

**INITIAL GROWTH PERFORMANCE OF VALUABLE TIMBER SPECIES
IN SOUTHERN BRAZIL: *Araucaria angustifolia*, *Balfourodendron riedelianum*, AND
*Parapiptadenia rigida***

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ABSTRACT – The initial growth of three Brazilian native timber species in the city of Dois Vizinhos-PR, Brazil, was described - *Araucaria angustifolia*, *Balfourodendron riedelianum*, and *Parapiptadenia rigida*, using four non-linear mathematical models (Gompertz, Logistic, Logistic 4P, and Chapman-Richards). In the first 4 years after planting, information about collar diameter (mm), total height (m), crown height (m), and crown diameter (m) was obtained twice a year for 12 individuals per species. Crown area (m²) and crown volume (m³) were estimated. The growth in these four variables (collar diameter, total height, crown area, and crown volume) was projected using the models, and their fitting was assessed based on the values of the Akaike Information Criterion, the Bayesian Information Criterion, the standard error of estimate, and the coefficient of determination. The models generated excellent statistics for all parameters in all variables, with better statistics for collar diameter (coefficient of determination higher than 0.65 and standard error lower than 30%) and total height (coefficients of determination higher than 0.72 and standard error lower than 37%). Considering the three species, *Parapiptadenia rigida* showed the fastest growth in all variables (median of 70.97 mm for collar diameter, median of 4.475 m for total height, median of 10.35 m² for crown area, and median of 15.30 m³ for crown volume at 48 months). Longer monitoring periods in this and other experiments are recommended to characterize the growth of these three Brazilian native timber species to adequately describe their performance in timber and forest restoration projects.

Keywords: Subtropical Atlantic Forest; Fitting models; Non-linear growth models.

**DESEMPENHO INICIAL DO CRESCIMENTO DE ESPÉCIES MADEIREIRAS
NA REGIÃO SUL DO BRASIL: *Araucaria angustifolia*, *Balfourodendron
riedelianum* E *Parapiptadenia rigida***

RESUMO – Foi avaliado o crescimento inicial de três espécies madeireiras nativas do Brasil - *Araucaria angustifolia*, *Balfourodendron riedelianum* e *Parapiptadenia rigida* – em Dois Vizinhos – PR, Brasil, usando quatro modelos matemáticos não lineares (Gompertz, Logístico, Logístico 4P e Chapman-Richards). Ao longo dos quatro anos iniciais após plantio, informações sobre diâmetro do colo (mm), altura total (m), altura de copa (m) e diâmetro de copa (m) foram obtidas semestralmente em doze indivíduos de cada espécie. Foi calculada a área de copa (m²) e volume de copa (m³) desses indivíduos. O crescimento em termos de diâmetro de colo, altura total,



área de copa e volume de copa foi projetado usando os modelos, e o ajuste dos mesmos foi avaliado em termos de Critério de Informação Akaike e Critério de Informação Bayesiano, Erro padrão da estimativa e Coeficiente de determinação. Os modelos geraram excelentes estatísticas para todos os parâmetros em todas as variáveis, com melhores estatísticas para diâmetro de colo e altura total. Considerando as três espécies, *Parapiptadenia rigida* apresentou o crescimento mais rápido em todas as variáveis (mediana de 70,97 mm para o diâmetro do colo, mediana de 4,475 m para altura total, mediana de 10,35 m² para área de copa e mediana de 15,30 m³ para volume de copa, aos 48 meses). Um monitoramento mais longo e outros experimentos são recomendados para caracterizar o crescimento dessas três espécies madeireiras nativas brasileiras para descrever seu desempenho para produção de madeira e também para projetos de restauração florestal.

Palavras-chave: Floresta Atlântica subtropical; Ajuste de modelos; Modelos não lineares de crescimento.

1. INTRODUCTION

Farmers have been discouraged to manage natural forests in Brazil due to factors such as bureaucracy, technical deficiency, little funding, uncertainty related to wood use, and the lack of studies on the Brazilian flora. This has led to the strengthening and spreading of exotic timber species as well as to the conversion of native forests into other land use types, particularly agricultural fields, followed by an ecological and traditional knowledge loss about the use and management of these species (Coradin, et al., 2011).

In Southern Brazil, after the European colonization (from the end of the 19th century to the beginning of the 20th century), many native forest resources have been extremely explored, not only by farmers, but also by companies, aiming to provide raw material for buildings and agriculture and to generate income from timber sale. In this scenario, *Araucaria angustifolia* (Bertol.) Kuntze, *Balfourodendron riedelianum* (Engl.) Engl. and *Parapiptadenia rigida* (Benth.) Brenan had their populations reduced, opening up space for ecological restoration projects (Ruschel, et al., 2003; Coradin, et al., 2011).

Excessive harvesting resulted in the dramatic decline of these species (Ruschel, et al., 2003; Mósen and Dillenburg, 2004; Souza, 2007), and they are now listed as threatened by extinction, for example in the list produced by the Environmental Institute of Parana (IAP, 1995), by the Brazilian Institute of Environment and Renewable Natural Resources - IBAMA (MMA, 2014), or even in the International Union for Conservation of Nature and Natural Resources (IUCN, 2018) Red List of Threatened Species (IUCN, 2018). *Araucaria angustifolia* has been classified as

rare by the IAP, as endangered by the IBAMA, and as critically endangered by the IUCN; *B. riedelianum* has been listed as rare by the IAP, as almost endangered by the IBAMA, and as endangered by the IUCN, while *P. rigida* has not yet been recorded in the lists produced by IBAMA or assessed for the IUCN Red List. However, there is still a lack of knowledge about the initial performance of these Brazilian native timber species in reforestation.

Araucaria angustifolia, Araucariaceae, is a large evergreen Brazilian pine that reaches 50 m in height and a diameter at breast height (dbh) of 250 cm or more when adult. Its trunk is straight and almost cylindrical, and it has a moderately dense white-yellowish wood, used for sawmill, lumber, plywood, pulpwood, pulp, and paper. This species was the most commercially important timber species in South Brazil over the last century and the only valuable conifer of natural occurrence in the country. Regarding its cultivation, it highly depends on soil quality and fertility; because of this, in the same climate, *A. angustifolia* stands can show an annual increment of 26 m³.ha⁻¹ or only 1 m³.ha⁻¹. It is also culturally important where it naturally occurs because of its edible seeds (Soares, 1979; Carvalho, 2002a; Zandavalli, et al., 2003; Mósen and Dillenburg, 2004).

Balfourodendron riedelianum, Rutaceae, is a deciduous tree that presents up to 35 m in height and 100 cm in dbh when adult. Its trunk is also straight and cylindrical, reaching 15 m in length. It occurs at elevations from 70 to 1,000 m and prefers well-drained, deep, and fertile soils. It is mainly found in the Seasonal Semideciduous Forest, where it appears in the forest canopy, in the Seasonal Deciduous Forest, and in Araucaria Forests. The wood is dense

and whitish, used for furniture, civil construction, pulpwood, and other purposes (Carvalho, 2004).

Parapiptadenia rigida, Fabaceae, is a semideciduous tree, reaching 20 or 35 m in height when mature. Its trunk is cylindrical, rarely straight, and slightly tilted. It can be found in several forest types at elevations of 30 to 1,100 m and with well-distributed rainfall. Its wood is dense, white-yellowish, highly durable, and largely applied in rural constructions, carpentry, energy, and other purposes (Carvalho, 2002b).

Despite the widespread potential of native timber species, as a consequence of the factors mentioned above, there is little information regarding the silviculture of native tree species (Kageyama and Castro, 1989), particularly in terms of growth, neglecting their potential to establish forest stands. Knowledge about individual tree growth is essential, and the modeling of growth relations should have a data basis which considers such information (Nutto, 2001).

In this sense, studying the silviculture and growth of Brazilian native timber species is crucial to design management and restoration projects for these species. This paper describes the initial growth of three Brazilian native timber species, *A. angustifolia*, *B. riedelianum*, and *P. rigida*, using mathematic modeling.

2. MATERIAL AND METHODS

The study was carried out at the Federal University of Technology - Parana, in the municipality of Dois Vizinhos, south of Brazil (25°41'37" S - 53°06'07" W). The region has an average elevation of 502 m and deep, moderately fertile soil, characterized as typical dystrophic red oxisol (Embrapa, 2006). The climate is classified as Cfa subtropical, with the occurrence of frosts and the absence of a dry season. The average temperature of the coldest month is below 18°C and that of the warmest month is above 22°C; average annual temperature ranges between 19 and 20°C (Alvares, et al., 2014). The vegetation is classified as an ecotone of *Araucaria* Forest influenced by Seasonal Semideciduous Forest; both forest types belong to the Atlantic Forest biome.

In the experimental area, 70 native trees were planted in December 2010, with 30-50-cm high

seedlings distributed in four plots of 40 x 50 m, resulting in an area of 8,000 m². In each plot, 360 seedlings were planted, divided into 180 plants of early pioneer species (10 spp.) and 180 plants of non-pioneer species (60 spp.). The pioneer and non-pioneer species were switched within the lines, with a spacing of 3 m between lines and 2 m between plants. We assessed the three non-pioneer species, *A. angustifolia*, *B. riedelianum*, and *P. rigida*, each with 12 (3 x 4) individuals planted, resulting in 36 trees evaluated.

As fertilization, 36 g of NPK fertilizer (5-20-10) were used per plant, and hydro retainer was applied into the holes. The seedlings were protected with cardboard mulching and received cover fertilization of 40 g of urea per plant and year. Biannually, weeds were controlled by cutting, followed by chemical weeding until the third year.

Data collection started in May 2011, followed by biannual evaluations (one per semester). The collar diameter measurements were taken using a digital pachymeter, which was positioned on the plant collar next to the soil surface. To standardize the measurements, the direction of the plot's greater length was used as reference for the pachymeter positioning.

The variables total height and crown height were measured using a graduated scale of 10 m, with 0.05-m intervals. The equipment was positioned vertically as close as possible to the plant, settling its base on the soil level. Total height was considered as the distance between the plant's basis to the highest branch and crown height as the length between the plant's basis and its first branch fork.

In addition, two measurements of the crown diameter were taken, perpendicularly to one another, using a measuring tape. After that, the crown area was calculated through the ellipse formula: $ca (m^2) = dl.de.\pi/4$, where ca is the crown area and dl and de are the crown diameters (m) measured. The crown volume was obtained using the following formula: $cv (m^3) = ca*cl$, where cv is the crown volume, ca is the crown area (m²) obtained by the previous formula, and cl is the crown length, obtained by the result of the subtraction of the total height by the crown height.

The meteorological data were collected from the meteorological station at the Federal University of

Technology, Parana, Dois Vizinhos, to compare the species growth with the temperatures. All data were stored in electronic spreadsheets on Microsoft Office Excel™, and the mathematical modeling for growth was conducted using the statistical R software (R Core Team, 2017).

Regarding the growth modeling, four non-linear models were tested to project the growth in collar diameter, total height, crown area, and crown volume in terms of age. The Non-linear Least Square (NLS) and the SelfStart (SS) functions in the R software were used to calculate the initial estimates of the model parameters. It was not possible to generate the Chapman-Richards model parameters in the R Software, and therefore, the Statistica™ software was used.

The models used were Gompertz, Logistic, Logistic 4 Parameters, and Chapman-Richards, as described in the following functions:

$$\text{Gompertz: } y = \beta_0 * e^{-\beta_1 + \beta_2 x}, \quad (\text{Eq 1})$$

where y is the predictable variable, β_0 is a numeric parameter representing the asymptote, x represents a numeric vector of values at which to evaluate the model (in this case, age), β_1 is a numeric parameter related to the value of the function at $x = 0$, β_2 represents a numeric parameter related to the scale in the x axis.

$$\text{Logistic: } y = \beta_0 / [1 + e^{(\beta_1 - x)/\beta_2}], \quad (\text{Eq 2})$$

where y is the predictable variable, β_0 is a numeric parameter representing the asymptote, x is a numeric vector of values at which to evaluate the model (age), and β_1 represents a numeric parameter representing the x value at the inflection point of the curve. The value of SSlogis will be $Asym/2$ at x_{mid} ; β_2 represents a numeric scale parameter on the *input* axis.

$$\text{Logistic 4 Parameters: } y = \beta_0 / (1 + e^{(\beta_1 - x)/\beta_2}), \quad (\text{Eq 3})$$

where y is the predictable variable, β_0 is a numeric parameter representing the horizontal asymptote on the left side (very small values of input), β_1 is a numeric parameter representing the horizontal asymptote on the right side (very large values of input), *input* represents a numeric vector of

values at which to evaluate the model (age), and β_2 is a numeric parameter representing the input value at the inflection point of the curve. The value of SSfpl will be midway between A and B at x_{mid} ; β_3 is a numeric scale parameter on the input axis.

$$\text{Chapman-Richards: } y = \beta_0 * [(1 - e^{(-\beta_1 * x)})^{\beta_2}], \quad (\text{Eq 4})$$

where y is the predictable variable, β_0 is the maximum value for the predictable variable (asymptote), β_1 represents an empirical growth parameter, x represents a numeric vector of values at which to evaluate the model (age), and β_2 is related to the plant's biology (Burkhardt and Tomé, 2012).

To evaluate the quality of the model fitting, Akaike's Information Criterion (AIC), the Bayesian Information Criterion (BIC), the standard error of estimate (S_{yx}), and the coefficient of determination (R^2) were used, all obtained via the R statistical program (except the BIC for Chapman-Richards model fits, which could not be calculated). For these criteria, the best model would be the one with smaller AIC, BIC, and standard error values and a higher coefficient of determination.

3. RESULTS

Regarding the mathematic modeling applied to the growth variables tested, the fit results for each model are detailed in Table 1. Similar values for standard error, coefficient of determination, AIC, and BIC were obtained for all models in all variables tested. Because of this, each variable was better fitted by a different model, so distinct models could be selected to project the growth for each variable. For example, the logistic model was the one that presented the best fitting statistics to estimate the growth in crown area for *A. angustifolia*, collar diameter, total height, and crown volume for *B. riedelianum*, and collar diameter for *P. rigida*. On the other hand, the CP model was the one with the best statistics to estimate collar diameter, total height, and crown area for *A. angustifolia*, crown area for *B. riedelianum*, as well as crown area and volume for *P. rigida*. The Log 4P was the best-fitted model only for total height of *P. rigida*. The Gompertz model was least suitable to predict species growth and was therefore not selected for any of the variables.

Table 1 – Statistical parameters obtained for the model fitted for collar diameter, total height, crown area, and crown volume for the studied species.**Tabella 1** – Parâmetros estatísticos obtidos para os modelos ajustados para diâmetro de colo, altura total, área de copa e volume de copa para as espécies estudadas.

	<i>A. angustifolia</i>				<i>B. riedelianum</i>				<i>P. rigida</i>			
	GO	LO	LO 4P	CP	GO	LO	LO 4P	CP	GO	LO	LO 4P	CP
Collar diameter												
β_0	0.00005442	378.529		481.982	153.437	88.627	13.43	279.575	120.65442	86.797	12.368	489.928
β_1	0.1092	92.491		0.002426	2.83366	33.816	68.39	0.005164	2.43689	28.554	73.739	0.002003
β_2	0.9964	25.679		1.00121	0.9761	15.983	31.352	0.997692	0.97009	15.177	28.407	0.830544
β_3							8.246				9.342	
Syx	27.57	27.57	NF	26.31	28.4834	28.3575	28.2784	29.19	29.0221	28.9483	29.0404	29.42
R ²	0.7617	0.7617		0.7294	0.6761	0.6789	0.6848	0.6597	0.6515	0.6533	0.6554	0.6418
AIC	628.5725	629.5914		388.0349	627.5375	626.8202	627.3225	399.6588	671.7496	671.3215	672.8118	433.6643
BIC	638.4818	638.5007			637.1153	636.398	639.2947		681.4729	681.0447	684.9659	
Total height												
β_0		166.595	0.4031	239.414	10.048942	6.197	0.6332	28.6046	6.34985	5.2213	0.8884	30.4634
β_1		127.285	6.8492	0.0013172	2.814995	32.966	5.1853	0.0034346	2.59113	24.2467	4.6765	0.002630
β_2		20.807	48.2456	1.52355	0.974061	15.478	30.9578	0.988614	0.95636	11.5317	26.1975	0.874673
β_3			11.4903				10.3769				6.7641	
Syx	NF	36.45	36.5717	34.09	18.6538	18.5514	18.5614	19.48	23.7542	23.4999	23.3315	24.19
R ²		0.756	0.7572	0.7256	0.8337	0.8356	0.8375	0.8186	0.7552	0.7604	0.7668	0.7461
AIC		162.7101	164.2484	-78.7203	131.6369	130.7447	131.7867	-129.414	188.8312	187.0235	186.7718	-48.4751
BIC		172.6195	176.635		141.2147	140.3225	143.759		198.5545	196.7468	198.9259	
Crown area												
β_0	7.47379	3.904	0.1628	46.5849	4.44729	4.0187	-0.3037	6.81112	9.98398	9.049	-1.209	10.3606
β_1	7.42688	38.11	3.4931	0.0081659	8.14836	29.9784	4.1976	0.0356283	8.55359	27.205	9.906	0.076999
β_2	0.95653	7.529	37.1154	2.41311	0.91923	6.986	27.4131	2.67474	0.9154	6.691	26.585	6.15373
β_3			5.677				8.3735				9.344	
Syx	62.37	61.86	62.02	63.28	61.2412	61.3799	61.7091	61.451	62.2728	62.5856	62.8072	62.23
R ²	0.6897	0.6947	0.6968	0.5942	0.5032	0.501	0.5021	0.4998	0.5205	0.5156	0.5182	0.5210
AIC	196.5916	195.1515	196.5544	-22.5748	282.3096	282.6761	284.4976	51.0007	431.1570	431.9989	433.5491	190.6773
BIC	206.5009	205.0609	208.9411		291.8874	292.2539	296.4698		440.8802	441.7222	445.7032	
Crown volume												
β_0				169.804	7.94643	7.664	0.02429	36.5132	35.19192	24.569	-7.045	86.8015
β_1				0.0158596	54.35497	30.125	7.65958	0.0154251	5.92998	37.384	86.318	0.016167
β_2				5.11997	0.86445	4.496	30.15917	2.31563	0.95478	9.593	72.933	2.49371
β_3							4.4668				26.022	
Syx	NF	NF	NF	88.71	91.6972	91.5237	92.1157	93.81	85.6672	85.9099	86.1274	85.58
R ²				0.5990	0.4051	0.4073	0.4073	0.3774	0.4317	0.4285	0.4327	0.432835
AIC				120.3324	441.9688	441.6619	443.6613	213.787	578.7292	579.2045	580.5857	338.1942
BIC					451.5466	451.2397	455.6335		588.4525	588.9278	592.7398	

Note: GO = Gompertz's model; LO = Logistic model; LO 4P = Logistic 4 Parameters; CP = Chapman-Richard model; NF = no fitting; β_0 , β_1 , β_2 and β_3 = models' parameters; S_{yx} = standard error of the estimate (%); R² = coefficient of determination; AIC = Akaike's Information Criterion; BIC = Bayesian Information Criterion.

Nota: GO = Gompertz; LO = Logístico; LO 4P = Logístico 4 parâmetros; CP = Chapman-Richard; NF = sem ajuste; β_0 , β_1 , β_2 e β_3 = parâmetros dos modelos; S_{yx} = erro padrão da estimativa (%); R² = coeficiente de determinação; AIC = Critério de Informação Akaike; BIC = Critério de Informação Bayesiano.

The fitting of the models generated excellent statistics. For collar diameter and total height of all species as well as crown area of *A. angustifolia*, values of coefficient of determination higher than 0.65 were observed, with values above 0.72 for total height in all species. For these variables, besides total height and crown area of *A. angustifolia*, the values of Standard error were lower than 30%, indicating a great growth projection for these variables performed by the tested

models. On the other hand, higher Standard error values were noticed for crown area and volume, especially for crown volume, smaller coefficients of determination for such variables were observed as well, varying from 0.40 to 0.52.

The species showed considerable initial growth for all variables in the first 48 months of age. Overall,

they showed exponential growth over time, reaching the highest values at the end of the evaluation period (42 to 48 months), as expected; *P. rigida* showed the fastest growth.

Regarding the collar diameter, *P. rigida* (median of 70.97 mm at 48 months) and *B. riedelianum* (median of 61.56 mm at 42 months) reached the highest growth rates (Fig. 1). Both kept or even reduced their values of collar diameter at 12 months, probably as a response to the cold and dry winter of 2011, where minimum temperatures dropped to -4°C . Both species, at 36 months (after winter of 2013), showed again a slight decrease in collar diameter, most likely as a result of the low temperatures in that period, which reached -2°C . *Araucaria angustifolia* did not show significant decreases in collar diameter in both winters, showing resistance to colder temperatures since it naturally grows in regions with mesothermal climates and at elevations higher than 700 m, where the temperature tends to be colder (Carvalho, 1981; Webb, et al., 1984).

In terms of total height, *P. rigida* (median of 4.475 m at 48 months) presented the highest rates, followed by *B. riedelianum* (median of 4.425 m at 42 months) and *A. angustifolia* with the lowest values (median value of 4.0 m at 48 months) (Fig. 2). For this variable, the frost in 2011 probably affected *B.*

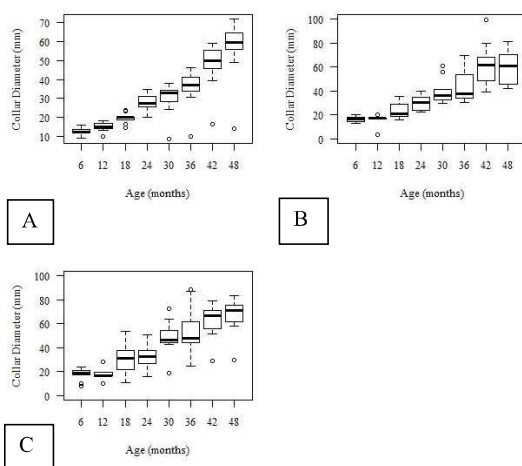


Figure 1 – Initial growth of the collar diameter of the species over time. A: *Araucaria angustifolia*, B: *Balfouredendron riedelianum*; C: *Parapiptadenia rigida*.

Figura 1 – Crescimento inicial do diâmetro de colo das espécies ao longo do tempo. A: *Araucaria angustifolia*, B: *Balfouredendron riedelianum*; C: *Parapiptadenia rigida*.

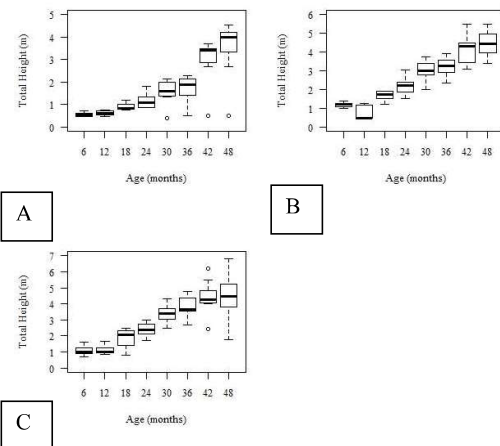


Figure 2 – Initial growth of the total height of the species over time. A: *Araucaria angustifolia*, B: *Balfouredendron riedelianum*; C: *Parapiptadenia rigida*.

Figura 2 – Crescimento inicial da altura total das espécies ao longo do tempo. A: *Araucaria angustifolia*, B: *Balfouredendron riedelianum*; C: *Parapiptadenia rigida*.

riedelianum, while the cold temperatures in 2013 reduced the values of total height for *A. angustifolia*. Although the cold temperatures affected these two species in terms of total height, no decrease in this variable was noticed for *P. rigida*.

In terms of crown area, *P. rigida* (median of 10.35 m^2 at 48 months) achieved rates around three times higher than *B. riedelianum* (median of 3.37 m^2 at 42 months) and almost four times larger than *A. angustifolia* (median of 2.91 m^2 at 42 months) (Fig. 3). For all species, the lowest values of crown area were noted in the first year; after that, a significant increase was observed, especially in *P. rigida*. Frost had no effect on crown area growth, irrespective of the species.

The behavior of crown volume for all species was similar to that of crown area (Fig. 4). In the first year, the crown volume of the three species was small, close to 0 m^3 , and increased from 18 months on, especially for *P. rigida*, which reached rates (median of 15.30 m^3 at 48 months) significantly larger than those of *B. riedelianum* (median of 6.86 m^3 at 42 months) and *A. angustifolia* (median of 6.02 m^3 at 48 months).

4. DISCUSSION

The non-linear models tested to estimate growth in collar diameter, total height, crown area, and volume produced excellent statistics, especially

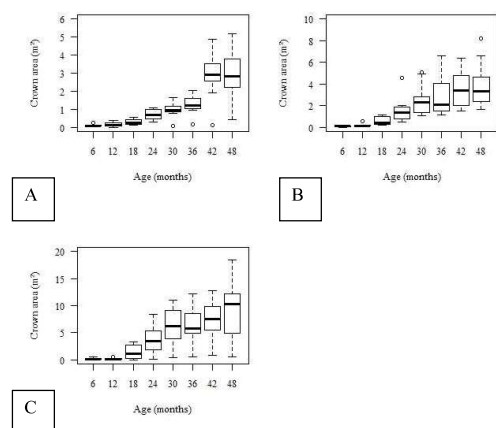


Figure 3 – Initial growth of the crown area of the species over time. A: *Araucaria angustifolia*, B: *Balfourodendron riedelianum*; C: *Parapiptadenia rigida*.

Figura 3 – Crescimento inicial da área de copa das espécies ao longo do tempo. A: *Araucaria angustifolia*, B: *Balfourodendron riedelianum*; C: *Parapiptadenia rigida*.

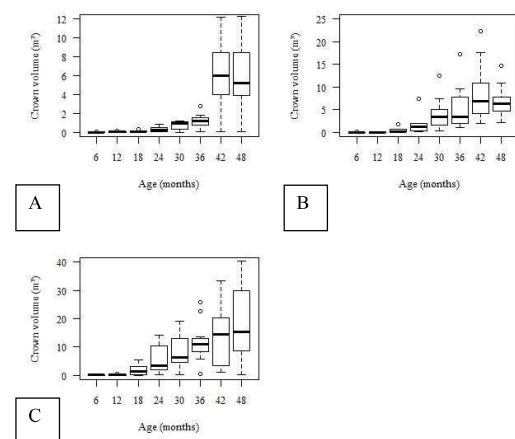


Figure 4 – Initial growth of the crown volume of the species over time. A: *Araucaria angustifolia*, B: *Balfourodendron riedelianum*; C: *Parapiptadenia rigida*.

Figura 4 – Crescimento inicial do volume de copa das espécies ao longo do tempo. A: *Araucaria angustifolia*, B: *Balfourodendron riedelianum*; C: *Parapiptadenia rigida*.

when compared to other studies. Hess, et al. (2009), using regression models, obtained coefficients of determination from 0.73 to 0.98 to estimate dbh as a function of age for *A. angustifolia*. Machado, et al. (2008), using regression to estimate height based on dbh for *A. angustifolia*, found coefficient of determination rates around 0.2, which are considered very low.

Concerning growth modeling, there is an emerging consensus that traditional growth modeling, such as linear and exponential approaches, has become outdated. New technologies have facilitated the manipulation of non-linear models, which have the advantage that they consider different growth rates (Paine, et al., 2012).

Several studies have used nonlinear models to model the growth of some tree variables. For example, Calegario, et al. (2005) developed a non-linear mixed-effects model to represent the height growth pattern of eucalypts clonal stands in Brazil and described the non-linear modeling approach as flexible, precise, and accurate. Also, Misik, et al. (2016) tested 10 non-linear height-diameter functions for dominant woody species in a temperate oak forest in Hungary, and Zhang (1997) fitted six non-linear growth functions to tree height-diameter data of six conifer species in the United States.

The non-linear functions used in this study have been widely applied to numerous data sets. For example, Zhang (1997), assessing the performance of non-linear models to tree height-diameter prediction of conifer trees in the United States, observed that the Gompertz function underestimated tree height for large-sized trees, while Richard's function as well as Schnute's and Weibull's functions produced the best predictions for his data set. Maia, et al. (2009), testing non-linear regression growth models for *Musa* spp. (banana), noticed that the best function was the logistic model. Scheeren, et al. (1999) found that the three-parameter Chapman-Richards model was the most precise model to estimate the height of *A. angustifolia* in terms of age.

Such results are in agreement with the idea that the models provide specific estimates according to the data set used, making it important to select the appropriate models and/or functions. When fitted to the data, many functions can provide similar results according to the data set used to estimate the equation's coefficients, but their behavior might change when extrapolated, depending on the mathematical properties (Burkhart and Tomé, 2012).

In terms of the growth behavior of the species, it is possible to associate their growth with their successional characteristics. While *B. riedelianum* is classified as a late secondary species, it has a slow

to moderate growth, and although *P. rigida* could be denominated as initial secondary species, it shows a moderate to slow growth (Carvalho, 2003; Carvalho, 2002b). *Araucaria angustifolia* has been grouped into different successional categories, such as pioneer (Webb, et al., 1984; Klein, 1960), secondary (Imaguire, 1979), or even climax species (Duarte, et al., 2002), since it is an opportunistic species. However, it shows a relatively slow growth, especially in the first 3 years, with a subsequent increase in growth rate (Carvalho, 2002a).

In addition, it is necessary to emphasize the damage that frosts caused in the development of the individuals in this period, especially during the first and third years when winter was more severe. Frost, depending on the damage degree and on the species, could become a limiting factor for forests (Caron, et al., 2011). For example, Carvalho (2002b) states that *P. rigida* did not pursue a good performance in some cities in the south of Brazil due to the occurrence of frost. However, in our study, *A. angustifolia*, *B. riedelianum*, and *P. rigida* showed an increased growth after frost periods, suggesting a high resilience to cold temperatures and frost.

It is important to emphasize that, in order to acquire more information about these species' initial growth, it is necessary to extend the observation window as well as to conduct further studies in other subtropical regions, with other soil-climatic conditions and with more individuals. This was an initial performance study, which proved that mathematical models could be used to project the species' growth based on a data set.

5. CONCLUSIONS

Based on the results obtained in this study, it can be stated that:

- *P. rigida* presented a better performance in initial growth compared to *B. riedelianum* and *A. angustifolia*, behaving as a pioneer – initial secondary species;
- The models tested presented similar statistics for all variables considered, and their fitting generated excellent statistics, with better statistics for collar diameter and total height;
- It is statistically plausible to apply non-linear models to predict the initial growth of native species,

but their performance depends on the data set, since a different model fitted better to each variable analyzed in this study;

- Longer monitoring in this and other experiments are recommended to characterize the initial growth of these three Brazilian native timber species and to better describe their performance in timber and forest restoration.

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