Pesquisa Florestal Brasileira
Brazilian Journal of Forestry Research
http://pfb.cnpf.embrapa.br/pfb/
e-ISSN: 1983-2605
Articles

Non-linear growth models for tree species used for forest restoration in Brazilian Amazon Arc of Deforestation

Marcela de Castro Nunes Santos Terra[1], Marcos Gabriel Braz de Lima[1†], Juliano de Paulo dos Santos[1], Natielle Gomes Cordeiro[1*], Kelly Marianne Guimarães Pereira[2], Daniel Dantas[1], Natalino Calegario[1], Soraya Alvarenga Botelho[1]

[1]Universidade Federal de Lavras, Departamento de Ciências Florestais, Avenida Doutor Sylvio Menicucci, 1001, Aquenta Sol, CEP 37200-000 Lavras, MG, Brazil
[2]Universidade Federal de Lavras, Departamento de Ecologia e Conservação, Avenida Doutor Sylvio Menicucci, 1001, Aquenta Sol, CEP 37200-000 Lavras, MG, Brazil
†In memoriam

*Corresponding author:
natiellegcordeiro@gmail.com

Index terms:
Forest plantations
Logistic analysis
Modelling

Termos para indexação:
Florestas plantadas
Análise logística
Modelagem

Received in 31/01/2021
Accepted in 24/11/2021
Published in 13/06/2022

Abstract - The large amount of degraded areas and productive potential of the legal reserves in Brazil make restoration an environmental demand and a commercial opportunity. We modelled the diameter growth as a function of age of eight tree species in restoration plantations in the Brazilian Amazon. From 14 years of annual forest inventory data, for each species, we tested variations of logistic function: simple logistic, logistic with covariant (plant area at the time of planting), logistic with random effect, logistic with random effect and covariant. Amongst the studied species, *Schizolobium parahyba* var. *amazonicum*, *Tectona grandis* and *Simarouba amara* showed the highest growth rates while *Cordia alliodora*, *Cedrela odorata* and three species of the genus *Handroanthus* showed slower growth. The gains from using the covariant in modeling were small for both fixed and mixed-effect models. Gains from the inclusion of the random effect were substantial. Mixed-effect models had the best performance in modeling the growth of the species. Our results provide basis for a critical view of the criteria and possibilities for degraded areas restoration and management practices in legal reserves of the Amazon. An economic analysis is required to ensure the viability of these areas' sustainable exploitation.

Modelos de crescimento não linear para espécies de árvores usadas na restauração florestal no Arco do Desmatamento da Amazônia brasileira

Resumo - A grande quantidade de áreas degradadas e o potencial produtivo das reservas legais no Brasil tornam a restauração uma demanda ambiental e oportunidade comercial. Modelamos o crescimento do diâmetro em função da idade de oito espécies de árvores em plantações de recomposição na Amazônia brasileira. A partir de 14 anos de dados de inventário florestal anual, testamos variações da função logística: logística simples, logística com covariante (área da planta na época do plantio), logística com efeito aleatório, logística com efeito aleatório e covariante. As espécies *Schizolobium parahyba* var. *amazonicum, Tectona grandis* e *Simarouba amara* apresentaram as maiores taxas de crescimento, enquanto *Cordia alliodora, Cedrela odorata* e três espécies do gênero *Handroanthus* apresentaram crescimento mais lento. Os ganhos com o uso da covariante na modelagem foram pequenos para modelos de efeitos fixos e mistos. Os ganhos com a inclusão do efeito aleatório foram substanciais. Os modelos de efeitos mistos tiveram o melhor desempenho na modelagem do crescimento das espécies. Nossos resultados fornecem subsídios para uma visão crítica sobre os critérios, possibilidades de recomposição e práticas de manejo de áreas degradadas em reservas legais na Amazônia. Uma análise econômica é necessária para garantir a viabilidade da exploração sustentável dessas áreas.

https://doi.org/10.4336/2022.pfb.42e202102180

Introduction

Despite several initiatives for forest protection and conservation, deforestation and degradation are still serious environmental issues in Brazil. For instance, in January 2019 the Legal Amazon lost 108 km² of forests, an increase of 54% compared to the same period in 2018, according to data released by the Amazon Institute of Man and Environment (Imazon, 2019). This scenario of devastation has been reported in many international studies (e.g. Carvalho et al., 2019; Qin et al., 2019). Historically, deforestation, mainly for cattle ranching and grain production, has deteriorated the Brazilian Amazon, leaving many hectares of degraded areas (Gollnow et al., 2018). Currently, Brazil has 20 million ha of degraded areas in the Amazon (Zanetti & Souza, 2018) and, through the National Plan for Native Vegetation Recovery (Brasil, 2017), has committed to recover 12.5 million ha of native vegetation over the next 20 years, considering areas all over the Country (Brancalion et al., 2016). If restored, these areas will have high potential for ecosystem services, such as carbon sequestration and storage, with mitigation of global climate change effects, and in some cases generation of economic incomes for landowners.

Even facing the possibility of planting exotic species and commercially manage the legal reserve (LR) (Brasil, 2012), the rural landowner often chooses not to deal with it. There are many discouraging reasons, remarkably the lack of information and techniques for planting and maintaining the LR, lack of knowledge about the forest species production potential, and difficulties for forest inputs and supplies acquisition. A crucial technical information concerns the growth of different native and exotic tree species in these environments. We still know little about how tree species growth under different environmental conditions, different densities and planting consortia. Studies have been developed to describe the growth of tree species in the Amazon (Andrade et al., 2019) and other Brazilian vegetation domains (Scolforo et al., 2017). However, such studies commonly use information of only few field measurements, with relatively short intervals (Scolforo et al., 2017; Batista et al., 2020) or are reconstructions and simulations made from growth rings (Free et al., 2014; Cunha et al., 2016). Information from long-term forest inventories could shed light on the growth potential of tree species under measurable field conditions. This information combined with information on wood quality, multiple-uses of forests, phenology, and ecology of the species can be decisive when debating the suitability and feasibility of managing these species.

There are many proposed models for the tree growth description, most of them with sigmoidal tendency (Pödör et al., 2014). Among these models, the logistic function (Verhulst, 1838) has been widely used for growth and yield studies in different forest types, mainly due to its asymptotic shape with inflection point and parameters with biological interpretation (e.g. Mendonça et al., 2017). The use of a covariant in the parameters of this model may represent gains in the model fitting and allows testing other sources of variation to the response variable (Alves et al., 2017). This covariant may be, for example, site or competition indicators.

Another approach that has represented gains in forest modeling is that of mixed-effects models (Calegario et al., 2005). The possibility of working with longitudinal data (repeated measurements of each tree) with a nested structure has driven the use of mixed-effect models. Thus, the inclusion of a random effect element in modeling can reduce error because the random effect parameters explain the different sources of stochastic variability (Zobel et al., 2011). These models can capture the correlation between observations within the same group, which is often observed in this type of data. However, most of the growth models that bring these innovations have been developed and applied to temperate forests, and the lack of information for tropical forest species is remarkable.

Here, we gather information on eight tree species used in forest restoration of degraded areas in the Amazonian Arc of Deforestation assessed yearly for 14 years. Our main goals were to describe and to model the growth of these eight tree species by testing variations of the logistic model, fixed and mixed-effect approach, and covariant use.

Material and methods

Study area

Data were collected in ocated in Contriguaçu, northwest of Mato Grosso State, at the southern end of the Amazon rainforest, at São Nicolau farm, from Peugeot-Office National des Forêsts (Figure 1). Since 1998, this project manages over 2,000 ha of forest recomposition and restoration areas to capture and store the atmospheric carbon responsible for climate change (Arruda et al., 2010). The region is located in the Amazon domain, where *terra firme* and lowland rainforests are common, and areas with seasonal forests in the highest portions of the landscape are found (Brasil, 2012; Borges et al., 2014). The climate of the region according to Koppen classification is Am, tropical, hot and humid (Alvares et al., 2014), with an average temperature of 24 °C, relative humidity around 80% (Souza et al., 2013) and annual rainfall averages from 2,000 to 2,500 mm (Inmet, 2021).

Specifically, in the São Nicolau Farm (SNF), the annual rainfall average is 2,034 mm, with a dry season from April to September and a rainy season from October to March (Noronha et al., 2015). The predominant soils are Dystrophic Red Yellow Argisols characterized by base saturation < 50% (Santos et al., 2018). The forest recomposition plantations started in 1999 and continued annually during the rainy months until 2004. To operationalize the plantations, the study area was divided into plots with different dimensions, totaling 112 planting plots. Replanting was performed until the last year of reforestation. In all plots, the regeneration method was the planting of seedlings in total area, or enrichment in situations of greater expression of natural regeneration.

The present study used data from eight tree species (Table 1). Data collection in 134 permanent plots (50 x 20 m) began in 2003 and continued annually until 2017, totaling 14 years of annual measurements. All trees from the studied species were measured, totaling 4,217 trees sampled. The measurements were performed preferably between June and August of each year. Diameter at 1.3 m above ground level (DBH) and tree height were recorded using a tape measure and optical hypsometer, respectively. Data of the initial planting density of each plot were also used for the present study.

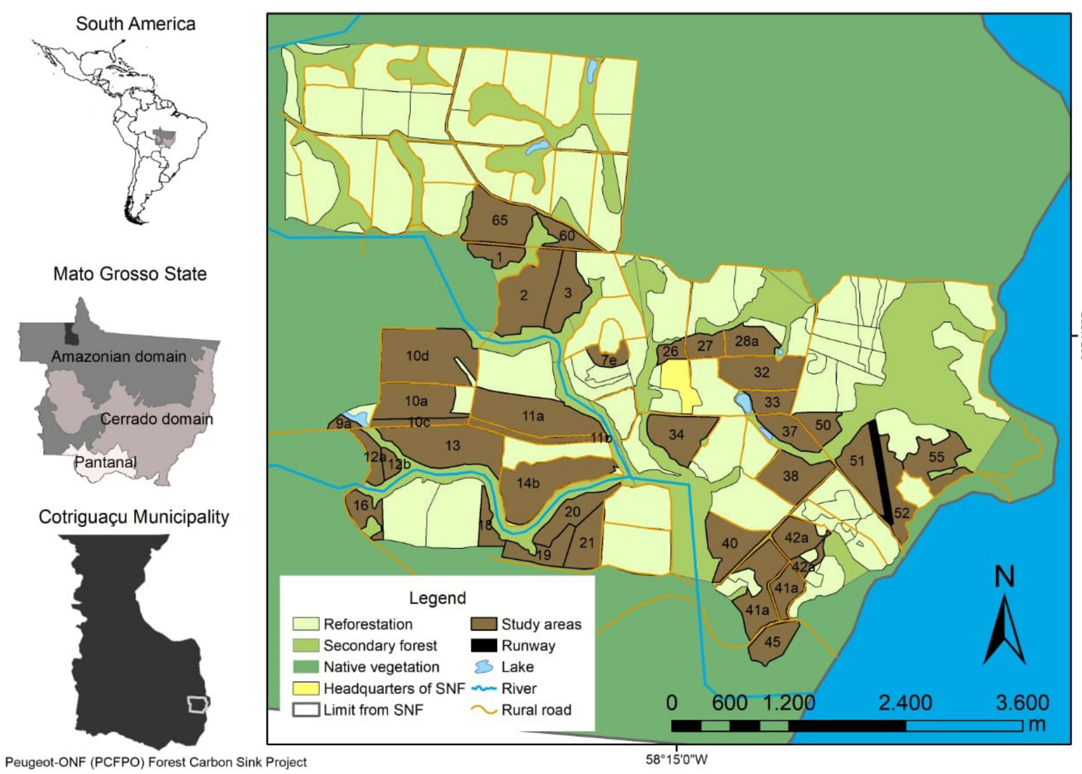

Figure 1. Study area location in São Nicolau Farm (SNF), Cotriguaçu, Mato Grosso State, Amazonian Arc of Deforestation, Brazil.

Table 1 Tree species used in forest restoration in the Brazilian Amazon Arc of Deforestation, evaluated in the present study.

Tree species	Family	Brazilian vernacular name	Origin	Commercial use	Number of trees
Cedrela odorata L.	Meliaceae	*Cedro rosa*	Native	Luxury furniture; musical instruments; medicinal; beekeeping	182
Cordia alliodora (Ruiz & Pav.) Cham.	Boraginaceae	*Freijó*	Native	Shipbuilding; furniture; cabinets; musical instruments	514
Handroanthus heptaphyllus (Vell.) Mattos	Bignoniaceae	*Ipê-rosa*	Native	Furniture; wood floor	1.687
Handroanthus impetiginosus (Mart. ex DC.) Mattos	Bignoniaceae	*Ipê-roxo*	Native		118
*Handroanthus serratifoli*us (Vahl) S.Grose	Bignoniaceae	*Ipê-amarelo*	Native		43
Schizolobium parahyba var. *amazonicum* (Huber ex Ducke) Barneby	Leguminosae	*Paricá*	Native	Multiple uses	179
Simarouba amara Aubl.	Simaroubaceae	*Caixeta*	Native	Paper; furniture; plywood and matches; construction; medicinal	285
Tectona grandis L.f.	Lamiaceae	*Teca, Teak*	Exotic (Asia)	Luxury furniture; shipbuilding; high standard frames	1.209

Growth modeling

We performed an exploratory data analysis with the inventory data, calculating the diameter at 1.3 m above ground level (DBH) descriptive statistics and mean annual increment (MAI), considering the last year of measurement for each species. The data collection was performed during an interval of 14 years (2003-2017). The field measurement's began when the trees were already 4 years old, ending at age of 18 years old (except to *C. odorata* - 16 years old). The MAI was calculated considering the species age at the last measurement (16 year to *C. odorata* or 18 years for the other species). For DBH growth modeling as a function of age by species, we tested variations of the logistic function: only with fixed effects – (1) simple logistic and (2) logistic with covariant - and mixed-effect models, using the individual trees as a random effect – (3) with and (4) without covariant (Table 2).

In the logistic function, the "A" parameter is the asymptote of the equation, which represents the maximum mean value of the response variable in time and its unit is the same as the response variable. The "I" parameter is the inflexion point of the curve, that is, the value of x at which the response is A/2 and represents the maximum growth rate of the organism. "E" is a scale parameter that represents the distance on the x-axis between the inflection point and the point at which the response is approximately 0.73A (Alves et al., 2017). The covariant tested on the asymptote (parameter A) was the area occupied by the plant at the time of planting, which is related to the idea of density/competition faced by the plant in the early stages of development. For the species *Handroanthus serratifolius*, no covariant was tested, since there was no variation in the

Table 2 Structure of the models used in the DBH growth modeling as a function of the age of eight tree species used in forest restoration at the Brazilian Amazon Arc of Deforestation.

Growth model	Equation
Logistic	$\frac{A}{\left(1+\exp\left(\frac{(I-age)}{E}\right)\right)}$
Logistic with covariant	$\frac{(A+cov)}{\left(1+\exp\left(\frac{(I-age)}{E}\right)\right)}$
Logistic – mixed effect	$\frac{A}{\left(1+\exp\left(\frac{(I-age)}{E}\right)\right)}$ | individual
Logistic – mixed, with covariant	$\frac{(A+cov)}{\left(1+\exp\left(\frac{(I-age)}{E}\right)\right)}$ | individual

A, I, E and cov are fitted parameters; A = asymptote; I = inflection; E = scale; cov = co-variant; individual = each tree measured. DBH = diameter at 1.3 m above ground level.

initial planting density (only one spacing was used).

The model's evaluation was performed based on the residual standard error (Syx), root mean square error (RMSE), Akaike information criterion (AIC) and residuals plots. All models were fitted and analyzed on the R platform (R Core Team, 2019), with qpcR (Spiess, 2018), nlme (Pinheiro et al., 2019) and tidyverse (Wickham, 2017) packages.

Results

All species presented positive average growth with higher (*Tectona grandis, Schizolobium parahyba* var. *amazonicum, Simarouba amara, Handroanthus heptaphyllus*) or lower (*Handroanthus impetiginosus*) sigmoidal tendency in the evaluated period (Figure 2; Table 3). The species *S. parahyba* var. *amazonicum, T. grandis* and *S. amara* presented the highest mean annual increment (MAI) values and the largest diameter averages at 18 years. *H. impetiginosus* had the lowest MAI and the lowest mean diameter at 1.3 m above ground level (DBH) at 18 years. The variability of diameters among individuals of each species was expressive and increasing over the years, reaching, for example, coefficient of variation (CV) of 77.5% at 17 years in *H. impetiginosus* (highest recorded CV). The fitted parameters of the models and their goodness-of-fit measures are presented in Table 4. Most of the fitted parameters were significant by the t-test ($p < 0.05$), except for the parameters of *H. impetiginosus* models and some punctual parameters of fixed and mixed-effect models of other species.

Overall, we observed a very small gain in the modeling using the covariant for most species within both approaches (fixed and mixed-effects), except *H. heptaphylus* for which covariant use in the mixed model showed no gain. Thus, the inclusion of the covariant in the models brought Syx average reduction gains of 0.39% in the fixed effect models and 0.22% reduction in the mixed-effect models. It is also possible to notice the outperformance of the mixed approach over the fixed effects approach, with Syx reductions of 69.6% and 69.8%, with and without covariant, respectively. Therefore, the mixed approach brought more substantial gains. For *H. impetiginosus*, the use of the mixed approach showed no remarkable gains

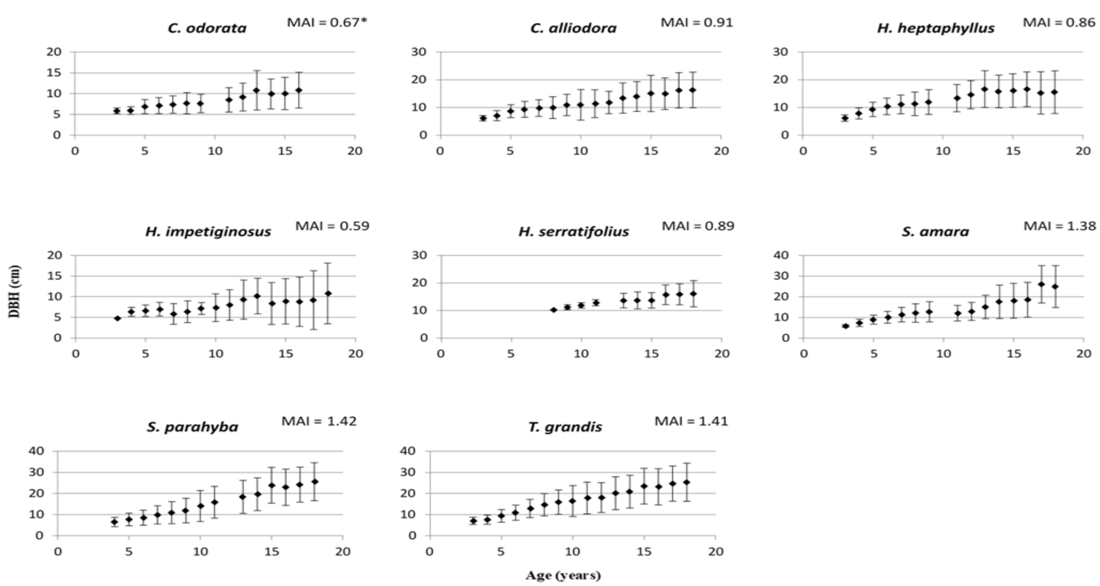

Figure 2. Average diameter at 1.3 m above ground - DBH (cm) (with standard deviation bars) over the different ages (years) and mean annual increment (MAI) at the age of 18 for eight tree species used for forest recomposition in the Brazilian Amazon Arc of Deforestation. *MAI at the age of 16.

Table 3. Average diameter at 1.3 m above ground - DBH (cm) over the different ages (years) and its coefficient of variation (CV%) of eight tree species used for forest recomposition in the Brazilian Amazon Arc of Deforestation.

Tree species		Age - time (years) since planting															
		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Cedrela odorata	DBH (cm)	5.9	5.9	6.9	7.1	7.4	7.7	7.6	-	8.5	9.2	10.8	9.9	10.0	10.8	-	-
	CV (%)	11.7	15.4	24.7	26.9	28.2	33.2	29.4	-	34.6	36.8	44.0	36.4	38.8	39.7	-	-
Cordia alliodora	DBH (cm)	6.1	7.0	8.7	9.3	9.8	9.9	10.9	10.9	11.3	11.8	13.4	13.9	15.1	15.0	16.2	16.3
	CV (%)	15.8	25.7	27.0	30.8	30.9	39.6	35.3	50.5	44.1	34.1	41.0	38.7	43.5	38.3	39.5	39.4
Handroanthus heptaphyllus	DBH (cm)	6.2	7.9	9.3	10.4	11.1	11.3	12.0	-	13.4	14.6	16.6	15.8	16.1	16.6	15.2	15.5
	CV (%)	19.1	25.3	27.8	28.9	30.6	37.7	37.2	-	36.8	35.0	39.9	37.4	37.7	37.8	50.3	49.6
H. impetiginosus	DBH (cm)	4.8	6.3	6.6	7.0	5.8	6.4	7.1	7.3	8.0	9.3	10.1	8.4	8.9	8.8	9.2	10.8
	CV (%)		17.1	21.1	23.5	43.3	41.3	20.0	45.7	46.2	51.1	42.5	60.7	61.9	68.0	77.5	68.2
H. serratifolius	DBH (cm)	-	-	-	-	-	10.2	11.1	11.8	12.8	-	13.6	13.6	13.7	15.7	15.9	16.1
	CV (%)	-	-	-	-	-	-	8.1	8.2	8.7	-	19.2	22.6	20.5	22.9	23.9	29.6
Schizolobium parahyba var. *amazonicum*	DBH (cm)	-	6.5	7.7	8.5	9.8	10.9	11.9	14.1	15.9	-	18.4	19.7	23.9	23.0	24.2	25.6
	CV (%)	-	22.2	22.7	28.5	32.5	36.7	38.7	42.5	44.8	-	43.5	42.7	41.4	42.8	42.3	40.9
Simarouba amara	DBH (cm)	5.8	7.4	8.9	10.1	11.3	12.1	12.7	-	12.1	12.9	15.1	17.6	18.1	18.5	26.0	24.9
	CV (%)	11.8	23.6	24.2	28.2	30.7	37.0	38.3	-	31.2	33.7	37.3	46.2	46.6	45.4	34.8	40.8
Tectona grandis	DBH (cm)	7.0	7.6	9.4	10.9	12.9	14.6	15.9	16.4	17.9	18.1	20.1	20.8	23.4	23.2	24.6	25.3
	CV (%)	24.2	29.0	31.9	33.1	33.5	35.9	36.3	44.6	42.2	39.2	38.9	37.3	36.1	37.0	33.8	35.7

Table 4. Growth model parameters (logistic model variations) fitted for each of the eight species used for forest recomposition in the Brazilian Amazon Arc of Deforestation.

Model	A	cov	I	E	RMSE	AIC	Syx
			Cedrela odorata				
fixed	18.59	-	12.18	11.92	3.16	7025.98	3.17
p-value	0.06	-	0.34	0.03			
fixed+cov	16.93	0.29	12.37	12.06	3.15	7020.30	3.16
p-value	0.06	0.13	0.35	0.03			
mixed	11.54	-	5.06	3.47	0.84	4868.96	0.94
p-value	0.00	-	0.00	0.00			
mixed+cov	7.36	0.65	5.11	3.46	0.84	4856.59	0.94
p-value	3×10^{-10}	2×10^{-4}	5×10^{-63}	1×10^{-139}			
			Cordia alliodora				
fixed	30.84	-	16.30	11.37	4.92	22318.29	4.92
p-value	0.00	-	0.01	0.00			
fixed+cov	23.98	0.15	12.88	10.55	4.90	22287.56	4.90
p-value	0.00	0.00	0.01	0.00			
mixed	14.71	-	6.11	2.20	1.60	17893.95	1.81
p-value	0.00	-	0.00	0.00			
mixed+cov	11.06	0.23	6.09	2.21	1.60	17869.68	1.81
p-value	0.00	0.00	0.00	0.00			
			Handroanthus heptaphyllus				
fixed	18.52	-	5.42	5.11	4.69	95338.10	4.69
p-value	0.00	-	0.00	0.00			
fixed+cov	20.40	-0.18	5.82	5.40	4.67	95180.76	4.67
p-value	0.00	0.00	0.00	0.00			
mixed	16.58	-	5.29	3.14	1.41	70756.75	1.56

Continuation...

Table 4. Continue.

			Handroanthus heptaphyllus				
Model	**A**	**cov**	**I**	**E**	**RMSE**	**AIC**	**Syx**
p-value	0.00	-	0.00	0.00			
mixed+cov	18.16	-0.21	5.28	3.14	1.42	70729.31	1.56
p-value	0.00	0.00	0.00	0.00			
			H. impetiginosus				
fixed	12.83	-	6.34	9.49	4.76	3249.54	4.77
p-value	0.05	-	0.50	0.28			
fixed+cov	193.56	-6.49	45.48	16.47	4.73	3243.35	4.74
p-value	0.91	0.91	0.82	0.39			
mixed	12.84	-	6.34	9.49	4.76	3251.54	4.76
p-value	0.05	-	0.50	0.28			
mixed+cov	193.43	-6.48	45.46	16.47	4.73	3245.35	4.73
p-value	0.91	0.91	0.82	0.39			
			H. serratifolius				
fixo	78.30	-	45.70	20.69	3.36	744.67	3.40
p-value	0.95	-	0.92	0.76			
mixed	16.65	-	-1241.50	-0.82	0.75	646.85	1.00
p-value	0.00	-	0.20	0.00			
			Schizolobium parahyba* var. *amazonicum				
fixed	34.21	-	12.00	5.42	6.91	7449.07	6.92
p-value	0.00	-	0.00	0.00			
fixed+cov	10.13	1.22	12.09	5.50	6.90	7449.38	6.92
p-value	0.59	0.20	0.00	0.00			
mixed	22.94	-	7.91	3.55	1.13	4875.63	1.30
p-value	0.00	-	0.00	0.00			
mixed+cov	8.37	0.74	7.88	3.55	1.13	4876.96	1.30
p-value	0.52	0.26	0.00	0.00			
			Simarouba amara				
mixed	21.41	-	6.19	3.69	1.14	9411.82	1.27
p-value	0.00	-	0.00	0.00			
mixed+cov	15.69	0.63	6.26	3.70	1.13	9385.48	1.27
p-value	0.00	0.00	0.00	0.00			
			Tectona grandis				
	A	cov	I	E	RMSE	AIC	Syx
fixed	28.59	-	8.36	5.04	6.77	58758.47	6.77
p-value	0.00	-	0.00	0.00			
fixed+cov	26.06	0.16	8.14	4.99	6.74	58667.93	6.74
p-value	0.00	0.00	0.00	0.00			
mixed	23.86	-	7.35	2.63	1.99	46237.43	2.25
p-value	0.00	-	0.00	0.00			
mixed+cov	19.85	0.29	7.38	2.63	1.99	46189.01	2.24
p-value	0.00	0.00	0.00	0.00			

A, I and E = logistic function parameters; A = asymptote; I = inflection; E = scale; cov = covariant; Syx = residual standard error; RMSE = root mean square error; AIC = Akaike information criterion. P-values of significant parameters at 0.05 are highlighted in gray.

over the fixed one.

The Akaike information criterion (AIC) and the root mean square error (RMSE) follow the observed trends for the residual standard error (Syx), with small reduction with the inclusion of covariant and expressive reduction in the mixed approach. Again, *H. impetiginosus* is an exception, since it presented a small increased AIC in the mixed and mixed with covariant approach. Residual plots reinforce the superiority of mixed models over fixed effects (Figure 3). We observed less dispersion of residuals in the mixed approach, as well as less heteroscedasticity and absence of trends. In the case of residual plots of *H. impetiginosus* mixed models, the discrete distribution of residues was maintained in the

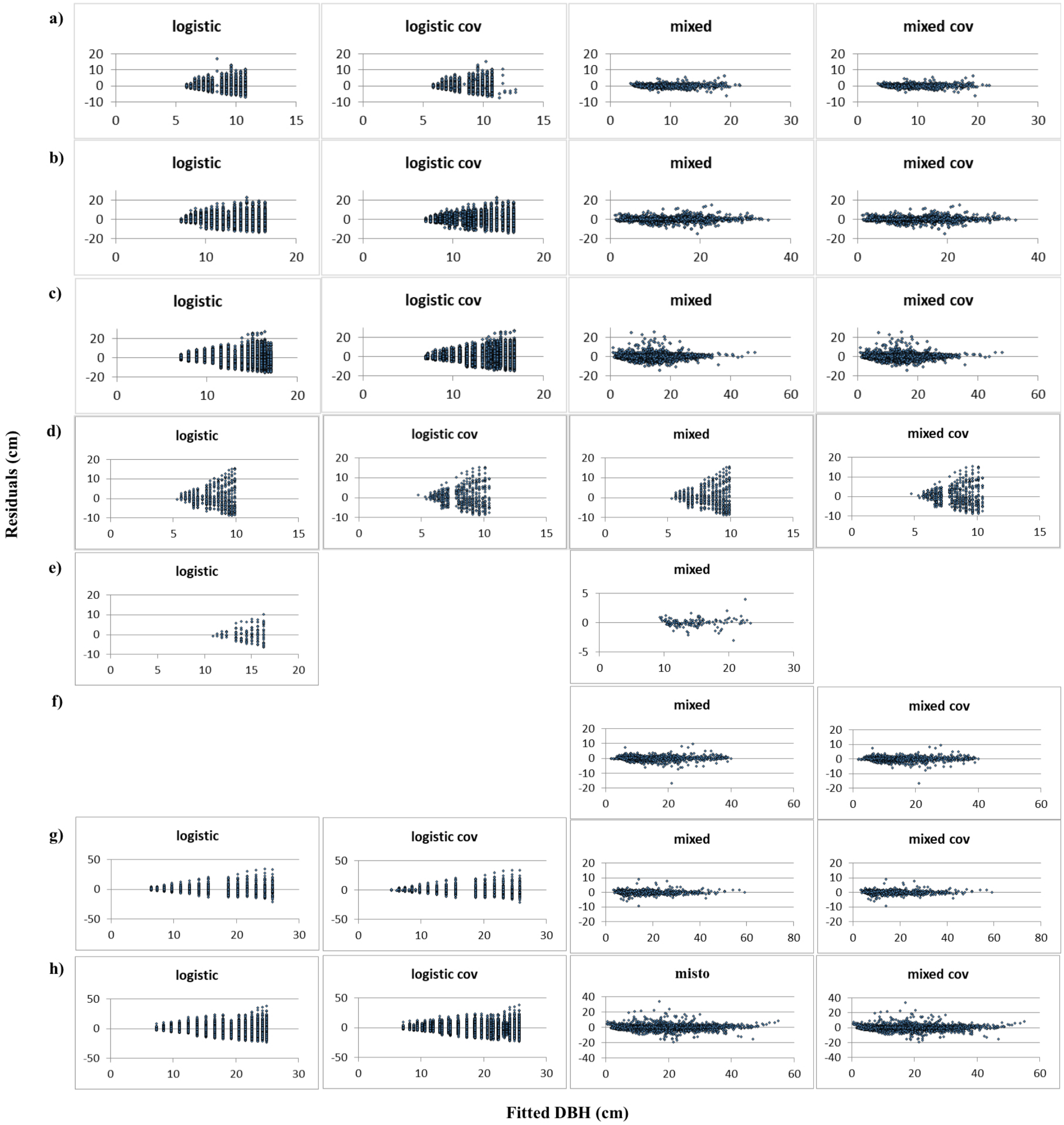

Figure 3. Residual plots of growth models in diameter at 1.3 m above ground level (DBH) fitted for tree species used in forest restoration at the Brazilian Amazon Arc of Deforestation. logistic = logistic function; logistic cov = logistic function with a covariant (plant area at the time of planting) in the asymptote; mixed = mixed-effect model (logistic function using the tree as random effect); mixed cov = mixed-effect model (logistic function using the tree as random effect) and the covariant (plant area at the time of planting) in the asymptote. a) *Cedrela odorata*; b) *Cordia alliodora*; c) *Handroanthus heptaphyllus*; d) *H. impetiginosus*; e) *H. serratifolius*; f) *Simarouba amara*; g) *Schizolobium parahyba* var. *amazonicum*; h) *Tectona grandis*.

mixed approach.

Discussion

Considering that the viability of forest management is based on technical and economic information on tree species, this study provided valuable information on the growth of eight species used in forest restoration in the Brazilian Amazon Arc of Deforestation. In the exploratory analysis, it is clear that *Schizolobium parahyba* var. *amazonicum, Tectona grandis* and *Simarouba amara* grow faster in the study area, presenting higher annual average increments at 18 years age. On the other hand, *Cordia alliodora, Cedrella odorata* and the three species of the genus *Handroanthus* showed relatively slower growth. The best models were the mixed approach and in most cases the mixed models with and without covariant were equivalent.

S. parahyba var *amazonicum* (paricá) presented the highest final mean diameter and highest MAI (1.42 cm at 18 years). The productive potential of this species is already known and has been exploited in plantations in the Amazon. Paricá occupies a planted area of 90.05 ha, corresponding to about 17% of the total area of forest plantations with other species (excluding *Eucalyptus* and *Pinus*) in Brazil (IBÁ, 2017). This species assumed particular importance in the forest scenario due to its fast growth and good adaptation to different edaphoclimatic conditions, including good performances in agroforestry and intercropping systems when compared to monoculture. This is an indicative of the exploitation potential of the species in legal reserves (Cordeiro et al., 2015). In addition, based on seedling survival and growth in the first six years after planting, Gomes et al. (2019) suggest *S. parahyba* var *amazonicum* for plantations in forest gaps, with areas from 200 m^2 caused by reduced impact logging.

The performance of *T. grandis* (teak) in the present study (second highest MAI; MAI = 1.41 cm at 18 years) corroborates other studies showing the good adaptation and growth of this species in the Amazon (Tonini et al., 2009). Although some authors claim that teak has adverse effects on the plant succession process, by affecting allelopathic properties (Healey & Gara, 2003) and decreasing the attraction of seed dispersers (Tewari, 1992), the species has great economic attractiveness, with special success in silvipastoral systems in the Amazon (Maneschy et al., 2009) and therefore potential for forest restoration projects in the region.

S. amara, which also presented relatively faster growth in the study area (MAI = 1.38 cm at 18 years), is known as a fast-growing species associated with gaps in old-growth forests and abundant in secondary forests (Ryan et al., 1994). In relation to the nonpioneers species, *S. amara* shows a different pattern, since the species has large growth, mainly among the juvenile size species (Clark & Clark, 2001).

C. alliodora, which is among the relatively slower-growing species in the study area (MAI = 0.91 cm at 18 years), is considered a fast-growing species with high potential for natural regeneration in pastures, fields, (semi) perennial crops (sugarcane, coffee, cacao) and annual crops in Costa Rica (Somarriba & Beer, 1986). In these environments, the species reaches a MAI of 3 cm $year^{-1}$ at age 5, 2 cm $year^{-1}$ at ages 5 to 10 and a diameter of 55 cm after 34 years (optimal biological rotation). A possible explanation for the relatively slower growth in the study area is the higher density and, therefore, greater competition to which this species was subjected in the evaluated plantations. Nevertheless, such mean annual increment of nearly 1 cm is considered high for the Amazon Forest (Silva et al., 2002).

C. odorata also presented relatively slower growth among the studied species (MAI = 0.67 cm at 16 years), however the species mean annual increment is in accordance with the values found to the Amazon Forest (Dünisch et al., 2003; Cunha & Finger, 2013; Braz et al., 2015). Despite showing a slow-growth, this species is a light-demanding tree species, which adapts to gap environments and is recommended for forest enrichment plantations after timber harvesting (Pinedo-Vasquez et al., 2001; Vieira et al., 2018). Again, the density and competition conditions may have harmed the growth of this species in the study area. In addition, *C. odorata* shows slow growth in drier periods of the year, thus presenting a dependence to water and light availability (Dünisch et al., 2003; Brienen & Zuidema, 2006).

The species of the genus *Handroanthus*, popularly known as *ipês*, showed relatively slower growth (MAI ranging from 0.59 to 0.89 cm at 18 years) and higher intraspecific diameter variability (CV%). These species are known to have slower growth (Andrade et al., 2019) and may take up to 100 years to reach an average diameter of 40 cm. However, its quality wood can guarantee good economic return and species-specific management practices can optimize production.

Regarding the growth modeling, the addition of the covariant led to very small gains in both approaches. The variable used (area occupied by the plant at the time of planting) is related to competition for resources that plants experience in the early stages of growth. In fact, growth is affected by competition and planting density issues (Naji et al., 2015). However, competition begins to intensify and express its effects a little later and over time, with eventual mortality by competition for light and shading when the tree crowns start tangling as the canopy closes. This probably has minimized the effect of the covariant used here, as it represented only the initial planting condition. Moreover, in the early stages, other factors not directly linked to density are more determinant for survival and growth, such as wind resistance and pest and pathogen attack (Marçais et al., 2017). Nevertheless, the use of a covariant has been shown to be possible and may be important for forestry decision making. Specifically, in the case of the covariant "planting density", if it varies with the evaluated ages (i.e., if the covariate is tree density), it would indeed represent a proxy for competition and could perform better in the model.

Therefore, here we prove that a traditional growth model can accommodate this hypothesis test (that competition affects growth) by means of a covariant incorporation in the model. Traditionally, the issue of competition has been dealt with by specific models that explicitly consider this variable, with or without distance-dependent competition indices (Kuehne et al., 2019), but these models require individual data from neighboring trees. Another constraint is that in the present case tree mortality modeling was not performed, which is an important element in the models at this level of approach, as it allows the simulation of stand structure over a period of time. In addition, parameters such as species composition, climate and soil variables may be included as covariant at the tree species growth modelling, since these characteristics have direct influence at trees survival, structure and establishment (Bartelt-Ryser et al., 2005; Toledo et al., 2010; Zhang & Dong, 2010).

The approach using mixed-effects, with individual trees as random effect was superior in all cases. Model fitting gains from the mixed approach have been reported in several papers (e.g. Calegario et al., 2005; Zobel et al., 2011; Kahriman et al., 2018). This methodology – widely used in repeated measurements - considers the presence of fixed and random effects in the database and it is quite flexible and more accurate when compared to methods that use only fixed effects in the models (Calegario et al., 2005). The correlation among the individual specific effect and the independent variables determines the fixed effect assumption. On the other hand, the random effects models overcome the fixed effects model when random effects assumption is accepted.. In the present case, the choice of the individual trees to summarize random effects was very efficient. Probably the effects of competition not explained by the covariant are contained in the random effect. In mixed models it is desirable large variability within the random effect. As already presented in the exploratory analysis, the variation between individuals of the same species is quite significant. Genetic variability, the variations in the plantation configurations, and different neighboring species lead to growth idiosyncrasies of each individual, which were captured by the random effect.

In the case of *H. impetiginosus*, where the gains from the mixed approach were not distinguished, there is a particularity. The variance and covariance matrix structure were not positively defined and the model fit did not converge. Hereupon different specifications of random effects were tested. The mixed model fit with random effects on all parameters asymptote (A), inflection (I) and scale (E) and each parameter separately. Among the possibilities tested, the only possible fitting for *H. impetiginosus* was the inclusion of a random effect only in the parameter E, since the random effects associated with parameters A and I were very close to zero, indicating that these parameters may be considered as fixed. As only one parameter of the mixed model of this species had a random effect, the performance of the mixed model may have been impaired since the separation of data into hierarchies was compromised. This probably also interfered with the form of residuals distribution.

Conclusions

Schizolobium parahyba var. *amazonicum, Tectona grandis* and *Simarouba amara* grow faster in the study area. On the other hand, *Cordia alliodora, Cedrella odorata* and the three species of the genus *Handroanthus* showed relatively slower growth compared to the abovementioned group of species. The best growth models belonged to the mixed-effect approach, and in most cases the mixed models with and without covariant were equivalent.

Our study presents data on tree growth that prove the viability of planting species with high commercial potential in legal reserve areas for recomposition purposes at Amazon as there is commercially management potential. Moreover, our results provide information that may be useful for the system of tree cutting in the Amazon, taking into account species-specific management to ensure the sustainability of the activity. In addition, economic and plant sanity analyses are required to ensure that the activity is indeed profitable.

Acknowledgment

The authors would like to thank the Projeto Poço de Carbono Florestal Peugeot-ONF for the logistical support. Special thanks go to the employees of Fazenda São Nicolau for their support in data collection; to Roberto Silveira for his assistance in data access and discussions on the subject; to Daniel D'Leslie Fernandes Botelho for his assistance in systematizing and correcting the database; and to the Universidade Federal de Lavras, and the Universidade Federal do Mato Grosso – Campus Universitário de Sinop, for qualification opportunities. The authors also thank the Fundação de Amparo à Pesquisa do Estado de Mato Grosso (FAPEMAT) for research grants. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

References

Alvares, C. A. et al. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, v. 22, n. 6, p. 711-728, 2014. https://doi.org/10.1127/0941-2948/2013/0507.

Alves, J. de A. et al. Equações hipsométricas para *Toona ciliata* com inclusão de covariantes. **Ciência Florestal**, v. 27, n. 2, p. 581-595, 2017. https://doi.org/10.5902/1980509827738.

Andrade, V. H. F. et al. Growth models for two commercial tree species in upland forests of the Southern Brazilian Amazon. **Forest Ecology and Management**, v. 438, p. 215-223, 2019. https://doi.org/10.1016/j.foreco.2019.02.030.

Arruda, C. R. et al. **Fichário dos plantios da Fazenda São Nicolau**. 2010. 246 p.

Bartelt-Ryser, J. et al. Soil feedbacks of plant diversity on soil microbial communities and subsequent plant growth. **Perspectives in Plant Ecology, Evolution and Systematics**, v. 7, n. 1, p. 27-49, 2005. https://doi.org/10.1016/j.ppees.2004.11.002.

Batista, A. et al. Modeling tree diameter growth of *Bertholletia excelsa* Bonpl. in the Brazilian Amazon. **Forests**, v. 11, n. 12, p. 1309, 2020. https://doi.org/10.3390/f11121309.

Braz, E. M. et al. Criteria to be considered to achieve a sustainable second cycle in Amazon Forest. **Pesquisa Florestal Brasileira**, v. 35, n. 83, p. 209-225, 2015. https://doi.org/10.4336/2015.pfb.35.83.941.

Borges, H. N. B. et al. (ed.). **Flora arbórea de Mato Grosso**: tipologias e suas espécies. Cuiabá: Entrelinhas, 2014. 255 p.

Brancalion, P. H. S. et al. Análise crítica da Lei de Proteção da Vegetação Nativa (2012), que substituiu o antigo Código Florestal: atualizações e ações em curso. **Natureza & Conservação**, v. 14, supp. 1, p. e1-e16, 2016. https://doi.org/10.1016/j.ncon.2016.03.004.

Brasil. **Decreto nº 8.972, de 23 janeiro de 2017**. Institui a Política Nacional de Recuperação da Vegetação Nativa. Available from: http://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/decreto/d8972.htm. Access on: Nov. 20, 2020.

Brasil. **Lei n° 12.651, de 25 de maio de 2012**. Dispõe sobre a proteção da vegetação nativa [...] e dá outras providências. Available from: http://www.planalto.gov.br/ccivil_03/_Ato2011-2014/2012/Lei/L12651compilado.htm. Access on: Jan 11, 2021. Publicada originalmente no Diário Oficial [da] República Federativa do Brasil, Brasília, DF, em 28 maio, 2012.

Brienen, R. J. W. & Zuidema, P. A. Lifetime growth patterns and ages of Bolivian rain forest trees obtained by tree ring analysis. **Journal of Ecology**, v. 94, n. 2, p. 481-493, 2006. https://doi.org/10.1111/j.1365-2745.2005.01080.x.

Calegario, N. et al. Estimativa do crescimento de povoamentos de *Eucalyptus* baseada na teoria dos modelos não lineares em multinível de efeito misto. **Ciência Florestal**, v. 15, n. 3, p. 285-292, 2005. https://doi.org/10.5902/198050981866.

Carvalho, W. D. et al. Deforestation control in the Brazilian Amazon: a conservation struggle being lost as agreements and regulations are subverted and bypassed. **Perspectives in Ecology and Conservation**, v. 17, n. 3, p. 122-130, 2019. https://doi.org/10.1016/j.pecon.2019.06.002.

Clark, D. A. & Clark, D. B. Getting to the canopy: tree height growth in a neotropical rain forest. **Ecology**, v. 82, n. 5, p. 1460-1472, 2001. https://doi.org/10.1890/0012-9658(2001)082[1460:GTTCTH]2.0.CO;2.

Cordeiro, I. M. C. C. et al. Avaliação de plantios de Paricá (*Schizolobum parahyba* var. *amazonicum* (Huber Ex Ducke) Barneby de diferentes idades e sistemas de cultivo no município de Aurora do Pará - PA (Brasil). **Ciência Florestal**, v. 25, n. 3, p. 679-687, 2015. https://doi.org/10.5902/1980509819618.

Cunha, T. A. da & Finger, C. A. G. Competição assimétrica e o incremento diamétrico de árvores individuais de Cedrela odorata L. na Amazônia ocidental. **Acta Amazonica**, v. 43, n. 1, p. 9-18, 2013. https://doi.org/10.1590/S0044-59672013000100002.

Cunha, T. A. da et al. Tree basal area increment models for Cedrela, Amburana, Copaifera and Swietenia growing in the Amazon rain forests. **Forest Ecology and Management**, v. 365, p. 174-183, 2016. https://doi.org/10.1016/j.foreco.2015.12.031.

Dünisch, O. et al. Dendroecological investigations on *Swietenia macrophylla* King and *Cedrela odorata* L. (Meliaceae) in the central Amazon. **Trees**, v. 17, p. 244-250, 2003. https://doi.org/10.1007/s00468-002-0230-2.

Free, C. M. et al. Management implications of long-term tree growth and mortality rates: a modeling study of big-leaf mahogany (*Swietenia macrophylla*) in the Brazilian Amazon. **Forest Ecology and Management**, v. 330, p. 46-54, 2014. https://doi.org/10.1016/j.foreco.2014.05.057.

Gollnow, F. et al. Property-level direct and indirect deforestation for soybean production in the Amazon region of Mato Grosso, Brazil. **Land Use Policy**, v. 78, p. 377-385, 2018. https://doi.org/10.1016/j.landusepol.2018.07.010.

Gomes, J. M. et al. *Schizolobium parahyba* var. *Amazonicum* (Huber ex Ducke) Barneby pode ser utilizada em enriquecimento de clareiras de exploração florestal na Amazônia. **Ciência Florestal**, v. 29, n. 1, p. 417-424, 2019. https://doi.org/10.5902/198050984793.

Healey, S. P. & Gara, R. I. The effect of a teak (*Tectona grandis*) plantation on the establishment of native species in an abandoned pasture in Costa Rica. **Forest Ecology and Management**, v. 176, n. 1-3, p. 497-507, 2003. https://doi.org/10.1016/S0378-1127(02)00235-9.

IBÁ. Industria Brasileira de Árvores. **Relatório Anual 2017**. Brasília, DF, 2017. Available from: https://iba.org/images/shared/Biblioteca/IBA_RelatorioAnual2017.pdf. Access on: July 20, 2020.

Imazon. Instituto Homem e Meio Ambiente da Amazônia. **Boletim Sistema de Alerta de Desmatamento**, jan. 2019. Available from: https://imazon.org.br/publicacoes/boletim-do-desmatamento-da-amazonia-legal-janeiro-2019-sad/. Access on: May 10, 2020.

Inmet. Instituto Nacional de Meteorologia. **BDMEP**: Banco de Dados Meteorológicos para Ensino e Pesquisa. 2021. Available from: https://portal.inmet.gov.br/servicos/bdmep-dados-hist%C3%B3ricos. Access on: July 14, 2021.

Kahriman, A. et al. A novel approach to selecting a competition index: the effect of competition on individual tree diameter growth of Calabrian pine. **Canadian Journal of Forest Research**, v. 48, n. 10, p. 1217-1226, 2018. https://doi.org/10.1139/cjfr-2018-0092.

Kuehne, C. et al. Comparing performance of contrasting distance-independent and distance-dependent competition metrics in predicting individual tree diameter increment and survival within structurally-heterogeneous, mixed-species forests of Northeastern United States. **Forest Ecology and Management**, v. 433, p. 205-216, 2019. https://doi.org/10.1016/j.foreco.2018.11.002.

Maneschy, R. Q. et al. Viabilidade econômica de sistemas silvipastoris com *Schizolobium parahyba* var. *amazonicum* e *Tectona grandis* no Pará. **Pesquisa Florestal Brasileira**, v. 60, p. 49-56, 2009.

Marçais, B. et al. Estimation of Ash mortality induced by *Hymenoscyphus fraxineus* in France and Belgium. **Baltic Forestry**, v. 23, n. 1, p. 159-167, 2017.

Mendonça, A. R. de et al. Growth and yield models for eucalyptus stands obtained by differential equations. **Scientia Agricola**, v. 74, n. 5, p. 364-370, 2017. https://doi.org/10.1590/1678-992x-2016-0035.

Naji, H. R. et al. Effect of intensive planting density on tree growth, wood density and fiber properties of maple (*Acer velutinum* Boiss.). **IForest**: Biogeosciences and Forestry, v. 9, n. 2, p. 325-329, 2015. https://doi.org/10.3832/ifor1333-008.

Noronha, J. C. et al. Update das espécies de anuros da Fazenda São Nicolau, Mato Grosso, Brasil. **Scientific Electronic Archives**, v. 8, n. 1, p. 15-25, 2015.

Pinedo-Vasquez, M. et al. Post-Boom logging in Amazonia. **Human Ecology**, v. 29, n. 2, p. 219-239, 2001. https://doi.org/10.1023/A:1011064031078.

Pinheiro, J. **Package 'nlme'**: linear and nonlinear mixed effects models description. 2019. Available from: https://cran.r-project.org/web/packages/nlme/nlme.pdf. Access on: Aug. 2, 2020.

Pödör, Z. et al. Application of sigmoid models for growth investigations of forest trees. In: van Do, T. et al. (ed.). **Advanced computational methods for knowledge engineering**: Proceedings of the 2nd International Conference on Computer Science, Applied Mathematics and Applications (ICCSAMA 2014). New York: Springer, 2014. p. 353-364.

Qin, Y. et al. Improved estimates of forest cover and loss in the Brazilian Amazon in 2000-2017. **Nature Sustainability**, v. 2, p. 764-772, 2019. https://doi.org/10.1038/s41893-019-0336-9.

R Core Team. **R**: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing, 2019.

Ryan, M. G. Woody-tissue respiration for *Simarouba amara* and *Minquartia guianensis*, two tropical wet forest trees with different growth habits. **Oecologia**, v. 100, n. 3, p. 213-220, 1994. https://doi.org/10.1007/BF00316947.

Santos, H. G. dos et al. (ed.). **Sistema brasileiro de classificação de solos**. Brasília, DF: Embrapa, 2018. 353 p.

Scolforo, H. F. et al. A new model of tropical tree diameter growth rate and its application to identify fast-growing native tree species. **Forest Ecology and Management**, v. 400, p. 578-586, 2017. https://doi.org/10.1016/j.foreco.2017.06.048.

Silva, R. P. da, et al. Diameter increment and growth patterns for individual tree growing in Central Amazon, Brazil. **Forest Ecology and Management**, v. 166, n. 1-3, p. 295–301, 2002. https://doi.org/10.1016/s0378-1127(01)00678-8.

Somarriba, E. & Beer, J. **Dimensiones, volumenes y crecimiento de *Cordia alliodora* en sistemas agroforestales**. Turrialba: CATIE. 1986. (Boletín técnico, 16).

Souza, A. P. et al. Classificação climática e balanço hídrico climatológico no estado de Mato Grosso. **Nativa**, v. 1, n. 1, p. 34-43, 2013. https://doi.org/10.31413/nativa.v1i1.1334.

Spiess, A.-N. Package "qpcR": Modelling and Analysis of Real-Time PCR Data. 2018. Available from: https://cran.r-project.org/web/packages/qpcR/qpcR.pdf. Access on: Aug. 2, 2020.

Tewari, D. N. **A monograph on teak (*Tectona grandis* Linn. f.)**. Dehra Dun: International Book Distributors, 1992.

Toledo, M. et al. Climate is a stronger driver of tree and forest growth rates than soil and disturbance. **Journal of Ecology**, v. 99, n. 1, p. 254-264, 2010. https://doi.org/10.1111/j.1365-2745.2010.01741.x.

Tonini, H. et al. Crescimento da Teca (*Tectona grandis*) em reflorestamento na Amazônia Setentrional. **Pesquisa Florestal Brasileira**, v. 59, p. 5-14, 2009. https://doi.org/10.4336/2009.pfb.59.05.

Verhulst, P. F. Notice sur la loi que la population poursuit dans son accroissement. **Correspondance mathématique et physique**, v. 10, p. 113-121, 1838.

Vieira, S. B. *Cedrela odorata* L. tem potencial para ser utilizada na silvicultura pós-colheita na Amazônia brasileira? **Ciência Florestal**, v. 28, n. 3, p. 1230-1238, 2018. https://doi.org/10.5902/1980509833361.

Wickham, H. **Package "tidyverse"**: Easily Install and Load the "Tidyverse". 2017. Available from: https://cran.r-project.org/web/packages/tidyverse/tidyverse.pdf. Access on: 10 Ago 2020.

Zanetti, E. A. & Souza, M. de C. Serviço Nacional de Carbono Rural da Amazônia (SNCRA). **Inclusão Social**, v. 12, n. 1, p. 95-102, 2018.

Zhang, J-T. & Dong, Y. Factors affecting species diversity of plant communities and the restoration process in the loess area of China. **Ecological Engineering**, v. 36, n. 3, p. 345-350, 2010. https://doi.org/10.1016/j.ecoleng.2009.04.001.

Zobel, J. M. et al. Comparison of Forest Inventory and Analysis surveys, basal area models, and fitting methods for the aspen forest type in Minnesota. **Forest Ecology and Management**, v. 262, n. 2, p. 188-194, 2011. https://doi.org/10.1016/j.foreco.2011.03.022.