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FORESTRY SCIENCE

Evaluating tree survival and modeling initial growth for Atlantic Forest restoration

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ABSTRACT: Ecological restoration has become an important complementary practice to protect natural resources and preserve biodiversity. However, native species may be used in restoration programs in ways that do not optimize their performance. This research evaluated the survival and to model the initial growth of 15 native tree species planted in "filling" and "diversity" lines in the post-planting phase of a restoration experiment in the subtropics of the Brazilian Atlantic Forest. We measured survival rate (%) one year after planting and collar diameter (mm), total height (m), crown projection area (m²) and crown volume (m³) in the first 48 months after planting. Growth modeling for each variable and species was based on the non-linear mathematical Logistic, Gompertz, and Chapman-Richards models. Model selection for each variable/species was supported by the Akaike Information Criterion, standard error of the estimate, and coefficient of determination. The highest survival rates were reported for *Cordia americana*, *Gochnatia polymorpha*, *Inga uruguensis*, *Peltophorum dubium*, *Prunus sellowii* e *Zanthoxylum rhoifolium* (91.7%) and for *Solanum mauritianum* (90.3%). The species with faster growth were, by increasing order, *Mimosa scabrella, Trema micrantha, Solanum mauritianum* and *Croton urucurana*. With a better understanding of the initial developmental potential of tree species, it is possible to increase the species and functional diversity of the filling group. There was no single model capable of describing the variables analyzed and different models were needed to describe different characteristics and species.
Key words: subtropical forest, reforestation, mathematic models.

Avaliação da sobrevivência e modelagem do desenvolvimento inicial de árvores para restauração da Mata Atlântica

RESUMO: A restauração ecológica tornou-se uma importante atividade complementar para proteger os recursos naturais e conservar a biodiversidade. No entanto, as espécies nativas podem estar a ser utilizadas em programas de restauração de formas que não otimizam as suas características. O objetivo deste trabalho foi avaliar a sobrevivência e modelar o desenvolvimento inicial de 15 espécies arbóreas nativas plantadas em linhas de "preenchimento" e "diversidade" na fase de pós-plantio numa experiência de restauração nos subtrópicos da Mata Atlântica Brasileira. Avaliou-se a taxa de sobrevivência (%) um ano após o plantio e o diâmetro do colo (mm), a altura total (m), a área de projeção de copa (m²) e o volume de copa (m³) nos primeiros 48 meses após o plantio. A modelagem de crescimento para cada variável e espécie foi baseada nos modelos matemáticos não lineares: Logístico, Gompertz e Chapman-Richards. A seleção do modelo para cada variável/espécie teve como base o Critério de Informação de Akaike, erro padrão da estimativa e coeficiente de determinação. Os percentuais de sobrevivência mais altos foram para *Cordia americana*, *Gochnatia polymorpha*, *Inga uruguensis*, *Peltophorum dubium*, *Prunus sellowii* e *Zanthoxylum rhoifolium* (91,7%) e para *Solanum mauritianum* (90,3%). As espécies de crescimento mais rápido, por ordem crescente, foram: *Mimosa scabrella, Trema micrantha, Solanum mauritianum* e *Croton urucurana.* Com o conhecimento do potencial de desenvolvimento inicial das espécies, é possível aumentar a diversidade de espécies e funcional do grupo de preenchimento. Não houve um modelo único capaz de descrever todas as variáveis de desenvolvimento analisadas. Foram necessários diferentes modelos para descrever as diferentes características e as diferentes espécies.
Palavras-chave: floresta subtropical, reflorestamento, modelos matemáticos.

INTRODUCTION

The United Nations established 2021 to 2030 as the decade for ecosystem restoration to halt degradation and restore ecosystems to achieve global goals (UN, 2021). Ecosystem restoration becomes thus a political priority to "enhance people's livelihoods, counteract climate change, and stop the collapse of biodiversity" (UN, 2021).

Tropical forests are hotspots for biodiversity, but they are currently subject to several anthropogenic degradation processes, such as

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fragmentation, deforestation, and selective logging (MALHI et al., 2014; SAFAR et al., 2020), which results in losses of biodiversity (NEWBOLD et al., 2015; BARLOW et al., 2016; BEIROZ et al., 2019; HE et al., 2020) with serious effects on ecosystem functioning (TILMAN et al., 2014).

Deforestation in the Atlantic Forest in the last decades has caused habitat loss and degradation increasing fragmentation and biodiversity loss, in particular endemic species (SCHNEIDER et al., 2018). In recent years, there is an apparent stabilization in the Atlantic Forest which hides; however, increasing loss and fragmentation of mature forests and expansion of secondary growth forests in marginal farmland (ROSA et al., 2021). To respond to increasing degradation in Atlantic Forest ecosystems and landscapes, planting native species in "filling" and "diversity" lines is currently the most used forest restoration technique in Brazil (RODRIGUES et al., 2009; RODRIGUES et al., 2011; TRENTIN et al., 2018; TOPANOTTI et al., 2019; BRANCALION & HOLL, 2020). "Filling" lines have the goal of covering the ground to control the establishment of invasive weeds, providing at the same time crown heterogeneity and shade favoring the growth of the species from the "diversity" group. The "diversity" group is composed of a much higher number of tree species which is crucial to restoring forest dynamics (NAVE & RODRIGUES, 2007; RODRIGUES et al., 2009).

Tree species of low economic interest are usually left out in research (PAIVA-SOBRINHO & SIQUEIRA, 2008). However, to better understand how forest restoration processes occur and how possible it is to implement successful restoration programs, it is necessary to acquire information about the initial silvicultural development of native tree species used in restoration projects (STOLARSKI et al., 2018; BECHARA et al., 2016; TRENTIN et al., 2018). Growth modeling is an important tool in this regard since it allows the integration of observed data in mathematical or statistical models to describe how species are expected to grow over time contributing to increasing the current knowledge on tree species performance which is key in the selection of species to use in forest ecological restoration.

This study evaluated survival and model the initial development of 15 native forest species in the post-plant phase of a controlled restoration experiment in the Iguazu River basin, Parana State, South Brazil. With this study, we aimed to better understand species characteristics that can support their selection in successful restoration programs.

MATERIALS AND METHODS

Study area

The study was conducted in a 7.2 ha restoration experiment located on the campus of the Federal University of Technology – Paraná (UTFPR), Dois Vizinhos, Southwest of Paraná State, Brazil (25º41'44" S; 53º06'07" W) (Figure 1).

The study area is in the Araucaria Forest region in the transition zone of the Semideciduous Seasonal Forest. The climate is humid subtropical (Cfa), without a defined dry season and with an average temperature of the warmest month of 22 °C, according to Köppen's classification (ALVARES et al., 2018). According to IAPAR (2021), frost occurs frequently from June to September in the southwest region of Paraná. Here, the absolute minimum temperature (-5.0 ºC) was observed in July. Altitude ranges from 475 to 510 m and soils are Nitisols.

The landscape where the restoration area is located is dominated by agricultural production areas, pastureland, and small patches of remnant forest. In the north of the experimental area, there is a secondary forest area (40 ha) approximately 20-30 years old. In the south, there is an area of annual crop production (oats, wheat, beans, corn, and soybean). From 2006 to 2008 the restoration area was a pasture of *Cynodon nlemfuensis* and *Arachis pintoi*. In 2009 the area was used for annual crops until the last harvest on October 15, 2009. On October 20, 2010, the area was isolated from disturbances and the restoration.

The experiment was established in December 2010 (BECHARA et al., 2016). For that the area was divided into four blocks where three ecological restoration treatments were implemented. The experimental design included 10 filling species and 60 diversity species, based on the minimum number of plants per species according to the size of the experimental area (RODRIGUES et al., 2009). All trees were planted at a spacing of 3 x 2 m in four plots of 54 x 40 m (one in each block) (Figure 1). In each plot, 18 filling and 3 diversity seedlings were planted.

At the time of plantation, seedlings, 30 to 50 cm in height, were fertilized with 36 g of NPK (5-20-10) + 40 g of urea, and three liters of hydrogel was applied in the holes. The control of leaf-cutting ants was carried out using baits applied every six months until 30 months after initial planting. The soil was protected with cardboard mulching and biannually, weeds were controlled by mechanical cutting followed by chemical weeding until the third year (GERBER et al., 2020). Dead plants were replanted twice until 12 months after initial planting.

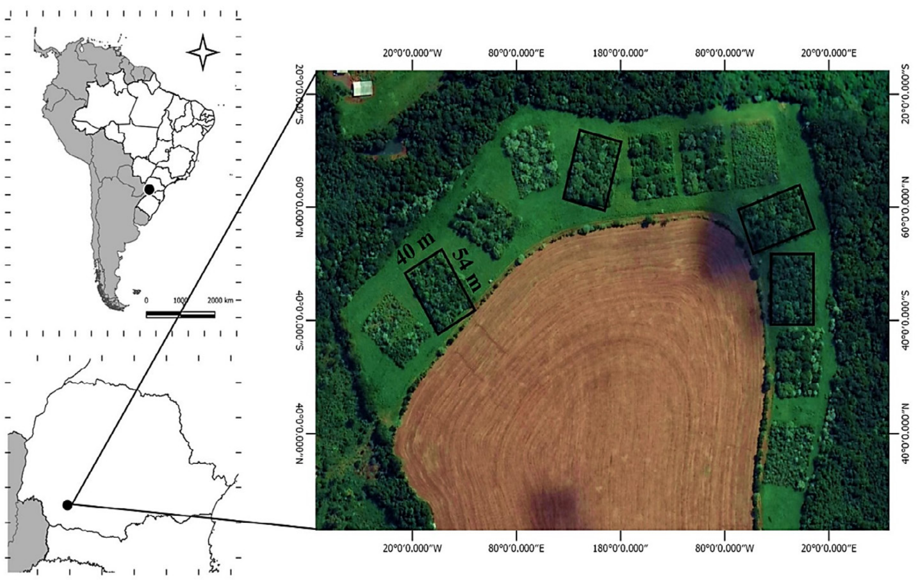

Figure 1 - Experimental restoration site at the Federal University of Technology - Paraná – Dois Vizinhos, Brazil. Plots marked in black refer to the filling and diversity planting lines treatment considered in this study.

For this study we selected 15 out of the 70 species in the experiment, according to their rate of growth. Eight were filling (*Schinus terebinthifolius* Raddi., *Trema micrantha* (L.) Blume., *Croton floribundus* Spreng., *Croton urucurana* Baill., *Bauhinia forficata* Link., *Mimosa scabrella* Benth., *Guazuma ulmifolia* Lam. and *Solanum mauritianum* Scop.) and seven diversity species (*Gochnatia polymorpha* (Less.) Cabrera, *Cordia americana* (L.) Gottschling & J.S.Mill, *Cordia trichotoma* (Vell.) Arráb. ex Steud., *Inga uruguensis* Hook. & Arn., *Peltophorum dubium* (Spreng.) Taub., *Prunus sellowii* Koehne and *Zanthoxylum rhoifolium* Lam).

Data collection

Data was collected for survival once on December 2010, 12 months after planting, and biannually for growth variables, such as collar diameter (cd), total height (h), crown height (ch) and crown diameter (dl and de), up to 48 months after planting.

Survival rate was calculated as the percentage of individuals in each species that survived one year after planting. Growth was assessed based on variation over time of the growth variables measured (cd, h, ch, dl and de). Collar diameter was measured using a digital pachymeter, positioned at the collar of the plant, near the soil surface. Total height was measured with a graduated scale at 0.05 cm intervals positioned vertically as close as possible to the tree. Total height was the distance between the base of the tree at the soil level and its uppermost point in the crown. The crown projection area was obtained by measuring the diameter of the crown with a tape measure based on two measurements, the first in the direction of the length of the plot (X) and the second (Y) perpendicular to it.

The crown projection area was later estimated through the ellipse area formula (SANTOS et al., 2015; STOLARSKI et al., 2018) (Equation 1):

$$ca\ (m^2) = dl.de.\pi/4 \quad (1)$$

where *ca* is the crown projection area, and *dl* and *de* are the crown diameters (m) measured in two perpendicular directions.

Crown volume was estimated, assuming that it is well described by an elliptical cylinder, multiplying the crown projection area by its height (KOIZUMI & HIRAI, 2006; SPINELLI et al., 2010; STOLARSKI et al., 2018) (Equation 2):

$$cv\ (m^3) = ca.ch \quad (2)$$

where *cv* is the crown volume, *ca* is the crown projection area, and *ch* is the crown height.

Growth models

The species' growth in collar diameter, total height, crown projection area, and crown volume was evaluated through three growth functions, which are normally used in forest modeling, such as Logistic, Gompertz, and Chapman-Richards. These have great explanatory power and are commonly applied in forest science. In forestry, they have been widely applied to describe the growth of dendrometric variables of species with timber potential (PÖDÖR et al., 2014; VENDRUSCOLO et al., 2017; SILVA et al., 2018) as well as to describe hypsometric relations (ALVES et al., 2017; ANDRADE, 2017; MACHADO et al., 2019).

These models are described by equations 3 to 5 (BURKHART & TOMÉ, 2012):

Logistic: $y = \beta_0 / [1 + e^{((\beta 1 - x)/\beta 2)}]$ (3)

where y is the predictable variable, β_0 is the asymptote, β_1 is the x value in the inflection point of the curve, β_2 is a numerical scale parameter in the input axis and x is the independent variable (age).

Gompertz: $y = \beta_0 * e^{(-\beta 1 * \beta 2\hat{}x)}$ (4)

where y is the predictable variable, β_0 is the asymptote, β_1 the function at x = 0, β_2 is a numerical parameter related to the scale in x-axis, and x is the numerical vector of input values (age).

Chapman-Richards: $y = \beta_0 * [(1 - e^{(-\beta 1 * x)})^{\beta 2}]$ (5)

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

Model selection for each species and variable was based on criteria such as coefficient of determination (R^2), standard error of the estimate (S_{yx}%), and Akaike Information Criteria (AIC) in addition to the biological interpretation of the parameters. The selected model must present the lowest AIC and S_{yx} and the highest R^2. These information criteria are usually applied in regression model selection (AKAIKE, 1973; SCHWARZ, 1978). All statistical analyses were performed in R (R CORE TEAM, 2020).

Cluster analysis

A cluster analysis was conducted to group tree species according to growth characteristics, in particular, mean increment in collar diameter (cd), total height (h), crown projection area (ca), and crown volume (cv), for the whole evaluation period (48 months). We used the nearest neighbor grouping method with the Mahalanobis distance as a dissimilarity measure. Cluster analyses were performed in R (R CORE TEAM, 2020).

RESULTS

Survival

The survival rate of the species evaluated 12 months after planting was in general high (>70%) or very high (>90%) (Table 1), according to levels of survival proposed by Carvalho (1982) when evaluating the silvicultural performance of native forest species in a subtropical forest in South Brazil, at 84 months of age.

According to the classification in table 1, seven species (47% of the species) showed survival rates above 90% (group 1), as follows: *C. americana, G. polymorpha, I. uruguensis, P. dubium, P. sellowii, Z. rhoifolium* and *S. mauritianum*.

Growth assessment

In ascending order, *M. scabrella, T. micrantha, S. mauritianum*, and *C. urucurana* showed the highest growth rates among all species for all variables (Figures 2 and 3; Supplementary Material). Differences between top-ranked species were often small. For instance, the mean height of *M. scabrella,* the species with the highest growth (7.56 ± 1.02 m), was just 15% higher than *S. mauritianum,* the species with the lowest (6.39 ± 0.76 m) growth. For crown projection area and volume, differences between the species with the largest and the smallest growth were also small: *T. micrantha* (34.65±8.55 m^2 and 135.65±38.29 m^3) and *Z. rhoifolium* (7.51±1.80 m^2 and 27.31±4.21 m^3), respectively.

Growth models

Based on the evaluation criteria applied for all species, the Logistic model showed the best fit for collar diameter for 8 of the 15 assessed species (*C. urucurana, B. forficata, I. uruguensis, G. ulmifolia, G. polymorpha, T. micrantha, P. dubium*, and *C. trichotoma*) (Table 2). The Gompertz model was the best to describe collar diameter growth for *C. floribundus*, *M. scabrella, Z. rhoifolium, S. mauritianum, P. sellowii*, and *C. americana*, and the Chapman-Richards model showed the best performance only for *S. terebinthifolius.*

Regarding total height, the Gompertz model presented the best fit for 11 out of 15 species (*S. terebenthifolius, C. urucurana, C. floribundus, B.*

Table 1 - Survival rate (%) after 12 months, and average growth in collar diameter (mm), total height (m), crown projection area (m^2) and crown volume (m^3) after 48 months of 15 tree species in a restoration experiment in Dois Vizinhos, Paraná, Brazil.

Species	Survival rate (%)	Group*	------cd (mm)-----		-------h (m)-----		------ca (m²)-----		-------cv (m³)------	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
C. americana	91.7	1	50.23	±13.41	3.51	±0.40	3.32	±1.43	5.15	±2.51
G. polymorpha	91.7	1	79.06	±16.35	4.76	±0.88	10.47	±1.49	25.81	±5.86
I. uruguensis	91.7	1	104.52	±17.67	5.07	±0.79	17.18	±4.11	40.24	±10.76
P. dubium	91.7	1	99.70	±11.44	5.99	±0.95	9.25	±1.80	37.37	±13.75
P. sellowii	91.7	1	74.72	±17.50	5.30	±0.97	3.39	±1.09	10.69	±5.27
S. mauritianum	90.3	1	156.25	±40.12	6.39	±0.76	26.41	±6.56	101.42	±30.38
Z. rhoifolium	91.7	1	106.87	±10.29	6.62	±0.72	7.51	±1.80	27.31	±4.21
B. forficata	86.1	2	74.88	±13.69	4.94	±0.69	6.05	±1.95	16.97	±6.30
C. trichotoma	86.1	2	78.30	±16.48	4.64	±1.04	5.05	±2.01	10.68	±3.64
C. urucurana	86.1	2	112.68	±15.75	6.92	±0.75	26.63	±7.77	98.36	±30.93
G. ulmifolia	88.9	2	126.19	±28.77	6.93	±1.21	14.01	±4.36	48.76	±21.02
M. scabrella	88.9	2	205.71	±56.27	7.56	±1.02	20.99	±5.53	72.16	±24.01
T. micrantha	86.1	2	158.35	±41.15	7.33	±0.83	34.65	±8.55	135.65	±38.29
C. floribundus	63.9	3	108.04	±26.34	6.63	±1.07	16.23	±5.90	57.21	±28.57
S. terebinthifolius	59.7	3	103.63	±19.20	4.78	±0.62	14.48	±4.60	35.61	±12.91

cd = collar diameter; h = total height; ca = crown projection area; cv = crown volume; SD = standard deviation. *Group classification according to Carvalho (1982).

forficata, I. uruguensis, G. ulmifolia, Z. rhoifolium, S. mauritianum, G. polymorpha, T. micrantha, and *P. sellowii*), the Logistic model for *P. dubium, C. americana* and *C. trichotoma*, and Chapman-Richards for *M. scabrella* (Table 3).

For the crown projection area (Table 4), the Gompertz model performed better for 8 of the 15 species (*C. urucurana, M. scabrella, Z. rhoifolium, S. mauritianum, G. polymorpha, T. micrantha, P. sellowii*, and *C. americana*) and the Chapman-Richard for *S. terebinthifolius, C. floribundus, B. forficata, I. uruguensis, G. ulmifolia, P. dubium,* and *C. trichotoma*. The Logistic model was not the best-fit one for any of the species in this variable.

The Chapman-Richards model presented the best fitting statistics for crown volume in 12 species, as follows: *S. terebinthifolius, C. urucurana, B. forficata, M. scabrella, I. uruguensis, G. ulmifolia, Z. rhoifolium, G. polymopha, T. micrantha, P. dubium, C. americana*, and *C. trichotoma* (Table 5). The Gompertz model was the best to describe crown volume for *S. mauritianum* and *P. sellowii* while the Logistic model showed the best fitting performance only for *C. floribundus*.

The model fitting criteria scores for crown volume are associated with the high standard error of the estimates, which varied from 51.1 to 101.6% (Logistic), 50.9 to 101.6% (Gompertz), and 61.4% to 103.6% (Chapman-Richards), due to the high variability of the dataset.

Cluster grouping

The hierarchical relationship of the 15 species plotted in the dendrogram of figure 4, enabled the establishment of three major groups of species based on their average growth in collar diameter, total height, crown projection area and volume during the evaluation period. As mentioned before and confirmed by the cluster analysis, the species *M. scabrella* showed the highest growth performance, and it compounded one group by itself. The other species were divided into two different groups.

DISCUSSION

Survival

Cordia americana, *G. polymorpha*, *I. uruguensis, P. dubium*, *P. sellowii*, *Z. rhoifolium*, and *S. mauritianum*, showed a survival rate greater than 90%. This indicated that these species were tolerant to stress caused by frost. According to the criteria

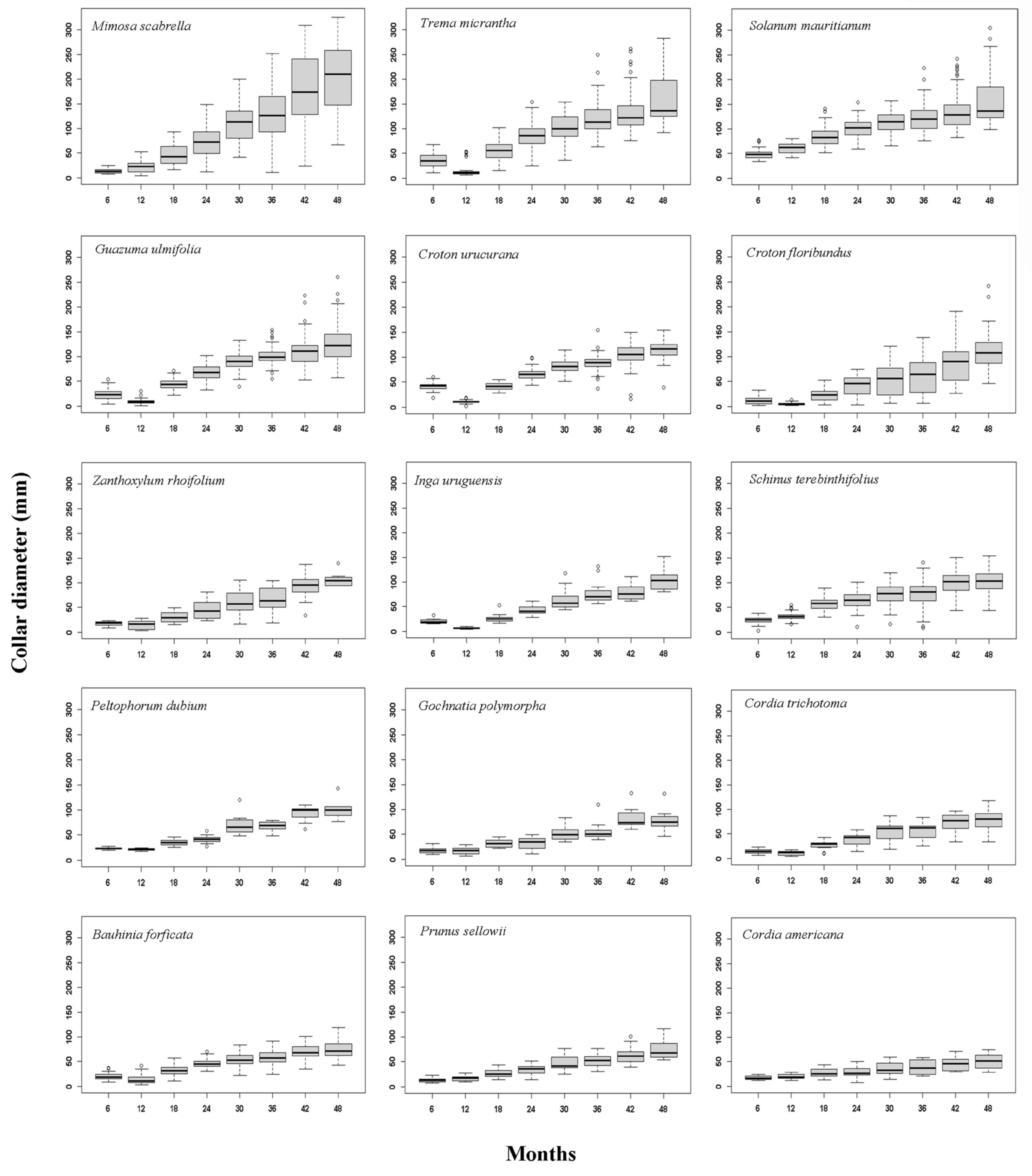

Figure 2 – Boxplots of collar diameter (mm) of 15 tree species over 48 months in a restoration experiment in Dois Vizinhos, Paraná, Brazil. Boxplots show median, quartiles, and outlier values.

established by HIGA et al., (2000) and CARON et al., (2011), tolerant species present 25-100% damage to leaf area and <25% of damage to stem, conditions found in the study. These species presented more rusticity and the ability to endure stressful conditions within bearable boundaries, as they are colonizing

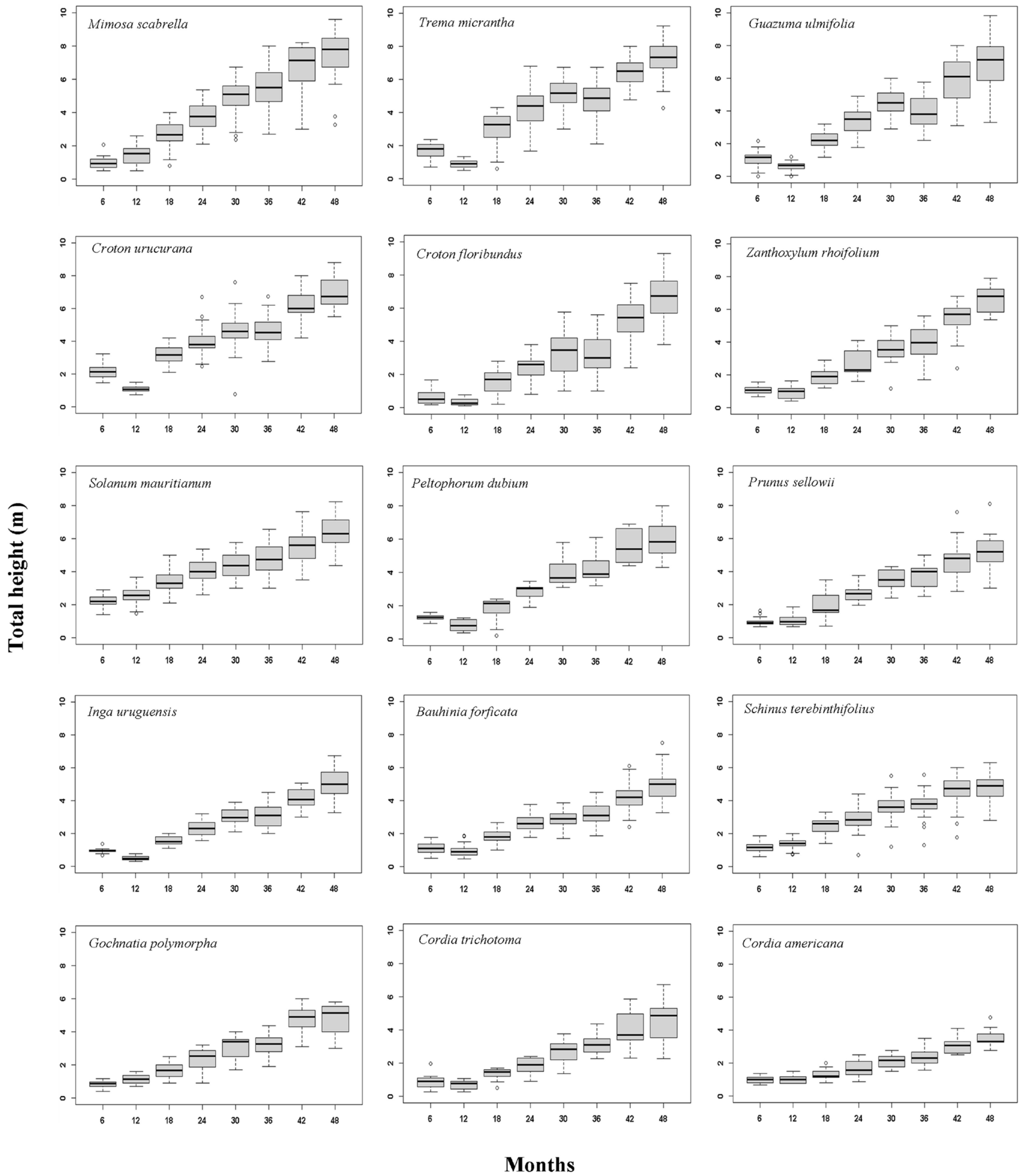

Figure 3 – Boxplots of total height (m) of 15 tree species over 48 months in a restoration experiment in Dois Vizinhos, Paraná, Brazil. Boxplots show median, quartiles, and outlier values.

species of degraded environments (STOLARSKI et al., 2018). The survival rate (91.7%) of *I. uruguensis* was relatively high in this study. VIEIRA et al. (2003), reported a survival rate of 94% when assessing the species' survival after frost in Florianópolis. Similarly, the high survival success of *C. americana* is emphasized by POESTER (2012), who observed survival rates of 94% eight months after planting.

Table 2 - Models' parameters and fitting statistics for collar diameter (mm) by species.

Species	Logistic					
	β_0	β_1	β_2	S_{yx} (%)	R^2	AIC
B. forficata *	82.291	23.293	11.096	26.9	0.73	3,882.492
C. americana	74.419	32.372	21.784	34.7	0.49	897.843
C. floribundus	186.580	44.247	13.430	52.6	0.60	4,000.305
C. trichotoma *	87.075	26.728	10.014	34.8	0.72	791.905
C. urucurana *	135.798	26.803	12.516	26.4	0.74	4,082.695
G. polymorpha *	118.814	35.282	14.291	36.0	0.68	690.935
G. ulmifolia *	125.248	23.516	7.619	32.6	0.76	4,763.732
I. uruguensis *	114.309	28.888	9.714	34.2	0.76	735.989
M. scabrella	257.520	33.838	10.343	45.0	0.64	4,413.369
P. dubium *	149.370	36.522	15.805	23.1	0.82	665.979
P. sellowii	97.422	32.375	13.724	32.7	0.73	845.385
S. mauritianum	183.630	22.150	16.540	27.9	0.58	4,893.702
S. terebinthifolius	113.875	3.529	2.056	27.0	0.68	4,919.210
T. micrantha *	175.806	26.671	10.906	35.1	0.67	4,539.595
Z. rhoifolium	156.298	37.454	13.752	37.0	0.70	755.397
Gompertz						
Species	β_0	β_1	β_2	S_{yx} (%)	R^2	AIC
B. forficata	97.319	2.654	0.952	26.9	0.73	3,885.56
C. americana *	107.197	2.101	0.979	34.7	0.49	897.75
C. floribundus *	419.400	4.549	0.975	52.5	0.60	3,998.56
C. trichotoma	107.331	3.454	0.950	34.9	0.71	792.35
C. urucurana	193.800	2.690	0.996	26.7	0.73	4,093.01
G. polymorpha	222.403	3.287	0.974	36.1	0.67	691.68
G. ulmifolia	141.000	4.429	0.929	32.7	0.75	4,768.86
I. uruguensis	155.088	3.826	0.954	34.4	0.76	737.07
M. scabrella *	364.100	4.489	0.957	44.9	0.65	4,412.55
P. dubium	294.000	3.159	0.977	23.2	0.82	666.75
P. sellowii *	146.433	3.052	0.969	32.7	0.73	845.20
S. mauritianum *	214.799	1.821	0.965	27.8	0.58	4,891.98
S. terebinthifolius	127.372	2.232	0.745	26.8	0.67	4,914.33
T. micrantha	223.700	3.110	0.955	35.1	0.66	4,541.37
Z. rhoifolium *	284.672	3.627	0.972	37.0	0.70	755.28
Chapman-Richards						
Species	β_0	β_1	β_2	S_{yx} (%)	R^2	AIC
B. forficata	208.000	0.009	0.981	27.3	0.72	3,897.95
C. americana	71.428	0.020	0.816	35.4	0.47	902.50
C. floribundus	295.918	0.020	2.245	52.8	0.60	4,002.77
C. trichotoma	172.000	0.018	1.460	35.2	0.71	793.89
C. urucurana	238.717	0.013	1.000	26.1	0.68	3,870.86
G. polymorpha	250.000	0.011	1.260	36.9	0.66	695.27
G. ulmifolia	148.000	0.058	2.900	33.0	0.75	4,778.31
I. uruguensis	285.000	0.015	1.620	34.9	0.75	739.51
M. scabrella	763.000	0.014	1.900	45.0	0.65	4,412.88
P. dubium	194.000	0.020	1.430	25.0	0.79	679.30
P. sellowii	143.000	0.020	1.430	33.4	0.72	849.56
S. mauritianum	214.286	0.020	0.816	28.2	0.57	4,906.36
S. terebinthifolius *	281.00	0.007	0.797	26.8	0.69	4,913.04
T. micrantha	668.000	0.007	1.140	35.4	0.66	4,549.38
Z. rhoifolium	224.000	0.020	1.630	37.7	0.69	758.68

Note: β = non-linear regression parameters; S_{yx} = standard error of the estimate (%); R^2 = coefficient of determination; AIC = Akaike's Information Criterion; * best fitting.

Table 3 - Models' parameters and fitting statistics for total height (m) by species.

Species	Logistic					
	β_0	β_1	β_2	S_{yx} (%)	R^2	AIC
B. forficata	8.495	42.690	18.256	22.4	0.82	908.03
C. americana *	12.120	69.970	25.050	21.4	0.82	135.26
C. floribundus	16.051	53.479	15.246	35.0	0.77	1,277.35
C. trichotoma *	6.524	35.903	13.288	31.0	0.78	218.18
C. urucurana	9.980	34.255	17.316	22.2	0.78	1,246.76
G. polymorpha	6.727	34.017	14.164	27.6	0.78	183.74
G. ulmifolia	8.187	30.718	11.587	29.7	0.80	1,532.15
I. uruguensis	7.605	38.721	14.804	25.7	0.83	172.57
M. scabrella	8.702	27.889	11.406	23.2	0.80	1,220.01
P. dubium *	7.451	30.336	12.307	24.8	0.82	210.29
P. sellowii	6.278	28.354	12.197	27.4	0.79	254.01
S. mauritianum	11.031	41.029	25.940	17.4	0.77	1,123.60
S. terebinthifolius	5.359	22.036	11.972	19.4	0.82	1,038.09
T. micrantha	8.371	26.748	12.685	23.8	0.78	1,340.54
Z. rhoifolium	13.837	49.939	17.066	27.0	0.81	220.94
Gompertz						
Species	β_0	β_1	β_2	S_{yx} (%)	R^2	AIC
B. forficata *	16.949	3.240	0.980	22.3	0.82	904.30
C. americana	5.714	2.755	0.965	22.7	0.79	149.47
C. floribundus *	61.892	5.172	0.983	34.9	0.78	1,274.03
C. trichotoma	12.207	3.575	0.972	31.1	0.77	218.84
C. urucurana *	15.832	2.667	0.976	22.1	0.78	1,245.43
G. polymorpha *	10.411	3.129	0.970	27.6	0.78	183.70
G. ulmifolia *	10.603	3.491	0.958	29.4	0.80	1,520.97
I. uruguensis *	13.860	3.500	0.974	25.5	0.83	171.71
M. scabrella	10.500	3.237	0.954	23.0	0.80	1,213.32
P. dubium	10.953	3.125	0.965	23.0	0.81	211.69
P. sellowii *	8.300	2.957	0.961	27.4	0.79	253.89
S. mauritianum *	17.987	2.297	0.983	17.3	0.77	1,121.15
S. terebinthifolius *	6.124	2.356	0.952	19.4	0.82	1,036.97
T. micrantha *	10.323	2.715	0.959	23.6	0.79	1,334.03
Z. rhoifolium *	47.211	4.350	0.983	26.9	0.81	220.44
Chapman-Richards						
Species	β_0	β_1	β_2	S_{yx} (%)	R^2	AIC
B. forficata	18.000	0.007	1.080	23.1	0.80	939.72
C. americana	6.122	2.771	2.209	25.3	0.74	174.54
C. floribundus	18.367	0.020	2.244	35.7	0.77	1,293.23
C. trichotoma	15.000	0.012	1.470	31.9	0.76	223.61
C. urucurana	15.758	0.009	0.862	21.5	0.75	1,177.63
G. polymorpha	11.500	0.015	1.330	28.2	0.77	186.91
G. ulmifolia	65.900	0.003	1.24	29.4	0.80	1,521.42
I. uruguensis	13.400	0.014	1.450	26.4	0.82	177.29
M. scabrella *	19.500	0.013	1.310	23.0	0.81	1,211.88
P. dubium	8.163	0.040	2.244	26.8	0.79	222.70
P. sellowii	10.200	0.020	1.430	28.0	0.78	258.60
S. mauritianum	6.122	0.041	0.816	19.8	0.70	1,258.46
S. terebinthifolius	13.800	0.007	0.845	19.6	0.82	1,047.01
T. micrantha	18.872	0.010	1.034	23.8	0.78	1,341.50
Z. rhoifolium	14.300	0.020	1.840	28.7	0.79	231.48

Note: β = non-linear regression parameters; S_{yx} = standard error of the estimate (%); R^2 = coefficient of determination; AIC = Akaike's Information Criterion; * best fitting.

Table 4 - Models' parameters and fitting statistics for crown projection area (m²) by species.

Species	β_0	β_1	β_2	S_{yx} (%)	R^2	AIC
			---Logistic---			
B. forficata	5.163	22.106	4.569	59.9	0.53	2,013.95
C. americana	4.181	37.178	8.095	77.7	0.58	330.87
C. floribundus	23.455	40.462	8.746	76.2	0.57	2,574.35
C. trichotoma	4.694	28.386	6.591	60.1	0.63	323.65
C. urucurana	31.451	31.932	8.882	56.6	0.62	3,198.59
G. polymorpha	11.939	29.466	7.786	36.4	0.80	340.59
G. ulmifolia	13.418	26.957	6.899	56.5	0.64	2,834.60
I. uruguensis	19.536	33.353	8.568	49.7	0.74	460.00
M. scabrella	20.823	29.196	5.539	54.3	0.65	2,618.33
P. sellowii	5.045	40.123	11.849	54.1	0.66	245.75
S. mauritianum	25.553	20.662	4.969	37.4	0.70	3,301.24
S. terebinthifolius	13.742	23.455	6.671	46.7	0.64	3,083.91
T. micrantha	109.168	60.431	15.549	54.1	0.64	3,238.47
Z. rhoifolium	12.149	42.925	9.603	56.4	0.71	320.78
			---Gompertz---			
Species	β_0	β_1	β_2	S_{yx} (%)	R^2	AIC
B. forficata	5.448	13.192	0.876	59.7	0.53	2,011.20
C. americana *	6.600	7.199	0.950	77.7	0.58	330.71
C. floribundus	41.861	7.127	0.958	76.1	0.57	2,573.01
C. trichotoma	5.358	8.782	0.919	59.4	0.64	321.50
C. urucurana *	37.504	5.822	0.941	56.1	0.62	3,189.29
G. polymorpha *	14.173	6.037	0.935	36.3	0.80	340.09
G. ulmifolia	14.800	7.869	0.917	55.6	0.65	2,818.84
I. uruguensis	23.127	6.764	0.939	48.8	0.75	456.83
M. scabrella *	23.154	14.916	0.903	54.2	0.65	2,616.81
P. sellowii *	9.557	4.593	0.969	54.0	0.66	245.01
S. mauritianum *	26.383	10.466	0.846	37.4	0.70	3,299.65
S. terebinthifolius	14.948	6.031	0.915	46.3	0.64	3,075.67
T. micrantha *	233.100	5.177	0.979	53.9	0.64	3,234.06
Z. rhoifolium *	31.400	6.459	0.968	56.4	0.71	320.61
			---Chapman-Richards---			
Species	β_0	β_1	β_2	S_{yx} (%)	R^2	AIC
B. forficata *	5.500	0.123	10.800	59.7	0.53	2,010.99
C. americana	9.370	0.030	3.840	77.6	0.58	330.74
C. floribundus *	84.300	0.020	3.370	76.1	0.57	2,572.53
C. trichotoma *	5.740	0.069	5.820	59.3	0.64	321.20
C. urucurana	38.000	0.047	3.480	54.2	0.60	3,001.20
G. polymorpha	15.700	0.050	3.650	36.3	0.80	340.23
G. ulmifolia *	15.800	0.070	5.130	55.5	0.65	2,816.26
I. uruguensis *	27.700	0.043	3.860	48.6	0.75	456.08
M. scabrella	23.500	0.095	12.300	54.2	0.65	2,616.91
P. dubium *	30.612	0.020	2.869	57.0	0.65	346.49
P. sellowii	8.160	0.024	2.040	54.3	0.65	246.52
S. mauritianum	26.500	0.127	8.960	37.4	0.70	3,299.93
S. terebinthifolius	15.600	0.073	3.960	46.3	0.64	3,074.64
T. micrantha	97.895	0.017	2.069	54.1	0.64	3,237.01
Z. rhoifolium	38.800	0.020	3.470	56.5	0.71	320.94

Note: β = non-linear regression parameters; S_{yx} = standard error of the estimate (%); R^2 = coefficient of determination; AIC = Akaike's Information Criterion; * best fitting.

Table 5 - Models' parameters and fitting statistics for crown volume (m³) by species.

Species						
	----Logistic----					
	β_0	β_1	β_2	S_{yx} (%)	R^2	AIC
C. floribundus *	116.883	48.151	8.218	101.6	0.52	3,706.60
C. trichotoma	13.060	36.857	7.288	63.2	0.70	449.76
G. polymorpha	32.798	36.358	8.375	51.1	0.75	505.31
G. ulmifolia	62.265	36.249	8.709	82.1	0.54	4,405.75
I. uruguensis	54.082	38.432	8.388	61.9	0.71	624.54
M. scabrella	70.072	31.051	5.611	69.0	0.58	3,755.39
P. sellowii	28.935	53.099	9.740	80.3	0.65	495.48
S. terebinthifolius	33.428	27.867	8.195	67.5	0.51	4,317.77
----Gompertz----						
Species	β_0	β_1	β_2	S_{yx} (%)	R^2	AIC
C. floribundus	100.500	9.187	0.975	101.6	0.52	3,706.75
C. trichotoma	18.277	9.402	0.941	63.0	0.71	449.13
G. polymorpha	47.990	6.786	0.950	50.9	0.75	504.58
G. ulmifolia	79.546	6.922	0.945	81.6	0.55	4,400.16
I. uruguensis	80.179	7.471	0.951	61.5	0.71	623.51
M. scabrella	80.647	15.877	0.908	68.8	0.58	3,752.12
P. sellowii *	977.200	9.481	0.984	80.3	0.65	495.47
S. mauritianum *	950.300	5.103	0.984	65.0	0.51	4,797.85
S. terebinthifolius	38.461	5.458	0.934	66.9	0.52	4,307.72
----Chapman-Richards----						
Species	β_0	β_1	β_2	S_{yx} (%)	R^2	AIC
B. forficata *	149.280	0.013	3.088	94.1	0.46	2,961.55
C. americana *	44.897	0.020	4.693	89.5	0.58	408.82
C. floribundus	89.796	0.061	10.000	103.6	0.50	3,722.98
C. trichotoma *	21.300	0.046	5.950	63.0	0.71	449.05
C. urucurana *	195.900	0.0417	5.625	73.0	0.59	4,088.09
G. polymorpha *	68.000	0.030	3.550	50.9	0.75	504.43
G. ulmifolia *	103.000	0.036	3.790	81.5	0.55	4,398.57
I. uruguensis *	114.000	0.031	3.980	61.4	0.71	623.19
M. scabrella *	82.600	0.088	12.700	68.8	0.58	3,751.99
P. dubium *	100.000	0.041	7.347	77.1	0.68	590.64
P. sellowii	95.900	0.020	4.690	80.8	0.65	496.72
S. mauritianum	95.918	0.061	3.877	65.9	0.50	4,811.58
S. terebinthifolius *	47.200	0.042	2.820	66.8	0.52	4,304.56
T. micrantha *	887.692	0.018	3.621	69.8	9.61	4,498.77
Z. rhoifolium *	100.000	0.041	9.390	74.0	0.73	511.08

Note: β = non-linear regression parameters; S_{yx} = standard error of the estimate (%); R^2 = coefficient of determination; AIC = Akaike's Information Criterion; * best fitting.

The intermediate results of mortality registered for species in group 2 were probably due to frosts in the winter of 2011. Although, other factors affect survival, the data from the meteorological station at the Federal University of Technology - Paraná, Dois Vizinhos (Figure 5) strongly supports frost as the most likely factor contributing to the observed mortality. In 2011 frosts occurred in June, July, and

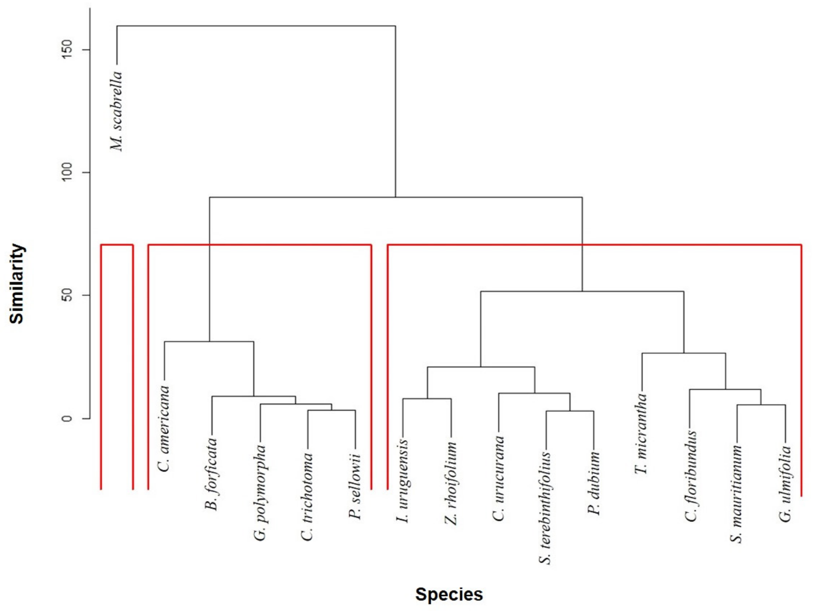

Figure 4 - Dendrogram of the cluster analysis (hierarchical, Euclidian distance) of dendrometric variables of 15 tree species in a restoration experiment, Dois Vizinhos, PR, Brazil.

August, with minimum absolute air temperature of -1.9, -0.1 and 1.0 ºC, respectively. Monthly rainfall was; however, relatively well distributed.

Our results suggested that frost might negatively affect the establishment of species in restoration initiatives, especially when only a few individuals are planted. The occurrence of less severe frost causes several physiological damages to the plants, which leads to a delay in their growth, particularly in the initial stages of development. The mortality rates for *C. floribundus* and *S. terebinthifolius* in this study were classified as high. This can indicate that the tolerance of these species frost in reforestation is low.

Growth assessment

Twelve and 36 months after planting, growth in total height, collar diameter, and crown projection area and volume dropped when compared to the previous period. The reduction in growth at month 12 occurred, probably, because of frosts in the winter season (Figure 5). In 2013, the frosts occurred in July and August, with minimum absolute air temperature of -2.4 and -1.8 ºC, respectively (GERBER et al., 2020). This is clearly visible in the case of collar diameter (Figure 2). However, at month 18, *G. polymorpha, C. trichotoma, T. micrantha, C. floribundus, C. urucurana, B. forficata, I. uruguensis, P. dubium, G. ulmifolia*, and *Z. rhoifolium* presented a considerable increase in collar diameter growth (Figure 2).

The height growth of the species at 12 and 36 months after planting also expresses the damages caused by frost in the apex of some individuals, reducing the mean height per species (Figure 3). By losing apical dominance, trees developed more than one lower branch but lost height. This emphasizes that these species are not so tolerant, but they are resilient to frosts due to their high sprouting capacity, as observed by GERBER et al. (2020).

Mimosa scabrella showed outstanding growth over the initial 48 months. The decrease in mean height increment at month 36 also happened due to winter frosts, but the species increased its height again 6 months later. This species is not considered tolerant to frosts (CARON et al., 2011), and damage caused by frosts can affect the apical meristem, which leads to bifurcation and, consequently, to a delay in the main tree axial growth (KOZLOWSKI et al., 1991).

For *T. micrantha*, a filling species, the crown projection area was five times larger than the planting spacing (6 m²), implying that it has great potential in controlling invasive grasses, an essential role in the establishment of new species in the under story (STOLARSKI et al., 2018).

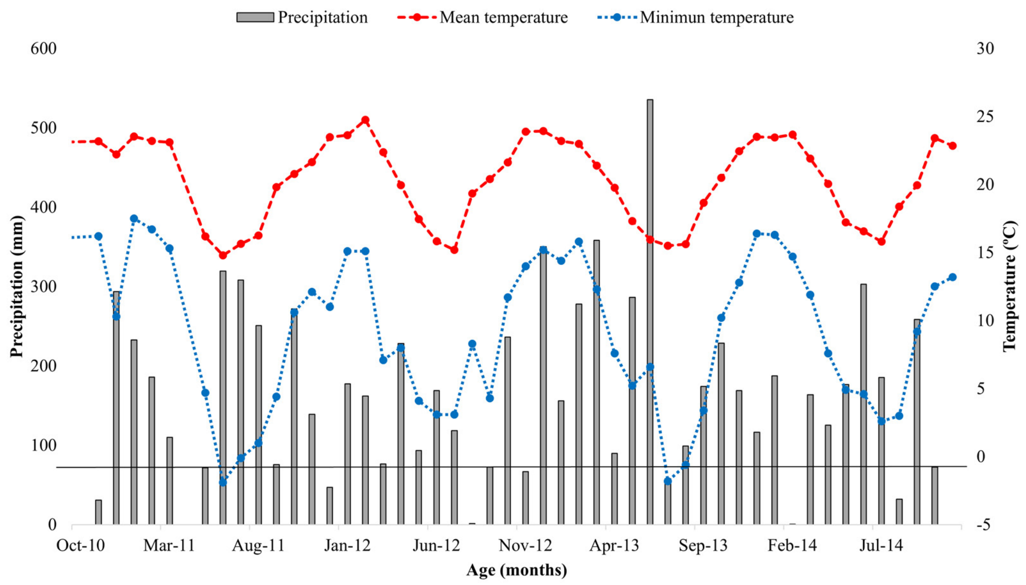

Figure 5 - Monthly rainfall (mm), mean temperature (ºC), and minimum absolute temperature (ºC) registered at the study area from October 2010 to November 2014.

In general, crown projection area and volume increased gradually over time (Supplementary material). There was an increase in the amplitude of the observed values due to the different levels of the species' development. Boxplots at 12 months showed less dispersion making the median to be lower than in other periods. Physical and physiological damage in cold-susceptible individuals during the period from May to September reduced their vegetative growth, probably resulting in the death of the aerial part of some plants, which was retaken after this period due to anatomical changes in the cambium region (SOUZA et al., 1991; GERBER et al., 2020).

In 2012, there was no frost in the region and plants grew normally, but in the months from June to August 2013, frost occurred again; consequently, causing a further reduction in growth in total height, crown projection area, and crown volume at 36 months. Even susceptible to frost, individuals of the 15 studied species managed to overcome competition with other tree species, occupying the upper layer of the canopy at month 42.

Growth modeling

Best models for each variable and species were selected based on the criteria AIC, R^2 and S_{yx}. It was possible to find a specific growth model fitted to each species and variable, noting that each species has different behavior in their growth. This pattern was observed especially in the first years of age when they are susceptible to different growth stimuli in the ecosystem undergoing restoration. However, it was not possible to fit the Logistical and Gompertz models to crown projection area for *P. dubium*. For crown volume, it was not possible to fit the Logistical and Gompertz models for *C. urucurana, B. forficata, Z. rhoifolium, T. micrantha, P. dubium* and *C. americana*.

There are few studies that analyze the long-term silvicultural performance of species of the Atlantic Forest using growth models. This is mainly due to the lack of long-term research on native Brazilian flora species. One of the biggest restrictions in this context concerns the lack of information on the growth of species in local restoration projects. Some of such studies are presented below.

TOPANOTTI et al. (2019) applied nonlinear regression models to estimate growth in collar diameter for three forest species with timber potential planted in a restoration area at 36 months. Here, the coefficient of determination was 0.76 for *Araucaria angustifolia* (Logistic model), 0.68 for *Balfourodendron riedelianum* (Logistic, 4 parameters) and 0.66 for *Parapiptadenia rigida* (Logistic, 4 parameters). MILANI et al. (2013) assessed diameter growth of 643 *Podocarpus lambertti* trees in different regions of southern Brazil and obtained a coefficient of determination of 0.85 using the Logistic model.

FIGUEIREDO-FILHO et al. (2017), using the Chapman-Richards model, assessed growth in diameter as a function of age for different regenerating native species, obtaining coefficients of determination of 0.67, 0.73, 0.74, 0.88, and 0.92 for *A angustifolia*, *Ocotea puberula*, *Cedrella fissilis*, *Clethra scabra*, and *Ilex paraguariensis*, respectively. The standard error of estimate varied between 15.23 and 30.57%. Similar results were reported for the Chapman-Richards model in our study, which ranged from 0.47 to 0.79 for the coefficient of determination, and from 24.99 to 52.80% for the standard error of the estimate. TONINI et al. (2003) used the Chapman-Richards model to describe the initial (nine years) growth of six Amazon Forest species, obtaining coefficient of determination values ranging from 0.63 to 0.79.

The logistic model was, in general, the best to describe collar diameter growth while the Gompertz model was better fitted for total height and crown projection area. The Chapman-Richards model showed the best performance for crown volume growth.

Models can be used in practice to describe the growth behavior of species and dendrometric variables and make short - to medium-term projections, aiming to point out their likely growth in the coming years. This is useful for the application of indicators and monitoring of forest restoration projects.

Cluster grouping

Three distinct groups were established for intermediate levels of similarity (or distance) in the cluster analysis (Figure 4). Due to its much faster growth in height, diameter and crown projection area, *M. scabrella* constituted an isolated group. The second group was formed by *C. americana*, *B. forficata*, *G. polymorpha*, *C. trichotoma*, and *P. sellowii*, species that showed the lowest performance of all in terms of growth of collar diameter, total height, and crown projection area and volume. The third group, the largest, included species with intermediate performance in the evaluated dendrometric variables and was formed into two clusters. The species *I. uruguensis*, *Z. rhoifolium*, *C. urucurana*, *S. terebinthifolius* and *P. dubium*, formed the first one and *T. micrantha*, *C. floribundus*, *S. mauritianum* and *G. ulmifolia*, were grouped in the second.

The fact that species of the Fabaceae family (*M. scabrella, P. dubium* and *I. uruguensis*) showed much higher growth than the others support the results from CHADA et al. (2004), in which the authors stated that species of this family show rapid growth in adverse environments mainly due to their ability to associate with mycorrhizal fungi and *Rhizobium* bacteria. Therefore, the species of this family are essential to ecological restoration projects. MACHADO et al. (2015) and BALIEIRO et al. (2017) suggest using fast-growing species that can generate N and C input to the degraded soil and consequently, increase the availability of other nutrients, organic matter, and promote nutrient recycling.

C. americana, B. forficata, *G. polymorpha*, *C. trichotoma*, and *P. sellowii* presented a slower growth, but their high percentage of survival added to the capability of most of these species to produce fruits favoring animals, make them of paramount importance in the ecosystem restoration process. According to ALMEIDA (2016) and BECHARA et al. (2016), the use of native fruit species in degraded areas is an interesting restoration tool to provide food and attraction to wildlife. This can be applied in areas close to forest fragments, where fruit production can encourage the movement of animals from surrounding forest areas to the area under restoration. These movements aim to bring propagules from the original forest to the recovering ecosystem.

CONCLUSION

The survival rate one year after planting was high for most species: 91.7% for *C. americana, G. polymorpha, I. uruguensis, P. dubium, P. sellowii* and *Z. rhoifolium*, and 90.2% for *S. mauritianum.* The lowest survival rate was observed for *C. floribundus* (63.9%) and *S. terebinthifolius* (59.7%).

From the filling species group, those that fulfill the role of presenting fast growth and high capacity as shading species were *M. scabrella*, *T. micrantha*, *S. mauritianum* and *C. urucurana*. However, *Z. rhoifolium* and *I. uruguensis*, classified as diversity species, presented desirable characteristics for filling species, that is, rapid growth in crown area and density.

It is expected that the selected species, especially in the filling group, will initially present a rapid growth that will help them to overcome the competition with grasses and to survive (and develop) even in face of abiotic adversity. Some species that were initially in the diversity group showed growth that suggests using them as filling species.

There was no single model capable of describing all the growth variables analyzed. Different models are needed to describe different characteristics of different species.

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DECLARATION OF CONFLICT OF INTEREST

We have no conflict of interest to declare.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to the conception and writing of the manuscript. All authors critically revised the manuscript and approved the final version.

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