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MODELING THE DIAMETER GROWTH OF PLANTED NATIVE TREES FOR THE RESTORATION OF MINED AREAS

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Resumo

Modelagem do crescimento diamétrico de árvores nativas plantadas para restauração de áreas mineradas. Os modelos de crescimento diamétrico de espécies arbóreas são ferramentas úteis que permitem acompanhar o desenvolvimento das espécies e identificar se a área restaurada está autossustentável. A modelagem pode ser expressa a partir de dados do crescimento diamétrico e constitui um importante parâmetro para predizer diâmetros presentes e futuros e auxiliar na tomada de decisão no setor florestal. Este estudo teve como objetivo desenvolver equações de crescimento para estimar taxas de crescimento diamétrico para algumas espécies nativas plantadas e regeneradas na restauração de áreas mineradas. Foi avaliada a performance das espécies florestais por um período 13 anos para espécies plantadas e oito anos para a regeneração acompanhante e utilizado um modelo de regressão e análise de variância, tendo como variável dependente o diâmetro. Os parâmetros ajustados do modelo exponencial para cada espécie arbórea resultaram em um baixo erro padrão da estimativa do coeficiente b e significância a 95%, para a maioria das espécies estudadas. O modelo proposto apresentou bons ajustes nos parâmetros das equações e pode ser utilizado para estimar o diâmetro de espécies arbóreas, e predizer produções presentes e futuras dos povoamentos florestais, desde que as condições da área sejam semelhantes às deste estudo.
Palavras-chave: Dinâmica florestal, Incremento, mineração, floresta tropical, Amazônia.

Abstract

Tree diameter growth models of tree species are useful tools that allow monitoring the development of species and identifying whether the restored area is self-sustainable. The modeling can be expressed based on diameter growth data and represents an important parameter for predicting present and future diameters and assisting in decision-making in the forestry sector. This study aimed to develop a growth equation to estimate diameter growth rates for some planted native species and regenerated species in the restoration of mined areas. The performance of forest species was evaluated for 13 years for planted species, and eight years for the accompanying regeneration, and a regression model and analysis of variance were used, with diameter as the dependent variable. The adjusted parameters of the exponential model for each tree species resulted in a low standard error of the estimate of the coefficient b and significance at 95% for most of the species studied. The proposed model presented a good fit to the parameters of the equations and can be used to estimate the diameter of tree species and predict present and future production of forest stands, as long as the area conditions are similar to those of this study.
Keywords: Forest dynamics, increment, mining, tropical forest, Amazon.

INTRODUCTION

Open-pit mining in the Amazon often involves removing all vegetation cover from a dense rainforest area. Beginning in the 1980s, restoration efforts focused on revegetation to prevent erosion and meet aesthetic aspects. Over time, the goal expanded to include recovering primary production and ecological functions (BRANCALION *et al.*, 2015), and later on, the structure and plant composition was also considered (SALOMÃO, 2015).

Various types of models in the literature estimate the growth and production of species (CONDIT *et al.*, 1993; VANCLAY, 1994; SCOLFORO *et al.*, 2008; CHASSOT *et al.*, 2011; SALOMÃO *et al.*, 2014), however, most mathematical growth models are for homogeneous and even-aged plantations (LUSTOSA *et al.*, 2019), based on increments as a function of the average characteristics of dimensional variables (average trees in the stand) and as a function of age (CHASSOT *et al.*, 2011).

Species growth models estimate future diameter and growth rates by using diameter data from monitoring surveys; there are still several obstacles, especially when the estimation occurs at the individual level, which can generate large errors (SCOLFORO *et al.*, 2017).

Some studies seek to extrapolate short-term data to the long-term by improving methods (CONDIT *et al.*, 1993). One of these was developed by Scolforo *et al.* (2008), in which negative growth rates were generated when the diameters of the highest classes were estimated. In this case, the correction consisted of replacing the parabolic model with the negative exponential model. One second model was later improved, using stand density to predict how different stand densities affect the growth of each tree species over time (SCOLFORO *et al.*, 2017).

Other growth models have been developed to estimate growth, or production, from stand-level attributes such as age, basal area, and site index (CLUTTER *et al.*, 1983; CAMPOS; LEITE, 2013). However, none of these studies' present diameter growth equations for Amazonian species in restoration areas, except in homogeneous forest plantations.

Studying the restoration trajectory requires indicators to demonstrate whether or not a given area under restoration will achieve sustainability (resilience). Through monitoring areas during the restoration process, it is possible to assess sustainability indicators, mainly in intensely degraded areas (SALOMÃO, 2015).

The mathematical models generated allow for monitoring the development of species, understanding the dynamics of planting, and predicting the future production of forest stands, based on current conditions (VANCLAY, 1994).

Tree diameter growth models are useful tools for selecting species for forest plantings and for understanding the role of these trees concerning ecosystem services, especially in the carbon cycle (SALOMÃO *et al.*, 2014). Given the importance of information on the growth of forest species to assist in decision-making in the forestry sector, the objective was to develop a growth equation to estimate diameter growth rates for some planted native species and species of the accompanying natural regeneration in the restoration of mined areas.

MATERIAL AND METHODS

Characterization of the study area

The study area was conducted in the Saraca Taquera National Forest, district of Porto Trombetas (1º 21' S – 56º 22' W), municipality of Oriximiná, State of Pará, where Mineração Rio do Norte S.A. (MRN) has been developing a bauxite mining-industrial project since 1979. Due to the impact that mining activity has on the environment, MRN, since 1981, has restored post-mining areas.

Data collection in sampling units

Planting of trees

In 1996, MRN restored a post-mined area using 92 tree species. To prepare the area, organic soil was added for surface spreading and organic fertilizer was added only to the plant holes. To monitor their development, 23 plots measuring 10 m x 25 m (0.025 ha) were implemented and monitoring lasted 13 years, with seven multi-year measurements 1996/97/98/99/00/07/09. All individuals from the forest plantation were registered, tagged, identified, and measured. To construct the diameter growth model, only individuals recorded in Year 0 (1996) that remained alive until Year 13 (2009) were considered, taking a minimum limit of five individuals per species.

Throughout the 13 years, the diameter at ground height (DGH) of each tree was measured from the start of monitoring when the seedlings were no taller than 50 cm, impeding the measurement of the diameter at breast height (DBH) at 1.30 m from the ground. Therefore, the diameter considered here for the growth equations of the planted species was the DGH.

Accompanying natural regeneration

The accompanying natural regeneration of tree species evaluated in this study refers to regenerating species in annual restoration plantations planted in the 1980s (1981-1987) and 1990s (1991-1996). To monitor the regeneration, two plots were installed in each annual area (1981-1987 and 1992-1995), and four for the 1996 restoration area, totaling 26 plots of all plantations. The assessments began in 2001 and lasted until 2009, totaling five measurements every two years.

All implemented plots were rectangular (10 m x 25 m) and all individual trees with a total height equal to or greater than 1.50 m were registered, labeled, and identified. Individuals, regardless of the year of forest restoration, were measured for diameter at breast height (DBH; height 1.30 m from the ground) and total height.

A minimum of five individuals per species was considered as a species selection criterion for constructing the equations, with only those recorded in the first year of assessment (2001) and alive until the last assessment (2009) included.

Analytical model

The methodology used to calculate the geometric growth rate of the diameter of forest species (DFS), in the period considered, was described by Santana (2003), whose model is expressed by:

$$DFS_t = DFS_0 \, (1 + r)^t \qquad (1)$$

Where DFS_t is the variable of interest and represents the diameter of forest species, according to the minimum qualification limit (DGH or DBH), analyzed in period *t*; DFS_0 is the value of the variable in the base year period if: (i) planting of trees - 1996 and (ii) accompanying natural regeneration – 2001; and *r* is the growth rate to be estimated. The equation is widely used to interpolate intercensal population or agricultural production data and to project data. Applications of this approach can be found at IBGE and FAO, for example.

When the data collected constitutes a historical series, the calculation of the growth rate must be carried out by estimating a regression. The transformation of Equation (1) into a regression is carried out by anamorphosis, applying natural logarithm to both sides of Equation (1), as follows:

$$lnDFS_t = lnDFS_0 + t \, ln(1 + r) \qquad (2)$$

Making $a = lnDFS_0$ and $b = ln(1 + r)$ and adding the random error term, the above equation can be rewritten as follows:

$$lnDFS_{it} = a + bt + e_{it} \qquad (3)$$

In which:

$lnDFS_{it}$ (C) is the natural logarithm of the diameter of species *i*, in period *t*, in cm

a is the regression constant or intercept

b is the coefficient associated with the trend of the equation

t is the value of the chronological time variable in the period of (i) planting of trees - 1996 to 2009 and (ii) accompanying natural regeneration – 2001 to 2009 - e_t is the random error term.

Parameter *b* of Equation (3) was estimated using the Ordinary Least Squares (OLS) method as it generates the best linear and unbiased estimates (Santana, 2003).

Once the estimates of *b* were obtained using the equations for each species, the statistical significance of the estimate of *b* was tested, adopting a reliability of at least 95%. For projection purposes, consider the standard error of coefficient b associated with the trend. The significance of the b coefficient was estimated by Student's T statistics and the adequacy of the regression model was defined by Snedecor's F statistic. As it is a simple regression estimated by OLS, b is the best linear unbiased estimator of the growth rate, in this case, F = t2. Thus, the p-value is valid for measuring the significance of the parameter and the adequacy of the regression model.

The value of the annual growth rate *r* was obtained as follows:

$$r = (antln\ b - 1)x100 \qquad (4)$$

where *r* is the estimated annual growth rate (or simply AGR).

With this rate, it is possible to estimate the probable diameter of each forest species for future periods. For example, the diameter of forest species *i* in 2024 can be obtained as follows:

$$DFS_{2024} = DFS_{2013} \, (1 + r)^t \qquad (5)$$

The estimated annual growth rate of the species refers to the average number of individuals of each species.

RESULTS

Planting of trees

To calculate the basal diameter growth rates, 32 species were selected, with the number of individuals (n) varying from 5 to 86. The average annual increase in basal diameter (IMA_{DGH}) of the 32 species was 0.53±0. 49 cm $year^{-1}$, varying from 0.15 cm $year^{-1}$ (*Pouteria speciosa* (Ducke) Baehni) to 2.50 cm $year^{-1}$ (*Tachigali vulgaris* L.F. Gomes da Silva & H.C. Lima). Nine species had IMA_{DGH} above the average, and among these, three had IMA_{DGH} greater than 1.0 cm $year^{-1}$: *T. vulgaris* (2.50 cm $year^{-1}$), *Tapirira guianensis* Aubl. (1.67 cm $year^{-1}$) and *Simaruba amara* Aubl. (1.31 cm $year^{-1}$). These species also presented the highest mean basal diameter values at 13 years of age, respectively, 34.04 cm, 22.86 cm, and 17.61 cm. (Table 1). Most species (27) had an average DAS below 10 cm, and of the 32 species selected, 20 belonged to the late secondary ecological group.

Estimates of annual growth rates (AGR) were calculated using a generic equation for average diameter (AD) growth. The estimates of the *b* coefficient associated with the trend of the equations for each species, when tested for statistical significance at 95%, demonstrated that out of the 32 species evaluated, 21 were significant (p-value<0.05), and 11 species were not significant at 95% (p-value>0.05). For growth projection purposes, when considering the 99% confidence level, significant AGR was found for only four species (*Mezilaurus itauba* (Meisn.) Taub. ex Mez, *Pouteria speciosa*, *T. guianensis*, and *Tachigali alba* Ducke; Table 1).

Nine species presented a negative trend equation, which is related to the species' low variation in growth, especially in the initial growth phase. Most species presented statistically significant regression equations, with a coefficient of determination (R^2) above 0.50 and a p-value<0.05. Among these, *P. speciosa* (0.80), *T. alba* (0.78), *T. guianensis* (0.77), *Aspidosperma macrocarpon* Mart. (0.77), and *M. itauba* (0.76) presented the highest values.

Table 1. List of species from the 1996 forest planting, with their respective ecological groups (EG), number of individuals (n_{09}), average diameter at ground height (DGH_{09}) in 2009, average annual increase (IMA) in basal diameter, generic growth equation (AD) and annual growth rate (AGR). Bold R^2 values are less than 50% and the P-value indicates significance at 90%. Data of species with a negative trend equation were transformed by antilog b(x).

Tabela 2. Relação de espécies do plantio florestal de 1996, com respectivos grupos ecológicos (GE), número de indivíduos (n_{09}), o diâmetro basal médio (DAS) e o incremento médio anual (IMA) do diâmetro basal, equação genérica de crescimento e taxa média anual de crescimento do diâmetro (TAC). Os valores em negrito de R^2 são inferiores a 50% e os de P-valor indicam significância a 90%. Para as espécies que apresentaram equação de tendência negativa é necessário aplicar o antilogb(x).

Species	EG	n_{09}	DGH_{09}	IMA_{DGH}	Generic growth equation (AD)	Trend equation	R^2	SE	P-value	AGR (cm)
Abarema turbinata	P	10	9.10	0.63	$AD_t = AD_{t0} * 1.1322^{t}$	C = 0.7237 + 0.1242 t	0.61	0.044	0.0383	0.13
Acacia polyphylla	P	16	13.43	0.92	$AD_t = AD_{t0} * 1.1282^{t}$	C = 1.1935 + 0.1206 t	0.57	0.047	**0.0505**	0.13
Astronium gracile	LS	39	4.67	0.31	$AD_t = AD_{t0} * 1.1110^{t}$	C = 0.2616 + 0.1053 t	0.66	0.034	0.0273	0.11
Bowdichia nitida	LS	20	12.79	0.94	$AD_t = AD_{t0} * 1.1857^{t}$	C = 0.4566 + 0.1703 t	0.67	0.053	0.0244	0.19
Caesalpinia ferrea	ES	35	4.80	0.29	$AD_t = AD_{t0} * 1.0786^{t}$	C = 0.6853 + 0.0757 t	**0.49**	0.034	**0.0797**	0.08
Dalbergia spruceana	LS	63	4.90	0.31	$AD_t = AD_{t0} * 1.0916^{t}$	C = 0.5644 + 0.0876 t	0.53	0.037	**0.0649**	0.09
Dipteryx odorata	LS	10	4.09	0.26	$AD_t = AD_{t0} * 1.1018^{t}$	C = 0.2599 + 0.097 t	0.59	0.036	0.0428	0.10
Enterolobium schomburgkii	LS	70	5.65	0.37	$AD_t = AD_{t0} * 1.1001^{t}$	C = 0.5873 + 0.0954 t	0.54	0.040	**0.0605**	0.10
Eriotheca globosa	LS	15	9.62	0.68	$AD_t = AD_{t0} * 1.1387^{t}$	C = 0.7378 + 0.1299 t	0.59	0.048	0.0437	0.14
Geissospermum sericeum	LS	44	4.87	0.33	$AD_t = AD_{t0} * 1.1210^{t}$	C = 0.1877 + 0.1142 t	0.62	0.040	0.0364	0.12
Genipa americana	LS	6	5.40	0.29	$AD_t = AD_{t0} * 1.0577^{t}$	C = 1.0036 + 0.0561 t	0.51	0.025	**0.0722**	0.06
Guatteria olivacea	LS	18	6.77	0.46	$AD_t = AD_{t0} * 1.1269^{t}$	C = 0.422 + 0.1195 t	0.68	0.037	0.0226	0.13
Guatteria umbonata	LS	11	4.22	0.27	$AD_t = AD_{t0} * 1.0863^{t}$	C = 0.4518 + 0.0828 t	0.54	0.034	**0.0597**	0.09
Hymenaea courbaril	LS	25	5.74	0.37	$AD_t = AD_{t0} * 1.1059^{t}$	C = 0.5235 + 0.1007 t	0.69	0.031	0.0215	0.11
Licania tomentosa	LS	14	6.61	0.49	$ADt = AD_{t0} * 1.1014^{t}$	C = 0.737 + 0.0966 t	0.58	0.037	0.0460	0.10
Lophanthera lactescens	ES	24	5.21	0.38	$ADt = AD_{t0} * 1.0852^{t}$	C = 0.6874 + 0.0817 t	0.55	0.033	**0.0560**	0.09
Mezilaurus itauba	LS	64	3.92	0.26	$AD_t = AD_{t0} * 1.1291^{t}$	C = -0.1366 + 0.1214 t	0.76	0.030	0.0101	0.13
Micropholis egensis	LS	10	3.96	0.27	$AD_t = AD_{t0} * 1.1157^{t}$	C = 0.0595 + 0.1094 t	0.59	0.041	0.0427	0.12
Oenocarpus bataua	ES	5	4.88	0.37	$AD_t = AD_{t0} * 1.2229^{t}$	C = -0.7767 +0.2012 t	0.57	0.078	0.0489	0.22
Oenocarpus mapora	ES	6	7.10	0.54	$AD_t = AD_{t0} * 1.3359^{t}$	C = -1.5344 + 0.2896 t	0.72	0.081	0.0162	0.34
Ormosia holerythra	LS	8	3.06	0.22	$AD_t = AD_{t0} * 1.1531^{t}$	C = -0.6301 + 0.1424 t	0.71	0.041	0.0170	0.15
Parkia multijuga	LS	65	8.82	0.58	$AD_t = AD_{t0} * 1.0990^{t}$	C = 1.0924 + 0.0944 t	**0.48**	0.044	**0.0838**	0.10
Parkia nitida	LS	8	7.76	0.51	$AD_t = AD_{t0} * 1.0973^{t}$	C = 0.9626 + 0.0929 t	**0.49**	0.042	**0.0802**	0.10
Platymiscium duckei	LS	5	2.48	0.16	$AD_t = AD_{t0} * 1.0863^{t}$	C = -0.0823 + 0.0828 t	0.53	0.035	**0.0634**	0.09
Pouteria speciosa	LS	7	2.49	0.15	$AD_t = AD_{t0} * 1.0964^{t}$	C = -0.2808 + 0.0921 t	0.80	0.021	0.0067	0.10
Simaruba amara	ES	11	17.67	1.31	$AD_t = AD_{t0} * 1.2055^{t}$	C = 0.599 + 0.1869 t	0.70	0.057	0.0189	0.21
Stryphnodendron polystachyum	P	11	5.23	0.37	$AD_t = AD_{t0} * 1.1468^{t}$	C = -0.0094 + 0.137 t	0.63	0.055	0.0327	0.15

Species	EG	n_{09}	DGH_{09}	IMA_{DGH}	Generic growth equation (AD)	Trend equation	R²	SE	P-value	AGR (cm)
Swartzia brachyrachis	P	16	2.96	0.20	$AD_t = AD_{t0} * 1.1188^t$	C = -0.27 + 0.1123 t	0.66	0.047	0.0254	0.12
Tabebuia serratifolia	LS	24	4.95	0.29	$AD_t = AD_{t0} * 1.0718^t$	C = 0.7893 + 0.0693 t	0.51	0.036	**0.0725**	0.07
Tachigali alba	P	10	5.07	0.35	$AD_t = AD_{t0} * 1.1534^t$	C = -0.2089 + 0.1427 t	0.78	0.031	0.0049	0.15
Tachigali vulgaris	P	9	34.04	2.50	$AD_t = AD_{t0} * 1.1835^t$	C = 1.4782 + 0.1685 t	0.64	0.030	0.0310	0.18
Tapirira guianensis	ES	86	22.86	1.67	$AD_t = AD_{t0} * 1.2011^t$	C = 0.8569 + 0.1832 t	0.77	0.045	0.0094	0.20

GE: Ecological Group; P: pioneer; ES: early secondary; LS: late secondary; n = number of individuals of the species; IMA = average annual increase in diameter (cm.year^{-1}); AD = average diameter at ground height (cm); t = period of years considered; C = $lnDFS_t$ periodic growth of the average diameter (cm) estimated for the species in period *t* (years); R² = coefficient of determination; SE = standard error; P-value = regression significance level at 95% ($p<0.05$), associated with statistics T and F; AGR = average growth rate (cm).

Accompanying natural regeneration

In the spontaneous vegetation of forest planting in reforested areas, 72 species were recorded from 2001 to 2009. Of this total, 32 tree species had more than five individuals and were selected, providing higher reliability for the evaluations.

Among the 32 species, 14 belong to the late secondary ecological group, eight are pioneers, and seven are early secondary. Only two species belong to the climax group.

The annual average increase in DBH (IMA_{DBH}) of these 32 species was 0.33±0.22 cm year^{-1}, ranging from 0.08 to 0.92 cm year^{-1}. Of this total, 12 species presented IMA_{DBH} above the average, with emphasis on *T. vulgaris* (0.92 cm year^{-1}) and *Byrsonima stipulaceae* A. Juss. (0.88 cm year^{-1}).

The annual growth rate, which allows for predicting the probable diameter for future periods, was calculated using the generic average diameter growth equation. The generated equations presented significant regressions (p-value<0.05) for all species. Considering the 99% reliability level, significance was observed for 24 species for the growth effect. The model for all species presented a low standard error of estimate, indicating that the proposed model presents a good fit to the data (Table 2).

Table 3. List of the 32 species selected from the accompanying natural regeneration, monitored between 2001 and 2009, with their respective ecological group (EG), number of individuals (n_{09}) and diameter at breast height (DBH_{09}) in 2009, average annual increase (IMA) of DBH, generic growth equation (AD) and annual growth rate (AGR). P-value indicates significance at 95%.

Tabela 4. Relação das 32 espécies selecionadas da regeneração natural acompanhante, monitoradas entre 2001 e 2009, com respectivos grupos ecológicos (GE), número de indivíduos (n_{09}), diâmetro a 1,30m do solo (DAP09), incremento médio anual (IMA) do DAP, equação genérica de crescimento e taxa média anual de crescimento do diâmetro (TAC). Os valores de P-valor indicam significância a 95%.

Species	EG	n_{09}	DBH_{09}	IMA_{DBH}	Generic growth equation (AD)	Trend equation	R²	SE	P-value	AGR (cm)
Aspidosperma macrocarpa	LS	7	2.66	0.11	$AD_t = AD_{t0} * 1.0549^t$	C = 0.5368 + 0.0534 t	0.96	0.006	0.0034	0.05
Bellucia grossularioides	LS	128	5.86	0.27	$AD_t = AD_{t0} * 1.0574^t$	C = 1.1311 + 0.0558 t	0.92	0.009	0.0093	0.06
Bocageopsis multiflora	NI	5	2.90	0.18	$AD_t = AD_{t0} * 1.0896^t$	C = 0.3010 + 0.0858 t	1.00	0.003	0.0001	0.09
Bowdichia nitida	LS	6	7.73	0.36	$AD_t = AD_{t0} * 1.0619^t$	C = 0.0601 + 1.5372 t	0.98	0.005	0.0016	0.06
Byrsonima aerugo	LS	10	13.04	0.62	$AD_t = AD_{t0} * 1.0599^t$	C = 2.0939 + 0.0582 t	0.91	0.010	0.0115	0.06
Byrsonima densa	LS	5	11.44	0.65	$AD_t = AD_{t0} * 1.0824^t$	C = 1.8039 + 0.0792 t	0.91	0.014	0.0109	0.08
Byrsonima stipulaceae	LS	9	19.29	0.88	$AD_t = AD_{t0} * 1.0582^t$	C = 2.4847 + 0.0566 t	0.96	0.007	0.0040	0.06
Croton lanjouwensis	P	61	6.41	0.21	$AD_t = AD_{t0} * 1.0393^t$	C = 1.5231 + 0.0386 t	0.98	0.003	0.0009	0.04
Dinizia excelsa	C	27	3.57	0.17	$AD_t = AD_{t0} * 1.0621^t$	C = 0.7790 + 0.0603 t	0.91	0.011	0.0119	0.06
Endopleura uchi	C	5	4.62	0.33	$AD_t = AD_{t0} * 1.1103^t$	C = 0.6329 + 0.1046 t	0.98	0.009	0.0013	0.11
Enterolobium schomburgkii	LS	9	4.78	0.19	$AD_t = AD_{t0} * 1.0486^t$	C = 1.1548 + 0.0475 t	0.99	0.003	0.0005	0.05
Goupia glabra	LS	74	3.81	0.18	$AD_t = AD_{t0} * 1.0599^t$	C = 0.8315 + 0.0582 t	0.99	0.003	0.0004	0.06
Hymenaea parvifolia	LS	6	2.53	0.16	$AD_t = AD_{t0} * 1.0874^t$	C = 0.2612 + 0.0838 t	0.89	0.017	0.0166	0.09
Hymenolobium pulcherrimum	LS	5	5.16	0.26	$AD_t = AD_{t0} * 1.0614^t$	C = 1.1229 + 0.0596 t	0.95	0.008	0.0049	0.06
Inga laurina	P	12	2.83	0.08	$AD_t = AD_{t0} * 1.0302^t$	C = 0.7837 + 0.0297 t	0.95	0.004	0.0053	0.03

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Species	EG	n_{09}	DBH_{09}	IMA_{DBH}	Generic growth equation (AD)	Trend equation	R²	SE	P-value	AGR (cm)
Isertia hypoleuca	ES	16	4.32	0.23	$AD_t = AD_{t0} * 1.0719^t$	C = 0.8552 + 0.0694 t	0.99	0.004	0.0004	0.07
Laetia procera	ES	51	6.55	0.13	$AD_t = AD_{t0} * 1.0223^t$	C = 1.7014 + 0.0221 t	0.91	0.004	0.0119	0.02
Miconia gratissima	ES	20	6.02	0.32	$AD_t = AD_{t0} * 1.0669^t$	C = 1.2467 + 0.0648 t	0.93	0.010	0.0083	0.07
Miconia poeppigii	ES	12	6.08	0.35	$AD_t = AD_{t0} * 1.0794^t$	C = 1.1601 + 0.0764 t	0.97	0.008	0.0022	0.08
Miconia pyrifolia	ES	11	9.35	0.42	$AD_t = AD_{t0} * 1.0569^t$	C = 1.7795 + 0.0553 t	0.94	0.008	0.0064	0.06
Palicourea guianensis	P	5	4.38	0.31	$AD_t = AD_{t0} * 1.1032^t$	C = 0.6652 + 0.0982 t	0.92	0.016	0.0093	0.10
Parkia multijuga	LS	26	8.59	0.19	$AD_t = AD_{t0} * 1.0245^t$	C = 1.9355 + 0.0242 t	0.99	0.001	0.0004	0.02
Tachigali vulgaris	P	7	8.73	0.92	$AD_t = AD_{t0} * 1.2557^t$	C = 0.2865 + 0.2277 t	0.95	0.017	0.0054	0.26
Tapirira guianensis	ES	10	5.21	0.50	$AD_t = AD_{t0} * 1.1899^t$	C = 0.2275 + 0.1739 t	0.91	0.031	0.0117	0.19
Trattinickia lawrencei var. bolivianum	LS	11	4.33	0.14	$AD_t = AD_{t0} * 1.0365^t$	C = 1.1358 + 0.0358 t	0.99	0.002	0.0003	0.04
Trattinickia rhoifolia	LS	9	5.66	0.19	$AD_t = AD_{t0} * 1.0394^t$	C = 1.4025 + 0.0387 t	0.98	0.003	0.0014	0.04
Vantanea parviflora	LS	20	7.86	0.64	$AD_t = AD_{t0} * 1.1402^t$	C = 0.9276 + 0.1312 t	0.98	0.011	0.0011	0.14
Vismia cayennensis	P	45	7.28	0.40	$AD_t = AD_{t0} * 1.0747^t$	C = 1.3994 + 0.0720 t	0.94	0.011	0.0071	0.07
Vismia cayennensis ssp. sessilifolia	P	25	3.12	0.23	$AD_t = AD_{t0} * 1.1129^t$	C = 0.2548 + 0.1070 t	0.93	0.017	0.0081	0.11
Vismia guianensis	P	50	4.61	0.29	$AD_t = AD_{t0} * 1.0854^t$	C = 0.8580 + 0.0820 t	0.89	0.016	0.0152	0.09
Vismia latifolia	P	166	3.52	0.17	$AD_t = AD_{t0} * 1.0626^t$	C = 0.7695 + 0.0608 t	0.90	0.012	0.0138	0.06
Xylopia nitida	ES	17	8.22	0.53	$AD_t = AD_{t0} * 1.0952^t$	C = 1.3220 + 0.0909 t	0.98	0.007	0.0011	0.10

GE: Ecological Group; P: pioneer; ES: early secondary; LS: late secondary; NI: no information; n = number of individuals of the species; IMA = average annual increase in diameter (cm.year^{-1}); AD = average diameter at breast height (cm); t = period of years considered; C = $\ln DFS_t$ periodic growth of the average diameter (cm) estimated for the species in period *t* (years); R² = coefficient of determination; SE = standard error; P-value = regression significance level at 95% (p<0.05), associated with statistics T and F; AGR = average growth rate (cm).

DISCUSSION

Planting of trees

The correct selection of tree species adapted to the conditions of degraded areas is crucial to achieving successful restoration; however, given the complexity of the behavior of these species and the influence of external factors, the successional process can follow different trajectories (BRANCALION *et al.*, 2015).

In the present study, most species showed diameters smaller than 10 cm at 13 years of age and great variation in the average annual increase in DGH (0.15 to 2.50 cm year^{-1}). One of the factors that can explain this effect is the ecological group of the selected species. Of the 32 species studied, 20 belong to the late secondary group. Although this group initially tends to grow vertically to occupy the upper canopy, the plants need better soil fertility conditions to express their productive potential (ALMEIDA, 2016). Furthermore, in the initial stages of development, species in late succession may have limited growth due to competition with pioneer trees (KRAINOVIC *et al*, 2023). Probably, soil preparation, fertilization, subsoiling, and liming at the beginning of planting were not enough to promote diameter growth of these planted species.

In the present study, the three species that presented IMA_{DGH} higher than 1.0 cm year^{-1} belong to the ecological group of pioneers and early secondary, whose main adaptation strategy is rapid growth, with high potential for soil cover and facilitating the establishment of species from other ecological classes (NOGUEIRA *et al.*, 2015). An average annual increase in DBH equal to 1.88±0.44 cm year^{-1} was also reported for species from the pioneer ecological group planted in mined areas at five and six years of age (BARBOSA *et al.*, 2022).

Two ecological groups (pioneer and early secondary) also contain species with a low increase in DGH (<0.40 cm year^{-1}). These species probably did not adapt to the site and may not be the most suitable for planting to restore mining areas. This behavioral trend of distinct species growth patterns between ecological groups was also reported by Nogueira *et al.* (2015), who concluded that each species has an individual performance independent of the ecological group. Therefore, this factor must be considered when selecting species for restoration programs in mined areas.

Accompanying natural regeneration

The evaluated species had values of IMA_{DBH} equal to 0.33±0.22 cm.year^{-1}, with the IMA_{DBH} varying from 0.08 to 0.92 cm.year^{-1} between species. Even though these increases are low compared to the average increases of species found in natural regeneration in planting areas of Mineração Paragominas SA, in the northeast of the State of Para (IMA_{DBH} of 0.70 to 2.08 cm.year^{-1}) (MARTINS *et al.*, 2020), seven species presented IMA_{DBH} greater than 0.50 cm.year^{-1} in the present study, with emphasis on *T. vulgaris* (0.92 cm.year^{-1}) and *B. stipulaceae* (0.88 cm.year^{-1}). These lower increments may reflect how the topsoil is stored, as well as the time of storage and distribution in the restored area, and how soil is spread out in the area. The topsoil removed during mining operations contains organic matter, nutrients, seed banks, and microorganisms, which are essential for successful restoration (QUINTELA-SABARÍS *et al.*, 2018). Nevertheless, when applied during the preparation of the planting area, the superficial layers of soil and deeper horizons mix, which can cause an increase in soil acidity and limit the availability of nutrients necessary for plant growth (QUINTELA-SABARÍS *et al.* 2018; MARTINS *et al.*, 2021).

Among the species studied, the late secondary ecological group presented a greater number of species and a higher abundance of individuals. In an understory, species from the early or late secondary ecological groups are those most capable of growing rapidly during a phase of rapid maturation (BRANCALION *et al.*, 2015).

In the studied areas, the occurrence of some species was also observed, which, according to Salomão *et al.* (2019), can be considered as structuring, occurring in primary forests, such as *Dinizia excelsa* Ducke, *Endopleura uchi* (Huber) Cuatrec., *Goupia glabra* Aubl., *Hymenaea parvifolia* Huber and *Laetia procera* (Poepp.) Eichler. This finding could be a good indicator of the recovery of this artificially reconstructed ecosystem. According to these authors, an ecosystem under restoration must have a floristic composition close to the reference ecosystem.

Growth model

Modeling the growth of trees is important for monitoring the growth of species and predicting the present and future production of forest stands (SCOLFORO *et al.*, 2008; CHASSOT *et al.*, 2011; SALOMÃO *et al.*, 2014).

The equation generated here to express the growth model of the studied species presented acceptable adjustments in terms of standard error of the b coefficient estimate and significance at 95% (p-value<0.05) for the accompanying natural regeneration, which can be attributed to the low variance in species growth rates. Chassot *et al.* (2011) studied diameter growth models for individual *Araucaria angustifolia* (Bertol.) Kuntze trees and concluded that the use of current diameter and sociological position were sufficient to estimate future diameter and that the models presented better estimates for emerging trees.

For planting, only 21 species presented an acceptable adjustment to the equations, with a low standard error of the estimate and significance at 95%. Parameter b of the equation was not significant for species that presented a low average annual diameter growth rate. These species showed a great variation in growth rate, which may be related to the behavior and individual adaptation of the species rather than to the physical environment (MARTINS *et al.*, 2021) since in the present study this was relatively homogeneous throughout the planting.

A study by Salomão *et al.* (2014), evaluating the growth of *Bertholletia excelsa* planted in a mined area, also used the log-linear regression equation to estimate future diameters. The authors obtained good adjustments to the equation and reported that these results may be due to the low variation in growth rates, which the species presented in this artificial ecosystem.

For tree species from the accompanying natural regeneration, and partially, from planting, diameter explained much of the variation in growth rate, and regression equations should be seen as good tools for estimating average growth rates.

The log-linear growth regression equation was statistically significant at 95% (p-value<0.05) and presented a low standard error of the estimate, demonstrating that the adjusted equations explain almost all of the variability in response data (growth in diameter) around its average. For most species in this study, the diameter growth rate was adequately estimated by the log-linear regression model.

Thus, the probable value of the species' diameter can be estimated for future periods under conditions similar to those of this study. Furthermore, it is important to emphasize that the model used is due to the estimation of growth in a given period. Using the regression technique makes work easier when using smaller samples, as it helps to eliminate irregular growth fluctuations in these samples. Another advantage of this technique is that the model makes it possible to calculate growth rates for diameter classes where information is missing (Scolforo *et al.*, 2008).

CONCLUSION

- The log-linear regression model presented good fits to the parameters of the equations and can be used to estimate the future diameter of tree species, as well as to calculate growth rates for diameter classes where there is a lack of data, as long as the conditions of the area are similar to those of this study.
- Our study provides information that allows us to monitor the dynamics of tree species in the restoration process, as well as predict the present and future production of forest stands. However, the use of the model to predict the growth of individual trees must be cautious due to the different environmental conditions existing in restored environments.

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