restore agroecosystems by enhancing nutrient cycling and soil fertility. The findings highlight the potential of native species-based AFS to promote ecological restoration and sustainable land use in southern Brazil.

Introduction

Areas with the implementation of agroforestry systems (AFS) can be seen as a form of environmental restoration that aims to bring back the tree component to degraded agroecosystems (Altieri and Nicholls 2011; 2019; Montagnini et al. 2015; Montagnini and Piotto 2011). To implement AFS, tree species that can establish themselves under limiting conditions (survive the site's environmental filters), attract fauna, grow quickly, and produce abundant litterfall are desirable (Chada et al. 2004).

Among the different types of agroforestry systems, this work evaluates a successional type (AFS) which is characterized by a mixture of tree species classified as pioneer and secondary (or filler and diverse, respectively) according to the ecosystem theory of ecological succession and is based on the objectives of re-establishing the community processes of plant succession, which in turn promote biodiversity and ecosystem services (Nair 1993; Peneireiro 1999; Brancalion et al. 2009; Renner et al. 2010).

Part of the successful implementation of AFS depends on the silvicultural behavior and the mix of tree species that bring the benefits desired by the farmer (Aguiar Junior et al. 2021; Peneireiro 1999; Carvalho et al. 1999; Carvalho 2003). The silvicultural behavior is defined by the form and rate with which a tree develops over time, the height, diameter at breast height, diameter and shape of the crown, duration of the life cycle, age until first flowering, as well as the analysis of the coverage index, salience, degree of slenderness, cover value index and importance (Carvalho 1982; Carvalho et al. 1999; Carvalho 2003; Renner et al. 2010). Thus, silvicultural behavior is defined, on the one hand, by the genetic conditions of the species that enable them to respond in a certain way to environmental variations and, on the other hand, by the interaction between the individual and the living community around it.

By assessing the vertical structure of plant populations, the ecological behavior and habits of each population can be identified (Sanquetta 1995). This analysis provides important information for understanding the characteristics of each species, providing a basis for understanding natural regeneration, growth, and survival strategies. In this sense, the use of native trees not only increases the chances of success of AFS but also helps restore degraded areas, as this mixture can recover the ecosystem functions and services lost due to previous deforestation.

In the southern region of Brazil, the history of land use has led to extensive deforestation, and even today, the largest land use is intensive agriculture with monocultures (Dean 1996; Leite and Candiotto 2015; Kischener et al. 2015). However, there are still forest fragments of various sizes and at various stages of plant ecological succession. Secondary forests are of great importance because they can be transformed into assisted restoration areas. In addition, according to Kumar et al. (2014), there is significant potential in South America to implement AFS, as most farms have at least 10% of their area covered with trees. Thus, there is an urgent need to develop more sustainable agricultural production systems and environmental restoration initiatives across most agroecosystems in southern Brazil. This can be achieved through AFS.

The aim of this study was to evaluate the silvicultural behavior of 26 native tree species in a successional agroforestry system (AFS) and to recommend the 10 species with the best growth for implementing these systems in the state of Paraná and in environmentally similar regions of southern Brazil.

Material and Methods

The study presents the results obtained by monitoring the growth of 26 native tree species from Brazil from 8 months to 72 months (6 years) after implementation, through six continuous inventories of tree vegetation, in an agroforestry system on the experimental farm of the Federal University of Technology - Paraná - Brazil (UTFPR), in Dois Vizinhos, Paraná. The study area is located at coordinates 25° 41’ 59.38” S and 53° 6’ 3.09” W, with an altitude ranging from 475 to 510 m (Fig. 1).

According to the Köppen classification, the region has a humid subtropical climate (Cfa), with rainfall throughout the year and a hot summer. The annual average temperature is 19°C, with an average minimum above 3°C and an average maximum below 30°C, and rainfall of 1,900-2,200 mm per year (Alvares et al. 2013).

The soil is of the area is Rhodic Khandiudox, characterized by having a B nitic horizon below the A horizon with a hue of 2.5YR or redder, with a clayey to very clayey texture, of basaltic origin, being acidic soils with relatively low fertility and variable aluminum (Al) contents, requiring fertility correction practices for agricultural use (Santos et al. 2018).

The original phytophysiognomy of the region was the Montane Mixed Ombrophilous Forest, with floristic elements of the Semideciduous mesophytic forest of the Iguaçu River (IBGE, 2012), and can be considered a transitional ecotone between these phytophysiognomies. In this region, 665 taxa were identified and cataloged in a review of existing studies (Bechara et al. 2018). Among the most common species are louro-pardo (*Cordia trichotoma*), grápia (*Apuleia leiocarpa*), Paraná pine (*Araucaria angustifolia*), palm heart (*Euterpe edulis*), with the most important families being Fabaceae, Asteraceae, Euphorbiaceae, Myrtaceae, and Lauraceae.

Among the various objectives of SAF implementation was the short-term formation of vertical stratification and canopy closure, allowing for shading and light control through canopy management and pruning, using this biomass to cover the soil and promote biological nutrient cycling. To achieve this, 26 tree species native to the southern region of Brazil (Atlantic Forest Biome) were selected, aiming to maintain diversity while prioritizing the most outstanding species for future studies and recommendations.

Then, the AFS was planted in June 2015 using 554 seedlings of 26 tree species native to the Atlantic Forest biome, 14 of which belong to the pioneer succession group (P) and 12 to the secondary succession group (S) (Carvalho 2003; Peneireiro 1999), as shown in Table 1, with lists the tree species planted with their respective families, scientific names, popular names, and number of individuals. The planting spacing was 3.5 m between rows and 0.5 m between trees, resulting in an average density of 0.57 individuals per m^2, in the total AFS area of 830 m^2. The planting sequence in each row followed a ratio of two secondary trees to one pioneer tree, i.e., S-S-P-S-S-P.

Table 1
Lists of the tree species planted with their respective families, scientific names, popular names, Ecological succession group, phytophysiognomies, and main uses.

Popular name, scientific, and Family (1)	**Ecological succession group**	**Geographic regions/ Biomass/ Phytophysiognomies** (1)	**Main uses** (2)
Fumeiro-bravo, *Solanum bullatum* Vell., (Solanaceae)	Pioneer	SE, S / Atlantic Forest / Anthropic Area, FES, FOD, FOM	Pulp and paper, forest restoration, and medicine
Timbaúva, *Enterolobium cortorstisiliquum* (Vell.) Morong (Fabaceae)	Pioneer	NE, CO, SE, S / Caatinga, Cerrado, Atlantic Forest, Pampa, and Pantanal / Caatinga (SS), Cerrado (LS), Riparian forest, FES, FOD	Wood for civil and naval construction, carpentry, crates, paper and cellulose, charcoal, saponin, tannin, animal feed, beekeeping, landscaping, and forest restoration
Tucaneiro *Citharexylum myrianthum* Cham. (Verbenaceae)	Pioneer	NE, SE, S / Caatinga e Atlantic Forest / Riparian forest, FES, FOD, FOM	Wood for musical instruments, animal feed, beekeeping, landscaping, medicinal, and forest restoration
Açoita-cavalo *Luehea divaricata* Mart. (Malvaceae)	Pioneer	NE, CO, SE, S / Caatinga, Cerrado, Atlantic Forest, Pampa, Pantanal / Anthropic Area, Rocky Field, Cerrado (LS), Riparian forest, FED	Wood for furniture and various uses, paper and cellulose, extraction of oils, resins, and tannins, beekeeping, medicinal, landscaping, and forest restoration
Aroeira-pimenteira *Schinus terebinthifolia* Raddi (Anacardiaceae)	Pioneer	NO, NE, CO, SE, S / Caatinga, Cerrado, Atlantic Forest, Pampa / Anthropic Area, Clean Field, Cerrado (LS), Riparian forest, FES, FOD, FOM, Manguezal, Restinga	Fence posts, firewood and charcoal, dye, insecticidal oil, resin, tannin, goat fodder, edible fruits, beekeeping, medicinal, landscaping, and forest restoration
Angico-vermelho *Parapiptadenia rigida* (Benth.) Brenan (Fabaceae)	Pioneer	CO, SE, S / Atlantic Forest, Pampa / FED, FES, FOD	Wood for construction and carpentry, high-quality firewood and charcoal, saponin, tannin, forage, medicine, landscaping, and forest restoration
Branquilho-leiteiro *Gymnanthes klotzschiana* Müll.Arg.	Pioneer	NE, CO, SE, S / Caatinga, Atlantic Forest /	Wood for crates and agricultural tools, firewood and high-calorific value charcoal, paper and cellulose, beekeeping, medicine, and forest restoration

Popular name, scientific, and Family (1)	Ecological succession group	Geographic regions/ Biomass/ Phytophysiognomies (1)	Main uses (2)
(Euphorbiaceae)		Caatinga (SS), Riparian forest, FES, FOD, FOM, Restinga	
Canafístula *Peltophorum dubium* (Spreng.) Taub. (Fabaceae)	Pioneer	NE, CO, SE, S / Caatinga, Cerrado, Atlantic Forest, Pantanal / Caatinga (SS), Carrasco, Cerrado (LS), Riparian forest, FED, FES, FOD, FOM	Wood of high economic value, suitable for civil construction, posts, sleepers, furniture and carpentry, paper and cellulose, saponin, tannin, beekeeping, medicinal, landscaping, and forest restoration
Caroba *Jacaranda micrantha* Cham. (Bignoniaceae)	Pioneer	SE, S / Atlantic Forest, Pampa / FED, FES, FOD	Wood for furniture, carpentry, musical instruments, and construction in general, paper and cellulose, medicine, landscaping, and forest restoration
Angico branco *Anadenanthera colubrina* (Vell.) Brenan *var. colubrina* (Mimosaceae)	Pioneer	NE, SE, S / Caatinga, Cerrado, Atlantic Forest / Caatinga (SS), Cerrado (LS), FES, FOD	Wood for construction, firewood and charcoal, tannin, medicinal, beekeeping, and forest restoration
Araticum *Annona cacans* Warm. (Annonaceae)	Pioneer	NE, CO, SE, S / Atlantic Forest, Pampa / FES, FOD	Wood for crates and toys, paper and cellulose, edible fruit (but purgative), landscaping, and forest restoration
Ingazeiro *Inga edulis* Mart. (Fabaceae)	Pioneer	NO, NE, CO, SE, S / Amazon, Caatinga, Cerrado, Atlantic Forest / Anthropic Area, Riparian forest, Floresta de Várzea, FES, FOD, Restinga	Wood for crates, high-quality firewood and charcoal, paper and cellulose, medicinal, beekeeping, edible pulp, landscaping, and forest restoration
Guajuvira *Cordia americana* (L.) Gottschling & J.S.Mill. (Cordiaceae)	Pioneer	CO, SE, S / Atlantic Forest, Pampa / FED, FES	Wood for civil construction, furniture and carpentry, firewood and charcoal, paper and cellulose, tannin, beekeeping, indigenous crafts, medicinal, landscaping, and forest restoration
Louro-pardo *Cordia trichotoma* (Vell.) Arráb. ex	Pioneer	NO, NE, CO, SE, S / Caatinga, Cerrado, Atlantic Forest, Pampa /	Wood for furniture, construction, carpentry and joinery, beekeeping, medicinal, landscaping, and forest restoration

Popular name, scientific, and Family (1)	Ecological succession group	Geographic regions/ Biomass/ Phytophysiognomies (1)	Main uses (2)
Steud. (Cordiaceae)		Anthropic Area, Caatinga (SS), Cerrado (LS), FED, FES, FOD	
Casca-de-anta *Rauvolfia sellowii* Müll.Arg. (Apocynaceae)	Secondary	SE, S / Atlantic Forest / FES	Wood for boxes and toys, paper and cellulose, medicine, landscaping, and forest restoration
Farinha-seca *Albizia edwallii* (Hoehne) Barneby & J.W.Grimes (Fabaceae)	Secondary	SE, S / Atlantic Forest / FED, FOD, FOM	Wood for crates and interior work, paper and cellulose, good quality firewood and charcoal, landscaping, and forest restoration
Ipê-roxo *Handroanthus heptaphyllus* (Vell.) Mattos (Bignoniaceae)	Secondary	NE, CO, SE, S / Cerrado, Atlantic Forest, Pampa / FES, FOD	Wood for civil and naval construction, carpentry, joinery, and in the manufacture of floorboards, high-quality firewood and charcoal, tannin, dyes, medicinal, landscaping, and forest restoration
Guaritá *Astronium graveolens* Jacq. (Anacardiaceae)	Secondary	NO, NE, CO, SE, S / Amazon, Caatinga, Cerrado, Atlantic Forest, Pampa / Anthropic Area, Cerrado (LS), Riparian forest, FES, FOD	Wood for interior finishes, exterior construction, furniture and carpentry, high-quality firewood, beekeeping, medicinal, landscaping, and forest restoration
Cedro-rosa *Cedrela fissilis* Vell. (vulnerável) (Meliaceae)	Secondary	NO, NE, CO, SE, S / Amazon, Caatinga, Cerrado, Atlantic Forest, Pampa, Pantanal / Cerrado (LS), Upland Forest, FED, FES, FOD	Wood for civil construction, naval construction, furniture and musical instruments, good quality firewood, essential oil, tannin, beekeeping, medicinal, landscaping, and forest restoration
Palmiteiro *Euterpe edulis* Mart. (vulnerável) (Arecaceae)	Secondary	NE, CO, SE, S / Cerrado, Atlantic Forest / Riparian forest, FOD	Stipe serves as wood for civil construction, paper and cellulose, animal feed (leaves and seeds), food (heart of palm and pulp), beekeeping, crafts (leaves), landscaping, and forest restoration
Canjarana *Cabralea canjerana (Vell.) Mart.* subsp.	Secondary	NO, NE, CO, SE, S / Amazon, Caatinga, Cerrado, Atlantic Forest, Pampa /	Wood for furniture, joinery, carpentry, civil construction (interior finishes), insecticide, dye, essential oil, perfume essence,

Popular name, scientific, and Family (1)	Ecological succession group	Geographic regions/ Biomass/ Phytophysiognomies (1)	Main uses (2)
Canjerana (Meliaceae)		Caatinga (SS), Cerrado (LS), Riparian forest, FED, FES, FOD	saponin, tannin, beekeeping, medicinal, landscaping, and forest restoration
Guabirobeira *Campomanesia xanthocarpa* (Mart.) O.Berg (Myrtaceae)	Secondary	CO, SE, S / Atlantic Forest, Pampa / FES, FOD, FOM	Wood for household utensils, tool handles and musical instruments, good quality firewood and charcoal, food (fruits), beekeeping, medicinal, landscaping, and forest restoration
Araucária *Araucaria angustifolia* (Bertol.) Kuntze (em perigo) (Araucariaceace)	Secondary	SE, S / Atlantic Forest, Pampa / Altitude Field, FES, FOM	Wood for general construction, furniture, carpentry, crate making, lamination, musical instruments, pine knot is an excellent fuel, paper and cellulose, resin, food (pine nut), crafts, medicinal, landscaping, and forest restoration
Ipê-amarelo *Handroanthus albus* (Cham.) Mattos (Bignoniaceae)	Secondary	SE, S / Atlantic Forest / Rocky Field, FOD	Wood for civil construction, joinery and carpentry, good quality firewood, food (flowers), beekeeping, medicine, landscaping, and forest restoration
Erva-mate *Ilex paraguariensis* A.St.-Hil. (Aquifoliaceae)	Secondary	CO, SE, S / Caatinga, Cerrado, Atlantic Forest, Pampa / Rocky Field, Cerrado (LS), Riparian forest, FEP, FES, FOD, FOM	Wood for laminating, alkaloids and tannins, wax (cosmetics), food (erva mate), landscaping and forest restoration
Espinheira-santa *Monteverdia ilicifolia* (Mart. ex Reissek) Biral (Celastraceae)	Secondary	CO, SE, S / Cerrado, Atlantic Forest, Pampa, Pantanal / Clean Field, Riparian Forest, FED, FES, FOM	Firewood and charcoal, medicinal, landscaping, and forest restoration

S: South; CO: MidWest; NO: North; NE: North East; SE: Southeast; SS: Stricto Sensu; LS: Lato Sensu; FES: Seasonal Semideciduous Forest; FED: Seasonal Deciduous Forest; FEP: Seasonal Evergreen Forest; FOD: Dense Ombrophilous Forest; FOM: Mixed Ombrophilous Forest. (1) JBRJ. (2024). **Lista Oficial de Espécies da Flora e Funga do Brasil**. Flora e Funga do Brasil. Available in: https://ipt.jbrj.gov.br/jbrj/resource?r=lista_especies_flora_brasil&request_locale=pt. Access in: July 31, 2025. (2) CARVALHO (2008). Source: own elaboration.

The silvicultural performance of the species was assessed using the following dendrometric variables: total height (ht), stem height (sh), circumference at breast height (cbh), and crown diameter (cd). Heights were measured using a digital hypsometer. The cbh and cd were measured using a tape measure. Using the CBH value, the DBH (diameter at breast height) was calculated. Also, the following morphometric indices were calculated: CL - crown length; CD - crown diameter; CA - crown area; CP - crown proportion (%); DS - degree of slenderness; OI - overhang index; BI - breadth index; CS - crown shape, according to Aguiar Junior et al. (2021).

Total height and seedling stem diameter measurements were taken continuously every 3 months for the first 20 months after planting. During this phase, height was measured with a hypsometric stick, and stem diameter with a digital caliper. After a period without management, the area was assessed again at 72 months of age. Previous measurements were repeated, including new ones such as diameter at breast height (dbh), stem height (sh), and crown diameter (cd), allowing calculation of indicators describing the silvicultural behavior of the species.

Through analysis of variance (ANOVA) at a 5% probability of error, using the R-Studio software (R Core Team 2018) and the ExpDes.Pt package (Ferreira et al. 2021). The performance of the trees was compared within their ecological groups. A Scott-Knott multiple comparison test was also carried out in order to rank the species from highest to lowest according to their total height (ht) and diameter at breast height (dbh) development.

Results and Discussion

The ANOVA results showed a difference in height development between pioneers and secondaries ($Pr(> F) = 0.03968$), with the pioneers showing the fastest growth during the first 15 months after planting. Table 2 shows the development of the pioneer and secondary trees in this study, from 8 to 72 months after planting. These results support one of the premises of this study, since the pioneer and secondary trees had different silvicultural behavior, as expected by the theoretical assumptions. This differentiated development of the trees led to the formation of a stratified vegetation physiognomy similar to that of the region's native forests.

Table 2
Plant development over 72 months of the 26 native tree species in each successional class in the AFS studied.

Class	I	ht min	ht med	ht max	sh min	sh med	sh max	sd min	sd med	sd max	dbh min	dbh med	dbh max
Pioneer	8	0.1	1.0	4.5	-	-	-	0.2	1.2	4.7	-	-	-
	12	0.1	1.4	4.7	-	-	-	0.2	1.5	6.5	-	-	-
	15	0.1	1.6	4.8	-	-	-	0.3	1.8	6.8	-	-	-
	17	0.2	1.7	4.8	-	-	-	0.4	2.1	7.3	-	-	-
	20	0.2	2.2	5.5	-	-	-	0.5	2.7	9.4	-	-	-
	72	0.5	5.6	21.0	0.2	2.5	8.7	-	-	-	0.5	5.1	21.9
Secondary	8	0.1	0.7	6.0	-	-	-	0.0	1.1	3.5	-	-	-
	12	0.1	0.8	4.0	-	-	-	0.1	1.1	3.8	-	-	-
	15	0.1	0.8	2.3	-	-	-	0.2	1.3	4.1	-	-	-
	17	0.2	0.9	2.7	-	-	-	0.3	1.5	4.5	-	-	-
	20	0.2	1.1	3.4	-	-	-	0.3	1.8	5.5	-	-	-
	72	0.5	4.1	13.7	0.2	2.0	7.1	-	-	-	5	3.5	13.5

I - AFS age in months; ht - minimum (min), average (med) and maximum (max) total height in m; sh - minimum (min), average (med) and maximum (max) stem height in m; sd - stem diameter in cm; dbh - diameter at breast height in cm. (-) - no information. Source: own elaboration.

The pioneers had an average total height of 1 m at 8 months after planting, 1.4 m at 12 months, 1.6 m at 15 months, 1.7 m at 17 months, and 2.2 m at 20 months (Table 2). This means that the average monthly growth rate was 9.5 cm month-1 during the first 20 months of planting; it was highest in the first 8 months (10.0 cm month^{-1}), decreased between 12 and 17 months (6.0 cm month-1), and increased to 17.0 cm month^{-1} at 20 months. For the secondary, the average monthly growth rate was 4.6 cm month-1 over the first 20 months of planting, reaching an average total height of 1.1 m. At 72 months of age, the pioneers had an average total height of 5.6 m and a stem height of 2.5 m, while the secondary trees had a total height of 4.1 m and a stem height of 2.0 m. Thus, the difference in height development already shows one aspect of the silvicultural behavior of both groups.

Regarding stem diameter (sd), the pioneers maintained a growth rate of approximately 0.1 cm month^{-1} during the first 17 months, increasing to 0.2 cm month^{-1} by the time the AFS were 20 months old. In turn, the secondary trees showed a rate of increase in dc of approximately 0.1 cm month^{-1} up to 20 months. Thus, at 20 months of age, the average DC was 2.7 cm and 1.8 cm for the pioneers and secondaries, respectively (Table 2). The diameter at breast height (DBH) of the pioneers at 72 months was 5.1 cm, and of the secondary trees was 3.5 cm.

The minimum and maximum values for each indicator in the trees across both ecological groups, by agroforest age (Table 2). For example, in the pioneer trees, the maximum total height was 21.0 m, and in the secondary trees, it was 13.7 m at 72 months. According to Vasconcellos and Beltrão (2018), multi-stratum agroforestry systems are most similar to natural forests, taking advantage of the varying intensities of solar radiation, humidity, and shading across vertical strata. This pattern can be observed in the results of this work, where the trees developed occupying different vertical strata, demonstrating the potential of these species for multi-stratum AFS design.

Using a multiple-comparison of means test, it is possible to see an ordering of the total heights of the 26 species (Fig. 2). For interpretation purposes, the amplitude of the vertical lines for each species in Figs. 2 and 3 refers to the variation observed at 72 months of planting age.

The total height of the trees was a variable that separated the 26 species into three groups (Fig. 2). The first group, shown in red and represented by the letter "a" in the left frame of Fig. 2, comprises species listed in Table 3. For example, the Tucaneiro, Casca-de-anta, Timbaúva, and Fumeiro-bravo, among which the greatest variability was observed in the Tucaneiro.

This separation of the data into three groups of trees based on height indicates greater variation than that observed in diameter at breast height (DBH), which separated only two groups (Fig. 3). The initial growth of forest species prioritizes carbohydrate allocation to root system formation and height growth, thereby expanding leaf area, with a subsequent focus on secondary growth, such as trunk diameter. Thus, pioneer trees, as well as some secondary trees, demonstrated this primary focus on initial growth, being classified in the first tier in the statistical analysis.

As shown in Fig. 3, the first group had the greatest dap development and included the species Timbaúva, Casca-de-anta, Tucaneiro, Açoita-cavalo, and Fumeiro-bravo. It appears that, firstly, the greatest growth in dbh was almost entirely composed of the same species that grew the most in height, with pioneers predominating and only Casca-de-anta as a secondary species, maintaining the ecological logic of maintaining a balanced height/dbh ratio. Furthermore, some secondary species also had more pronounced growth in dbh, such as Espinheira-santa.

Of the 26 species evaluated, this study shows that 10 (5 P and 5 S) are considered the best based on total height developed. As for the analysis of the best species within each ecological group, Table 3 lists the ten best, with the first five pioneers and the last five secondary.

Table 3 shows the species in descending order by total height, one of the main performance indicators for an AFS. Also shown are the results for stem height, which describe the species' potential for timber use and, in the vertical dimension, the height above ground at which the tree begins to develop lateral branches and twigs, which may also indicate the need for pruning management. The dbh data can represent the species' investment in secondary stem growth, which can be an indicator of stability and atmospheric carbon accumulation, depending on wood density. The species with the longest stem and largest dbh was Timbaúva, with 4.3 m and 11 cm, respectively.

Timbaúva and Aroeira were species highlighted in the study by Marcuzzo et al. (2015) for their good development and recommended for implementation in AFS. The study by Silva (2016) also recommends the

Açoita-cavalo and Angico-vermelho species for their good development in agroforestry plantations.

The survival percentage (%) was highest for the Açoita-cavalo (94.4%), a species that can be used economically due to the value and different uses of its wood, as well as the medicinal potential of its bark. The species with the lowest survival rate was Fumeiro-bravo, with 46.6%. According to Carvalho (1982), the survival of these species shown in Table 2 can be considered "high", with only the Fumeiro-bravo being considered to have "regular" survival, i.e., none of the species had low survival.

Table 3
Dendrometric variables and morphometric indices of ten species featured in the AFS studied at 72 months after planting.

Species	ht	sh	dbh	% S	CL	CD	CA	CP	DS	OI	BI	CS
Tucaneiro	8.9	3.6	0.09	75.9	5.3	3.1	2.4	59.3	158.3	61.7	0.39	0.694
Timbaúva	8.2	4.3	0.11	85.5	4.0	2.9	2.3	51.4	84	35.9	0.412	0.854
Fumeiro-bravo	7.6	3.3	0.08	46.6	4.3	2.5	1.9	57.8	115.7	54.3	0.416	0.789
Açoita-cavalo	7.2	2.4	0.09	94.4	4.8	3.9	3.1	63.5	86.1	48.3	0.573	0.956
Aroeira	4.6	1.8	0.03	75.9	2.7	2.3	1.8	58	180.2	92.7	0.581	1.060
Casca-de-anta	8.6	3.8	0.09	62.3	4.9	3.7	2.8	56.5	98.4	43.7	0.439	0.823
Farinha-seca	6.7	2.9	0.05	81.8	3.7	2.7	2.1	51.2	162.2	70.8	0.436	1.060
Guaritá	5.2	2.7	0.05	78.9	2.6	2.1	1.6	48.4	131.7	52.9	0.413	0.907
Ipê-roxo	4.2	1.7	0.03	75.9	2.5	1.7	1.3	57.9	175.0	70.7	0.422	0.807
Cedro	3.3	2.3	0.03	57.8	0.9	0.5	0.4	26.5	95.4	19.7	0.169	1.723

ht - average total height in m; sh - average stem height in m; dbh - average diameter at breast height in m; %S - survival percentage. CL - crown length in m; CD - crown diameter in m; CA - crown area in m^2; CP - crown proportion in %; DS - degree of slenderness; OI - overhang index; BI - breadth index; CS - crown shape. Source: own elaboration

Among the species characteristic of the Mixed Ombrophilous Forest (FOM), Cedro has been reported in the literature as suitable for planting in agroforestry systems, given the importance and variety of uses for its wood. This species, in particular, has greater resistance to *Hypsipyla grandella* (cedar borer) when planted in association with other tree species, as is characteristic of AFS, because it increases its regrowth capacity, allowing it to reach heights beyond the reach of the aforementioned pest (Ruggiero et al. 2021; Montagnini et al. 2015). In this study, this species stood out and had a development rate considered normal, in contrast to Carvalho's (2003) results. As noted by Carvalho (2005), pure planting of this species is not recommended due to its greater susceptibility to this pest.

Gerber et al. (2020) evaluated the initial performance of the pioneer species *Guazuma ulmifolia* (Mutambo) in a mixed ecological restoration plantation in the same region as this study. The species showed excellent performance at 48 months of age, with high survival (96%), collar diameter (6.8 cm), total height (12.8 m), canopy projection area (14.36 m^2), and canopy volume (49.86 m^3).

Regarding morphometric variables, the highest CL was calculated for the Tucaneiro, which also had the second-highest CD. This made the species the second highest in CP value (59.3%). Açoita-cavalo had the second-highest CL value (4.8 m) and the highest CD value (3.9 m), with a CP indicator of 63.5%. Among the secondary species, Casca-de-anta had the highest CL and CD and was therefore the species with the highest CP in the group (56.5%), as seen in Table 3.

Açoita-cavalo developed the largest crown proportion (CP = 63.5%) followed by Tucaneiro (59.3%). This means that these species have more than half of the stem occupied by the crown, which has also developed a large diameter. Cedro had the lowest CP (26.5%), and individuals in the agroforest had an average total height of 3.3 m, with stems up to 2.3 m, i.e., little canopy development, with a CL of approximately 0.9 m and a CD of 0.5 m.

The degree of slenderness (DS) is an indicator that relates the total height of the tree to the DBH. The higher the index, the greater the gradual increase in height, accompanied by a gradual increase in DBH. Aroeira had the highest DS (180.2), followed by Ipê-roxo (175.0) and Farinha-seca (162.2).

The following three indicators: OI, BI, and CS, relate the nd first to the DBH, then to the total height of the tree, and finally to the length of the crown. Of these three, the first two, the overhang index and breadth, give an idea of the tree's horizontal breadth, and the larger the crown diameter, the higher the results for these indicators. The crown's aspects are very important, as they define the level of shading provided to the other members of the AFS. Regarding these aspects, among the pioneer species, the aroeira stood out in both indices, showing a relatively large crown size compared to its DBH and height. Other species, such as the tucaneiro (OI) and açoita-cavalo (BI), also stood out. Among the secondary species, the farinha-seca (OI and BI) stand out, as well as the ipê-roxo (OI) and casca-de-anta (BI).

The crown shape (CS) will help us determine whether this structure is more spherical or elliptical. Thus, if the CL is greater than the CD, the crown will have a vertical elliptical shape; if both measurements are close, a spherical crown can be observed; and the CS will be 1. The trend observed in Table 3 is that in all species the CD was always lower than the CL, which is why most of the CS results are less than 1, but when the CD approaches the CL, as can be seen in the Açoita-cavalo, Aroeira, and Farinha-seca species, the indicator shows results close to 1 and the species have more rounded canopies.

This behavior, shown by most of the species in this study, which developed greater CL than CD, may be associated with the densification of the plantation, since, according to Carvalho (2003), most of these species develop large-diameter canopies when growing in isolation. According to Aguiar et al. (2021), there are other tree species that, when they grow densely together with other varieties of trees in their surroundings, develop large SC, thus avoiding the formation of lateral branches and twigs at low height, managing to achieve an adequate proportion of light for their leaf area, even with high competition.

The species with the highest total height and the longest canopy, such as the Tucaneiro, Casca-de-anta, Timbaúva, and Fumeiro-bravo, have an oviform, elliptical vertical canopy shape, with an overhang that thickens from approximately 3 m above the ground. Species such as Farinha-seca, Guaritá, and Ipê-roxo, on the other hand, have developed more rounded canopies that form at lower heights, with larger canopy diameters that probably reflect greater horizontal exploitation of branches in search of sunlight filtering down from the upper canopy created by the first species mentioned.

The higher the wood density, the higher the CL and the greater the dbh, the more economically the species can be used. The density of the wood was not assessed in this study, but the species with the largest dap were Timbaúva (11 cm), Tucaneiro (9 cm), Açoita-cavalo (9 cm), and Farinha-seca (9 cm). These species can be used to make musical instruments, boxes, shoe heels, and other items, such as toys for children (Carvalho 2003). Even at a young age, these trees could already be used effectively. However, it is important to understand that, within the management applied to the AFS, the use of wood will occur within a few years to produce larger pieces with greater potential for use.

As mentioned above, the AFS evaluated in this research were made up of tree species classified by their ecological groups as pioneers or secondaries according to the theory of ecological succession. One of the aims of this type of AFS, in addition to providing a possible extra income for the producer and promoting biodiversity, is to create vertical stratification and a change in the microclimate that also allows the soil to be used for short-cycle crops in the understory, a fact that was observed in the results of this research. According to Matthes and Martins (1996), various factors can influence the differential development of tree species, including light, temperature, humidity, nutrients, herbivory, seed bank availability, and dispersal. Light, for example, is considered to be one of the main factors influencing the differential development of species that colonize not only clearings but also the understory of forest fragments (Gandolfi et al. 2007). In this work, luminosity levels and the simulation of clearings within the AFS can occur when the canopies of the species with the main dominance in the upper stratum are pruned and managed, as well as when some trees are harvested for economic use of the wood.

According to Chada et al. (2004), tree species with desirable characteristics for implementing AFS include Timbaúva, Fumeiro-bravo, Açoita-cavalo, and Tucaneiro, whose management during development provides biomass to cover the soil and promote the natural cycling of nutrients. These species also contribute to the formation of a stratified plant physiognomy, as in primary or mature forests.

Floristic studies conducted in natural forest fragments of the Mixed Ombrophilous Forest indicate that these locations host botanical families with greater species richness and individual abundance. Generally, the most diverse families are Fabaceae, Myrtaceae, Lauraceae, and Sapindaceae. This diversity of families includes species with different requirements for pollinators and seed dispersers, resulting in a diversity of species offerings in time and space to attract other animals and trigger synergistic processes. The results of this study show that well-established species such as Timbaúva (Fabaceae), Aroeira (Anacardiaceae), and Farinha-seca (Fabaceae) have potential for implementation in AFS in southern Brazil.

The vertical stratification observed, with differences in height and canopy shape between species, reflects not only the diversity of the system but also the complexity of ecosystem processes. In this way, the use of agroforestry systems can benefit farmers in terms of productivity and economic resilience, while also contributing to the conservation of biodiversity and ecosystem services essential to human and environmental well-being.

Conclusions

From the results obtained in this study on the performance of 26 tree native species to the Atlantic Forest biome in an Agroforestry System (AFS), we recommend the following species: tucaneiro, timbaúva, fumeiro-bravo, açoita-cavalo, aroeira, casca de anta, farinha seca, guaritá, ipê-roxo, and cedro. The success of these species demonstrates not only their ability to develop in agroforestry conditions but also their importance in the ecological restoration of agroecosystems, as they can be grown while maintaining the structure and functionality of natural ecosystems.

Based on the results obtained in this study on the performance of 26 native tree species from the Atlantic Forest biome in an Agroforestry System (AFS), it is understood that there is a set of pioneer and secondary species that can be prioritized for the initial phase of AFS implementation, such as the 10 species highlighted. This selection allows an AFS to structure and stratify more quickly and to create conditions for multiple products, both ecosystem services and timber and non-timber products.

The five pioneer species (Tucaneiro, Timbaúva, Fumeiro-bravo, Açoita-cavalo, and Aroeira) and the five secondary species (Casca-de-anta, Farinha-seca, Guaritá, Ipê-roxo, and Cedro) demonstrated good performance, as indicated by the variables analyzed, with the formation of vertical layers as early as 72 months. With appropriate management, multiple products can be produced within the available vertical and horizontal cultivation space.

Other studies in the area (data not shown) demonstrate the performance of natural regeneration, soil quality, and biodiversity in this environment, constituting a model for technical and scientific dissemination.

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Figures

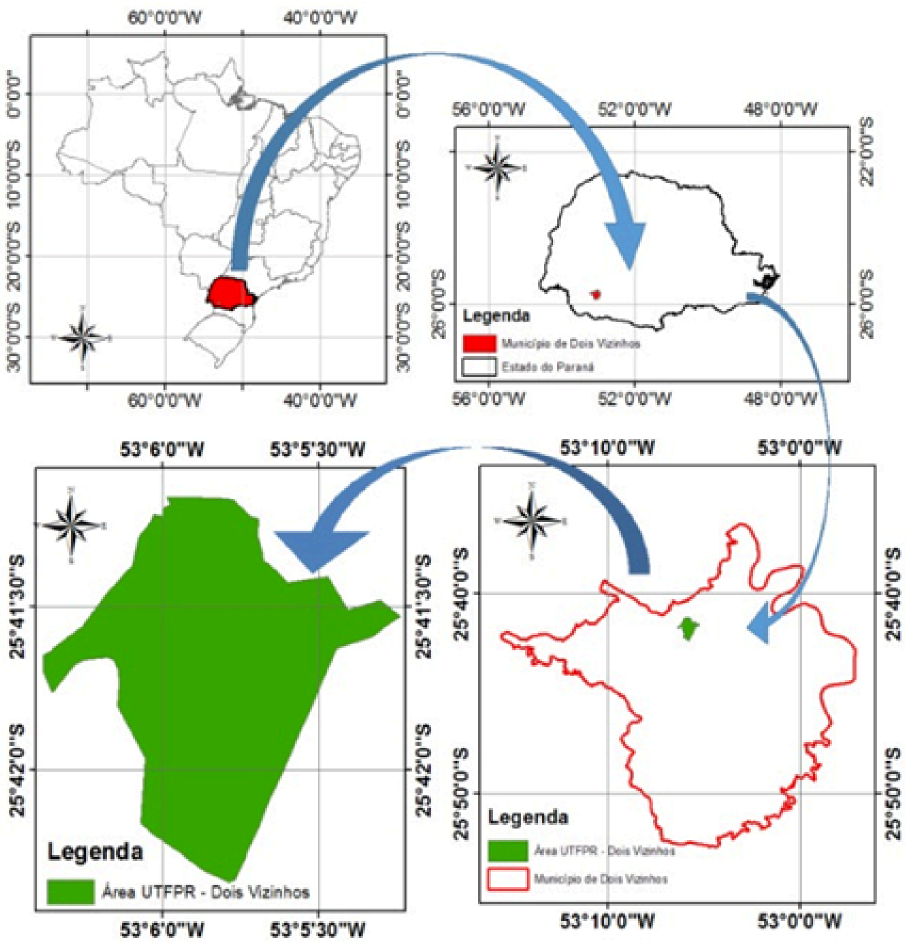

Figure 1

Location of the study area at the UTFPR in Dois Vizinhos, Parana, Brazil. Source: Coelho (2016).

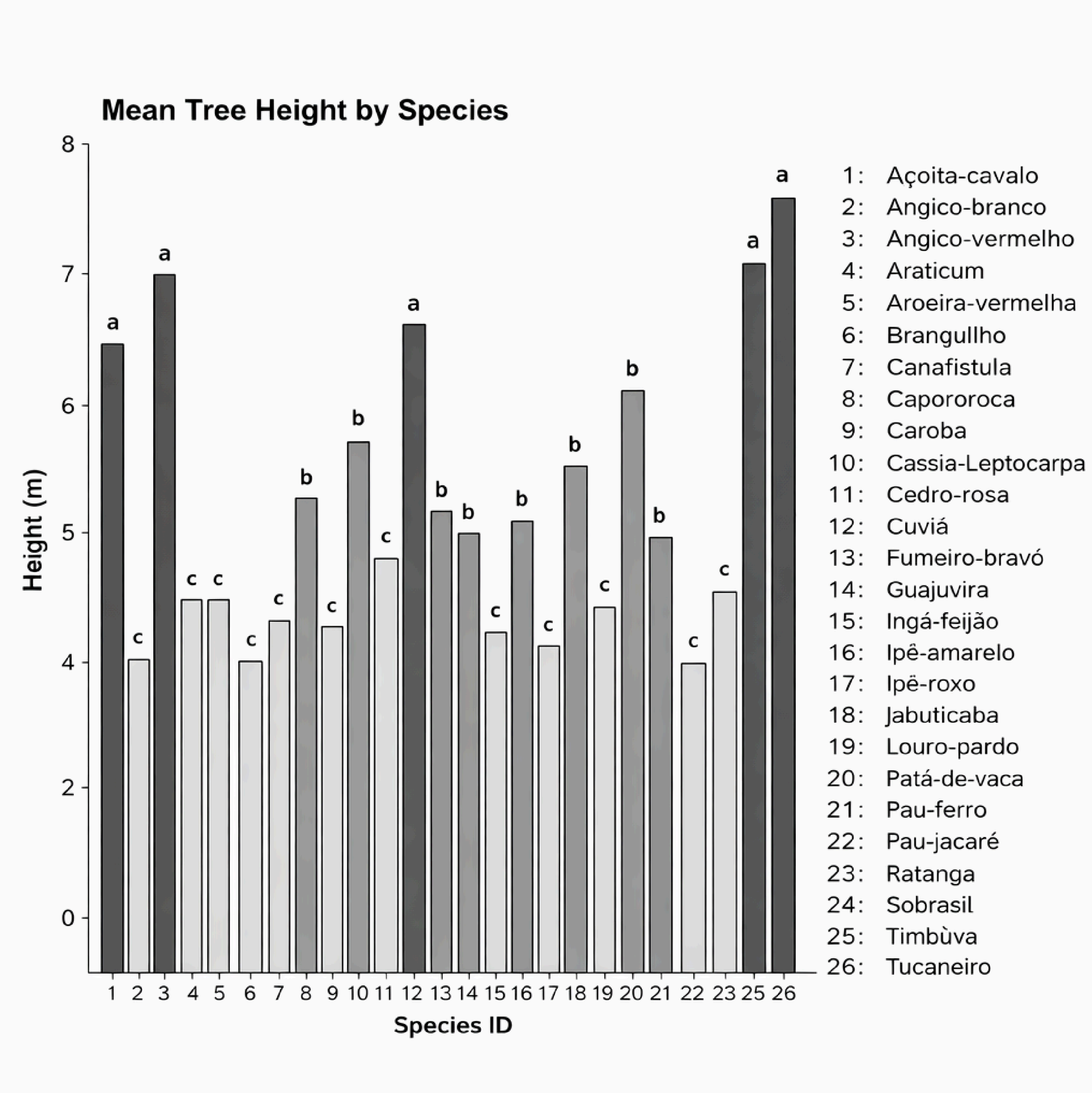

Figure 2

Total height (ht) at 72 months of the 26 native tree species in the AFS studied, with emphasis on the best species, according to the Scott-Knott test at 5% of error probability. Source: own elaboration.

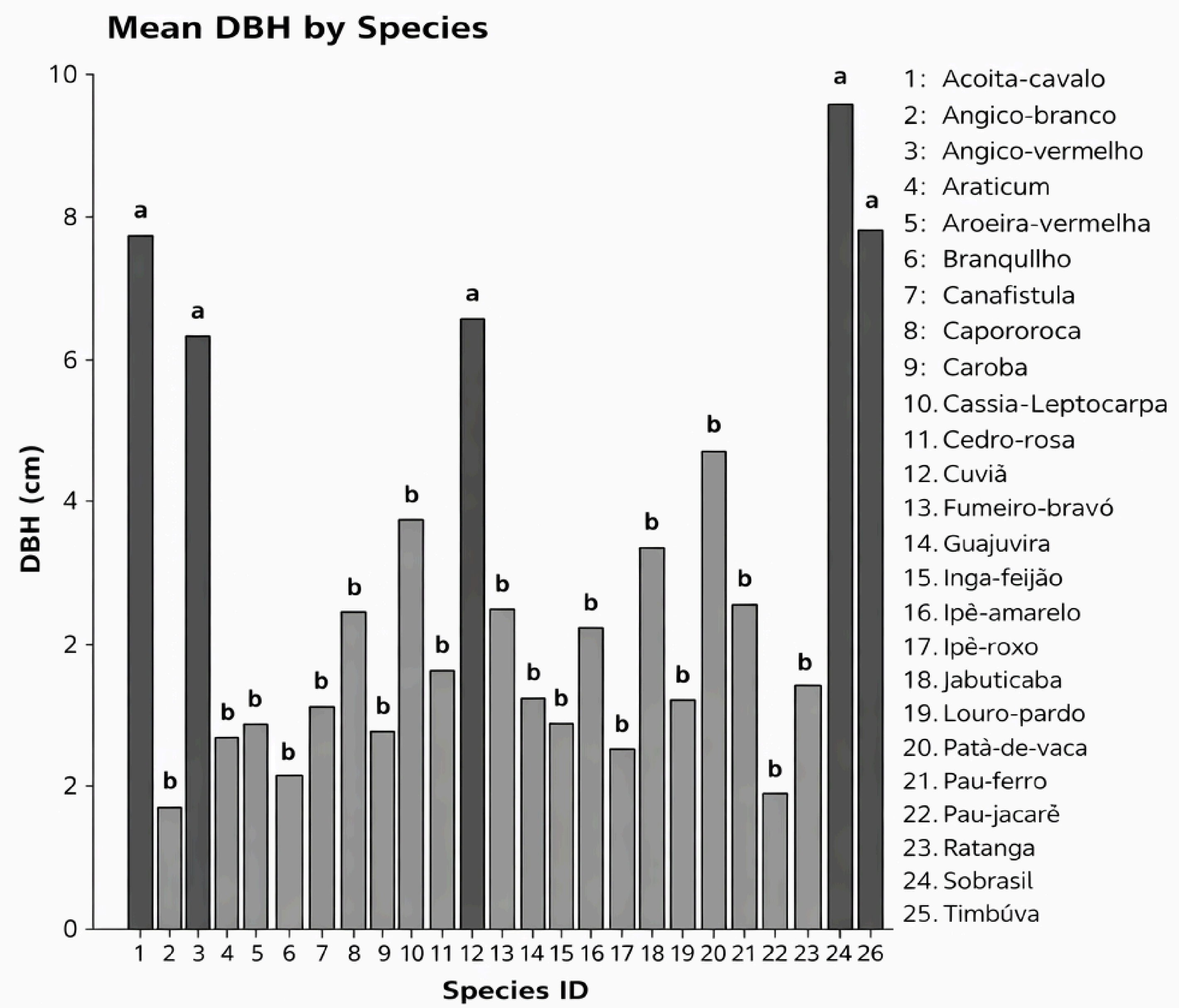

Figure 3

Diameter at breast height (DBH) of the 26 native tree species in the AFS studied, with emphasis on the best species, according to the Scott-Knott test at 5% of error probability. Source: own elaboration