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MODELING THE BASAL AREA INCREMENT OF *Araucaria angustifolia* (Bertol.) Kuntze IN OLD-GROWTH AND SECONDARY FORESTS OVER THE LAST 60 YEARS

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Resumo

Modelagem do incremento basimétrico de Araucaria angustifolia *(Bertol.) Kuntze em florestas de crescimento antigo e secundárias nos últimos 60 anos.* O manejo florestal em fitofisionomias com *Araucaria angustifolia* (Bertol.) Kuntze, é um tema relevantes ao longo dos últimos anos, mas ainda faltam abordagens estruturais para entender a dinâmica da espécie em diferentes cenários. Esse estudo dendrocronológico de 60 anos, tem como objetivo o uso de modelos lineares de regressão múltipla para definir variáveis que melhor expliquem o incremento periódico em área basal individual (I_gP) de *A. angustifolia*, em fragmentos de crescimento antigo e secundários. Para as análises foram utilizadas 45 árvores no crescimento antigo e 29 no secundário, que consistiram na determinação da largura dos anéis de crescimento ao longo do tempo, para posterior ajuste de modelos pela função *stepwise* por meio do método *backward*, visando a avaliação de suas variáveis quali-quantitativas. Os ajustes dos modelos de crescimento da floresta de crescimento antigo se mantêm estáveis e com precisão superior a 80% ao longo das décadas estudadas, enquanto, nas florestas secundárias, a qualidade dos ajustes tende a diminuir à medida que o tempo passa. Ambos os cenários apresentaram um crescimento de aproximadamente 0,063 m² de área basal individual ao longo dos 60 anos, porém com taxas individuais de incremento periódico diamétrico superior nas florestas secundárias (2,1-16,4 cm), em comparação as florestas de crescimento antigo (1,9-11,5 cm). Concluiu-se que pelo método stepwise, cinco variáveis foram ideais para modelar o crescimento de *A. angustifolia*, com taxas de crescimento basal semelhantes, mas distintas do crescimento diamétrico, sendo que as florestas de crescimento antigo apresentaram maior estabilidade que as secundárias.
Palavras-chave: pinheiro-brasileiro; manejo sustentável; área basal.

Abstract

Forest management in phytophysiognomies with *Araucaria angustifolia* (Bertol.) Kuntze has been a relevant topic over the last few years, but there is still a lack of structural approaches to understand the dynamics of the species in different scenarios. This 60-year dendrochronological study aimed to use linear multiple regression models to define variables which best explain the periodic basal area increment (BAI) of *A. angustifolia* individuals in of old-growth and secondary forest fragments. A total of 45 trees were used in the old-growth and 29 in the secondary forests for the analyses, which consisted of determining the growth ring width over time for later fitting in models by the stepwise function through the backward method, aiming to evaluate their quali-quantitative variables. The fits of the old-growth forest growth models remained stable and presented greater than 80% accuracy over the decades studied, while the fit quality in the secondary forest models tended to decrease over time. Both scenarios showed an increase of approximately 0.063 m² of individual basal area over the 60 years, but with higher individual periodic diameter increment rates in secondary forests (2.1-16.4 cm) compared to old-growth forests (1.9-11.5 cm). It was concluded that five variables in the stepwise method were ideal to model the growth of *A. angustifolia*, with basal growth rates similar to, but distinct from diametric growth, and the old-growth forests showed greater stability than secondary forests.
Keywords: Brazilian pine; forest management; basal area.

INTRODUCTION

The Mixed Ombrophilous Forest, also known as Araucaria Forest, constitutes an emblematic phytophysiognomy of the Atlantic Forest Biome in southern Brazil. However, intense overexploitation for timber, combined with commercial plantations and agricultural expansion (SILVA *et al*., 2023a) resulted in a drastic reduction of its original cover (RIBEIRO *et al*., 2009). It is currently estimated that less than 3% of the Araucaria forests are in an advanced conservation stage (GUERRA *et al*., 2002; VIBRANS et al., 2013; MOLINA-VALERO *et al*., 2021), also called old-growth or primary forests (SCIPIONI *et al*., 2021). This forest formation is characterized by the dominant presence of *Araucaria angustifolia* (Bertol.) Kuntze (Araucariaceae), a species which played an important role in the colonization and economic development of the region, especially during the 20th century (DOBNER Jr. *et al*., 2019). The intense exploitation of *A. angustifolia* caused it to be included in the list of endangered species, where restrictive measures were taken by the government at the end of the 20th century in order to stop exploitation of the species (BRASIL, 2014; GASPER *et al*., 2017); however, it continues to be exploited illegally (GUERRA *et al*., 2002; BRANDES *et al*., 2020).

Forest management in phytophysiognomies with *A. angustifolia* has been a relevant research topic in recent years, but there is still a lack of structural approaches which help understand its dynamics in old-growth and secondary-growth forests. Although several previous studies have evaluated the structure and growth of the species (LONGHI *et al*., 2018; BRANDES *et al*., 2021; SCIPIONI *et al*., 2021; SILVA *et al*., 2021; STEPKA *et al*., 2021), there is a lack of quantitative and qualitative approaches to support management through studies on the behavior and growth dynamics of the species. In this context, understanding how forest dynamics occur in old-growth and secondary fragments contributes to restructuring secondary forests, aiming at forest management and conservation.

The differentiated structure of old-growth and secondary fragments directly influences the growth of *Araucaria angustifolia* and reflects distinct development patterns, as can be observed in the studies by Vaz *et al*. (2022) and Silva *et al*. (2023b; 2024). The dynamics of these forests are conditioned by structural and environmental factors which affect tree growth stability, making the analysis of quantitative and qualitative variables essential to understand these processes. The basal area increment (BAI) not only reflects the individual growth of trees, but also the influence of disturbances and structural variations in the forest environment. Thus, understanding the interaction between these variables in the different growth scenarios of the species is essential to improve management and conservation strategies.

In view of the above, linear models in the growth period of *A. angustifolia* in the last 60 years were analyzed and fitted through multiple regression techniques in the present study, with the objective of testing which variables (quantitative and qualitative) best explained the periodic BAI of *A. angustifolia* in old-growth and secondary growth fragments, in addition to a differentiation analysis between them.

MATERIAL AND METHODS

Study location

The study area is located at the average coordinates of 28.01ºS and 50.80W, on the southern plateau of Brazil, specifically in the municipalities of Campo Belo do Sul and Capão Alto (Figure 1), in the Araucária Forest domain (VIBRANS *et al*., 2013) of the Atlantic Forest biome. The physical and meteorological characteristics are: Cambisol and Nitosol soils of volcanic origin (diabase and basalt); undulating topography to strongly undulating and natural fields; altitude: 500-1000 m; climate: humid subtropical (Cfb); temperature: average of 16°C, ≥0°C as an absolute minimum; precipitation: 1,400-1,800 mm per year, evenly distributed throughout the year; frosts: 2-30 days per year, concentrated in the months corresponding to autumn and winter in the southern hemisphere (ALVARES *et al*., 2013). The old-growth and secondary forest fragments studied were classified by the usage and conservation history reported by the area managers, being structurally distinct according to a study conducted by Vaz *et al.* (2022).

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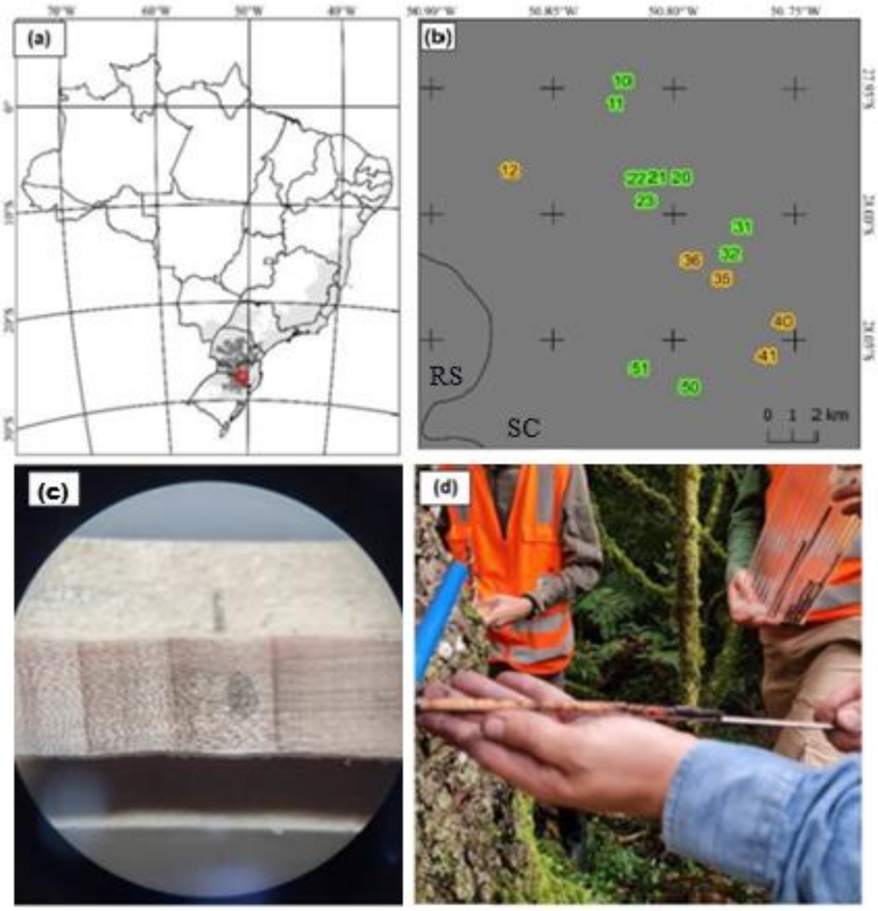

Figure 1. [a] Location of the fragments studied in the southern Brazilian plateau, [b] with the green fragments constituting the old-growth fragments and the orange fragments secondary growth; [c] analyzed in a fixed magnifying glass with a magnification of 12x; [d] increment drumsticks measured with an auger with an increment of 400mm x 3 threads in *A. angustifolia*.

Figura 1. Localização dos fragmentos estudados no planalto do sul do Brasil [a], sendo os em verde os fragmentos de crescimento antigo e os em laranja de crescimento secundário [b]; analisado em lupa fixa com aumento de 12x [d]; baquetas de incremento, com auxílio de trado de incremento de 400mm x 3 roscas, em *A. angustifolia* [d].

Sample collection and preparation

A total of 15 Araucaria Forest fragments were evaluated: 10 from old-growth forest and 5 from secondary forest. The number of individuals sampled for old-growth and secondary forest were 329 and 143 *A. angustifolia* individuals, respectively. All individuals presented the following quantitative and qualitative variables collected according to the methodology of the Santa Catarina Forest Floristic Inventory (*Inventário Florístico Florestal de Santa Catarina - IFFSC*) (VIBRANS *et al.*, 2012; Vaz *et al.*, 2022) and were used in fitting the models:

a) diameter at breast height (*d*): measured at 1.3 m height (cm);
b) total height (*h*): measured with Vertex IV Hypsometer (*m*);
c) stem height (*th*): distance between the tree's stem base and the midpoint where the photosynthetically active crown begins (m);
d) crown length (*cl*): difference between total height and stem height (m);
e) height to diameter ratio (*h/d*): total height divided by the tree's diameter (m).

The qualitative variables were:

f) stem quality (*tq*): classified as: (1) straight; (2) slightly crooked; or (3) crooked;
g) stem health (*thl*): classified according to four situations: (1) healthy, 0% visible damage; (2) low damage intensity, < 30% visible damage; (3) medium damage intensity, < 30% and > 50% visible damage; and (4) high damage intensity, < 50% visible damage;

h) sociological position (*sp*): characterization of the tree's vertical position in relation to its neighbors, being classified as belonging to the stratum: (1) dominant; (2) medium; and (3) dominated;
i) vascular epiphytes (*ve*): presence of vascular epiphytes on the individual;
j) lianas (*l*): presence of lianas on the individual.

The selection of individuals sampled in each fragment followed the Sturges class method (1926), which defines the number (k) and the amplitude of the classes (Ac) according to equations 1 and 2. This criterion is widely used in forestry studies and provides a standardized categorization and facilitates comparative analyses without compromising the data representativeness.

$$k = 1 + 3.3 \times \log(N)$$

In which: N is the number of *A. angustifolia* individuals sampled in the fragment.

$$Ac = \frac{> obs - < obs}{k - 1}$$

In which: > obs is the largest observation in *d* of the sample, < obs is the smallest observation in *d* of the sample, *k* is the number of classes.

The *k* according to the Sturges method (1926) was 9 and 8 classes for the old-growth and secondary fragments, respectively. They are highlighted in Table 1, with the class center and the lower and upper limits for each fragment type.

Table 1. Arrangement of classes by the Sturges method for different fragment types.
Tabela 1. Arranjo de classes pelo método de Sturges, para diferentes tipos de fragmentos.

Fragment	Classes	C.C. (cm)	L.L. (cm)	U.L. (cm)	Samples
Old-growth	1	10.1	2.6	17.6	6
	2	25.2	17.6	32.7	6
	3	40.2	32.7	47.7	7
	4	55.3	47.7	62.8	7
	5	70.3	62.8	77.8	8
	6	85.4	77.8	92.9	10
	7	100.4	92.9	107.9	7
	8	115.5	107.9	123.0	4
	9	130.5	123.0	138.0	4
Total					59
Secondary	1	10.0	5.0	15.0	6
	2	19.9	15.0	24.9	5
	3	29.9	24.9	34.9	7
	4	39.8	34.9	44.8	6
	5	49.8	44.8	54.7	6
	6	59.7	54.7	64.7	5
	7	69.7	64.7	74.6	3
	8	79.6	74.6	84.6	2
Total					40

Legend: C.C. class center (cm); L.L. lower limit (cm); U.L. upper limit (cm).

Wood samples were collected from a total of 99 *A. angustifolia* trees, with 59 from trees in old-growth fragments and 40 in secondary fragments. Each tree had two sampling replicates (198 increment drumsticks collected), obtained by a 40 cm increment and Ø5.1 mm auger. Each replicate per tree was collected at a height of 1.3 m in position *d* with a difference of 90º to better represent the shape and increment of the sampled trees (Figure 1d).

After collecting the samples, both were fixed to a wooden support measuring 25 mm x 25 mm x 450 mm, with the fibers being arranged vertically to facilitate visualizing the growth rings for later analysis. After drying the samples at room temperature (~20ºC) and already stored in the Forest Resources Laboratory I (LRF-I) of the Federal University of Santa Catarina (UFSC), the collected material was then polished aiming to show the growth rings of the species using an orbital sander with abrasive sandpaper with a grain size of 60 to 2,000 cm^{-2}, with subsequent pre-analysis under a magnifying glass with 12x magnification (Figure 1c). After analysis, 145 of the 198 increment drumsticks collected were considered viable for analysis, while 53 were discarded due to the presence of cracks, irregular grain and deformities in the wood. Thus, 49 *A. angustifolia* trees were analyzed in old-growth fragments and 29 in secondary fragments. Among the 78 sampled trees, 11 had only one viable drumstick, which was used in the study.

Growth ring analysis

Images of the pre-analyzed materials of *A. angustifolia* were scanned on a SHARP MX-M453N scanner at 600 dpi resolution, then loaded, and their dating, growth ring measurements and exclusion of false rings were performed using the Cybis CooRecorder version 9.6 program through Pearson's correlation, comparison between drumsticks and the master chronology, as detailed below. The samples with the highest correlation were selected for composing the master chronology and coding in the Cybis dendro dating (CDDendro) version 9.6 program. The samples were subsequently cross-dated in the COFECHA version 6.0 program using a cubic smoothing spline with a 50% wavelength cut-off for filtering in 30-year intervals and 15-year overlap. This procedure aimed to validate the growth ring dating in the last 40 cm of the stem (limited by the auger length used) and to correlate tree growth with previous years.

Increment drumsticks from the same tree were combined into a representative average of the sampled individual whenever they presented a correlation greater than 0.40, with 99% confidence by the Pearson's correlation test. This more flexible criterion was adopted due to the presence of false growth rings and variations in the stem shape, which is rarely a perfect circle. In situations where the increment drumsticks did not present a correlation greater than 0.40, the drumstick which presented the highest correlation with the other sampled trees was selected, ensuring that no additional trees were excluded from the master chronology. An intercorrelation greater than 0.4226 was sought when comparing trees from the same fragment, also with 99% confidence by the Pearson's correlation test as determined by the COFECHA program.

Next, a graph of the Current Annual Increment (CAI) in diameter was drawn up over the decades for the initial increment analysis, enabling visualization of the variations in growth over time. After this process, fits were made to linear multiple regression models with the aim of finding the variables which best explained the periodic basal area increment (BAI) of *A. angustifolia* individuals in each decade, verifying the differentiation between the types of fragments. Trees that presented negative growth rates in relation to the initial values of the study variables (Table 2 of the Results) in each period analyzed were excluded from fitting. As a result, 45 trees were considered in the old-growth fragments and 29 in the secondary-growth fragments, ensuring that only the trees effectively present at the site in each period were included in the analysis.

Fitting followed transformations of the quantitative variables, which were: x_i^2, $Ln(X_i)$, $Ln(X_i{}^2)$, $^1/_{x_i}$, $^1/_{x^2}$. The qualitative variables remained unchanged, while the response variable (BAI) was transformed to the natural logarithmic scale. All transformations were intended to reduce heterogeneity of variances, obtaining the highest fit correlation coefficient and lowest relative standard error. The analyses and fits of the models were performed with the statistical R Core Team (2021) program using the stepwise function using the "backward" method. This consists in adding all variables and removing them one by one in order to find the variables which best represent the fit for the projections of 10, 20, 30, 40, 50 and 60 years ago, reaching the initial period of forest interventions in the secondary fragments studied. The best fits were based on the highest coefficients of determination (R^2) of the multiple linear regression equation and the standard error of the relative estimate (S_{yx}%).

RESULTS

The result of the Current Annual Increment (CAI) in diameter over time is represented in Figure 2, with the aim of showing the increment variation between the old-growth and secondary fragments. In turn, the qualitative and quantitative characteristics presented in Table 2 are obtained from collecting the variables for each *A. angustifolia* individual used in the fitting, along with the descriptive statistics of the data.

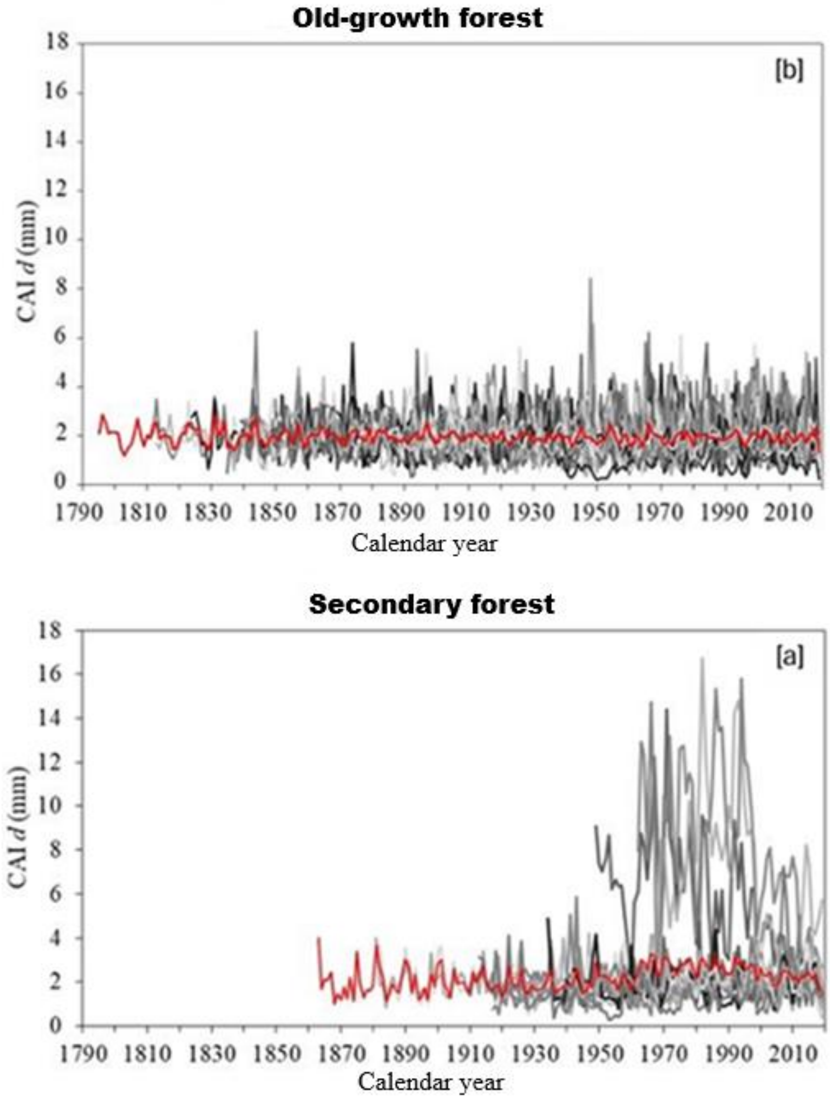

Figure 2. Current Annual Increment (CAI) in diameter (d in mm) of *Araucaria angustifolia* trees (gray scale) analyzed in [a] secondary forest, and of *Araucaria angustifolia* trees (gray scale) analyzed in [b] old-growth forest, with the average number of trees analyzed (red) for each situation.

Figura 2. Incremento corrente anual (ICA) em diâmetro (d em mm) de árvores de *Araucaria angustifolia* (escala de cinza, n=45) analisadas em floresta secundária, [b] e de árvores de *Araucaria angustifolia* (escala de cinza, n=29) analisadas em floresta de crescimento antigo, com a média de árvores analisadas (vermelho) para cada situação.

Table 2. Descriptive statistics of *A. angustifolia* individuals and average increments observed for each forest type over the decades of study.

Tabela 2. Estatística descritiva dos indivíduos de *A. angustifolia*, e incrementos médios observados para cada tipo florestal, ao longo das décadas de estudo.

Variables	Old-growth fragments			Secondary fragments		
	Mean	Amplitude	CV (%)	Mean	Amplitude	CV (%)
g (m^2)	0.443	0.005-1.474	88.78	0.205	0.009-0.504	68.38
d (cm)	66.45	8.50-137.00	53.16	47.48	11.20-80.10	40.96
h (m)	21.2	8.7-33.7	26.78	19.85	12.6-25.2	16.22
th (m)	16.54	7.4-26.2	24.91	15.25	9.7-21.0	22.33
cl (m)	4.94	0.5-15.5	72.51	4.61	1.8-8.6	42.68

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Variables	Old-growth fragments			Secondary fragments		
	Mean	Amplitude	CV (%)	Mean	Amplitude	CV (%)
h/d (m)	41.26	20.7-102.4	51.92	50.36	27.5-125.0	50.38
q_f	1.06	1-2	22.08	1.04	1-2	18.25
thl	1.02	1-2	13.48	1	1-1	0.0
sp	1.40	1-3	45.17	1.18	1.2	33.09
ev	0.87	0-1	39.38	0.36	0-1	136.63
l	0.09	0-1	312.80	0.21	0-1	195.00
BAI_{10} (m²)	0.423	0.003-1.435	90.54	0.189	0.007-0.454	69.89
BAI_{20} (m²)	0.404	0.002-1.397	92.40	0.173	0.004-0.430	70.93
BAI_{30} (m²)	0.391	0.001-1.351	92.46	0.155	0.002-9.496	72.77
BAI_{40} (m²)	0.386	0.000-1.311	91.36	0.143	0.001-0.384	72.15
BAI_{50} (m²)	0.383	0.000-1.275	89.26	0.142	0.006-0.362	65.45
BAI_{60} (m²)	0.380	0.000-1.229	86.77	0.153	0.004-0.342	56.45

Legend: CV. Coefficient of variation in percentage; *g*. individual basal area (m²); *d*. diameter at breast height 1.30 m (cm); *h*. total height (m); *th*. stem height (m); *cl*. crown length (m); *h/d*. height to diameter ratio (m); *tq*. stem quality; *thl*. Stem health; *sp*. sociological position; *ve*. vascular epiphytes; *l*. lianas; BAI. basal area increment in each period.

The best fits were selected from the largest adjusted coefficients of determination for each period in relation to the master chronology and the relative standard error of the estimate. The results are presented in Tables 3 and 4, respectively, for the fits of old-growth and secondary forests.

Table 3. BAI modeling statistics for old-growth fragments over the past 10, 20, 30, 40, 50, and 60 years. Dependent variable did not need to be transformed.

Tabela 3. Estatística da modelagem do BAI para os fragmentos de crescimento antigo, nos períodos de 10, 20, 30, 40, 50 e 60 anos anteriores. Variável dependente não precisou ser transformada.

Old-growth fragments	Independent variable	Mathematical parameters β_x	β_x value	R^2	S_{yx}%
10 years BAI_{10}		β_0	4.658×10^{-3}		
	d	β_1	2.318×10^{-4}		
	cl	β_2	1.888×10^{-4}		
	(*h/d*)	β_3	-5.832×10^{-5}		
	ve	β_4	-9.195×10^{-4}		
	h^2	β_5	4.167×10^{-6}	0.9801	15.81
20 years BAI_{20}		β_0	4.674×10^{-3}		
	d	β_1	5.633×10^{-4}		
	(*h/d*)	β_2	-4.013×10^{-5}		
	tq	β_3	-1.092×10^{-3}		
	th	β_4	7.157×10^{-5}		
	thl	β_5	-1.496×10^{-3}	0.9934	17.91
30 years BAI_{30}		β_0	1.216×10^{-2}		
	d	β_1	9.247×10^{-4}		
	sp	β_2	-1.539×10^{-3}		
	ln (*h*)	β_3	-3.323×10^{-3}		
	ve	β_4	-9.902×10^{-4}		
	thl	β_5	-2.582×10^{-3}	0.9967	19.71
40 years BAI_{40}		β_0	3.458×10^{-3}		
	d	β_1	1.209×10^{-3}		
	(*h/d*)	β_2	-4.326×10^{-5}		
	h	β_3	-1.395×10^{-4}		
	sp	β_4	-1.034×10^{-3}		
	thl	β_5	-9.543×10^{-5}	0.9984	17.81

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Old-growth fragments	Independent variable	Mathematical parameters β_x	β_x value	R^2	S_{yx}%
50 years BAI50		β_0	-3.226×10^{-3}		
	d	β_1	1.475×10^{-3}		
	(h/d)²	β_2	-5.803×10^{-7}		
	sp	β_3	-6.551×10^{-4}		
	thl²	β_4	-3.667×10^{-6}		
	h²	β_5	3.824×10^{-6}	0.9984	21.76
60 years BAI60		β_0	-7.508×10^{-3}		
	1/d	β_1	1.841×10^{-3}		
	ve	β_2	-7.196×10^{-3}		
	(h/d)²	β_3	-6.371×10^{-7}		
	1/cl²	β_4	1.013×10^{-1}		
	sp	β_5	-8.995×10^{-4}	0.9983	26.29

Legend: R^2. coefficient of determination adjusted for each period in relation to the master chronology; S_{yx}% relative standard error; *d*. diameter at breast height 1.30 m (cm); *h*. total height (m); *th*. stem height (m); *cl*. crown length (m); *h/d*. height to diameter ratio (m); *tq*. stem quality; *thl*. stem health; *sp*. sociological position; *ve*. vascular epiphytes; *l*. lianas; BAI. basal area increment in each period.

Table 4. BAI modeling statistics for the secondary fragments in the previous 10, 20, 30, 40, 50 and 60 years. Dependent variable underwent natural logarithmic transformation.

Tabela 4. Estatística da modelagem do I_gP para os fragmentos secundários, nos períodos de 10, 20, 30, 40, 50 e 60 anos anteriores. Variável dependente passou pela transformação logarítmica natural.

Secondary fragments	Independent variables	Mathematical parameters β_x	β_x value	R^2	S_{yx}%
10 years BAI10		β_0	-6.591		
	$\sqrt{d}$	β_1	3.543×10^{-1}		
	cl²	β_2	4.307×10^{-3}		
	(h/d)²	β_3	-1.069×10^{-5}		
	tq	β_4	7.985×10^{-2}		
	ln (h²)	β_5	-4.442×10^{-2}	0.9053	21.07
20 years BAI20		β_0	-2.224201		
	$\sqrt{d}$	β_1	0.492703		
	ln (thl²)	β_2	-0.837998		
	h²	β_3	0.002392		
	$\sqrt{cl}$	β_4	-0.378928		
	1/(h/d)	β_5	-15.179647	0.9042	22.08
30 years BAI30		β_0	-1.307040		
	$\sqrt{d}$	β_1	0.543939		
	ln (thl²)	β_2	-0.997523		
	h²	β_3	0.002709		
	$\sqrt{cl}$	β_4	-0.410671		
	1/(h/d)	β_5	-17.882762	0.8694	28.38
40 years BAI40		β_0	-5.1794108		
	$\sqrt{d}$	β_1	0.3229717		
	cl²	β_2	0.0056552		
	(h/d)	β_3	-0.0053054		
	ve	β_4	0.0844273		
	thl²	β_5	0.0005545	0.8453	31.70
50 years BAI50		β_0	-8.5263		
	$\sqrt{d}$	β_1	1.0019		
	ln (thl²)	β_2	-2.1451		
	$\sqrt{h/d}$	β_3	0.4685		
	$\sqrt{cl}$	β_4	-1.1512		
	ln (h)	β_5	3.2954	0.8150	30.84

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Secondary fragments	Independent variables	Mathematical parameters β_x	β_x value	R^2	S_{yx}%
		β_0	-1.555		
	1/d	β_1	-1.227×10^{-2}		
60 years	*ve*	β_2	3.991×10^{-1}		
BAI_{60}	*(h/d)²*	β_3	8.930×10^{-4}		
	1/cl²	β_4	8.103×10^{-1}		
	sp	β_5	1.556×10^{-1}	0.7644	31.32

Legend: *R²*. coefficient of determination adjusted for each period in relation to the master chronology; S_{yx}% relative standard error; *d*. diameter at breast height 1.30 m (cm); *h*. total height (m); *th*. stem height (m); *cl*. crown length (m); *h/d*. height to diameter ratio (m); *tq*. stem quality; *thl*. stem health; *sp*. sociological position; *ve*. vascular epiphytes; *l*. lianas; BAI. basal area increment in each period.

The mean basal growth rates (g) of *A. angustifolia* individuals for old-growth forests ranged from 0.380 to 0.443 m² (Table 2). When converted, these rates resulted in a periodic diameter increase of 0.08 to 1.19 mm, with averages of 0.19 to 1.15 mm (Figure 2). A BAI of 0.064 m² was observed over six decades, corresponding to a diameter increase of 28.5 cm in this interval, with values close to those found in secondary forests. The mean growth rates in secondary forests in g were 0.142 to 0.205 m² (Table 2). When converted, they resulted in periodic diameter increases of 0.17 to 4.76 mm, with averages of 0.21 to 1.64 cm in the analyzed periods (Figure 2). Thus, a BAI of 0.063 m² per tree was recorded over a 60-year period, corresponding to an average increase in diameter of 28.3 cm (Table 2). Comparatively, old-growth forests showed lower average diameter increase rates (0.19 to 1.15 mm) than secondary forests (0.21 to 1.64 cm) over the same time interval (Figure 2).

The coefficient of variation (CV) in old-growth forests was higher than that observed in secondary forests. However, when analyzing the qualitative and quantitative variables, the BAI in old-growth forests (0.380 to 0.423 m²) showed more stable growth rates over the years, with CV ranging from 86% to 93% (Table 2). This stability was maintained when transformed into diameter, with an average of 0.38 to 1.15 mm and CV ranging from 7% to 11%. However, the trend was different for secondary forests. It is worth noting that the BAI in these fragments presented an average amplitude in the analyzed periods between 0.142 and 0.189 m², with a CV of 56% to 73% (Table 2). When transforming g into diameter, the average diametrical increase varied from 0.21 to 1.63 mm, with an amplitude of 0.17 to 4.76 mm and a CV of 31% to 69%, from the smallest to the largest period analyzed.

The linear multiple regression model fits for araucaria trees in old-growth fragments presented the best R² and S_{yx}% values in the longest periods analyzed (30 to 60 years) (Table 3). Moreover, the models had a better fit for shorter periods (10 to 30 years) in secondary forests (Table 4), evidencing the expressive variation in the growth of these areas over time. The stepwise method applied with the backward function demonstrated better performance with the use of five variables. The inclusion of a sixth variable provided an irrelevant gain, while the exclusion of a variable compromised the fit quality in terms of S_{yx}% and R².

DISCUSSION

The regression models fitted for *A. angustifolia* trees in old-growth areas showed excellent performance over the years, while the fits for secondary areas were more accurate in the first decades, but lost quality over time. This indicates that growth in secondary forests is more variable over the decades, while the stability in growth rates in old-growth forests enabled more robust fits over time. In addition, the R² values were higher and the S_{yx}% lower regarding the model fits in old-growth areas, thereby enabling reliable fits over longer periods. The presence of large disturbances in short periods in secondary areas resulted in greater variability in growth rates, compromising the models' accuracy for longer periods and resulting in lower R² values. Furthermore, the fits presented high errors in some secondary forests, even when the coefficient of variation (CV) was low, suggesting that additional factors may be influencing the models' accuracy. However, it is important to emphasize that this result reflects the current reality of the trees analyzed, whose qualitative and quantitative characteristics were obtained recently and may not accurately represent the growth conditions in previous periods, which could have greater variation.

The stability of growth rates in old-growth areas can be explained by the lower incidence of disturbances, which occur on a smaller scale and naturally, allowing for less variation in the growth of individuals and consequently more precise fits over the years. According to Vaz *et al*. (2022), this behavior is due to the greater environmental stability in these areas which favors more homogeneous growth patterns. Introduction of new *A. angustifolia* individuals and the increasing occurrence of disturbances in secondary areas over time resulted in greater variability in growth rates and higher errors in model fits.

The results of this study differ from those presented by Stepka *et al*. (2012), who modeled the basal growth of *A. angustifolia* in a Mixed Ombrophilous Forest in south-central Paraná and fitted 10 models to estimate the DBH growth. The authors stratified the data according to phytosanitary characteristics, stem quality, vertical position, crown quality and diameter classes, while in this study these variables were directly incorporated into the fits. The best results of Stepka *et al*. (2012) occurred in trees with better phytosanitary conditions, but with R^2 ranging from 0.1991 to 0.2761 and S_{yx}% from 78.19 to 82.25, constituting lower values than those found in the present study (Table 4). This indicates that models with multiple variables can better represent the growth of the species, reducing error and providing greater precision in fitting.

Costa *et al*. (2016) fit growth models for *A. angustifolia* in the Lages, SC region, using generalized linear models (GLMs) with three independent variables. Their models presented consistent fits, allowing growth projections for the next five years. The diametric amplitude obtained in these models differs from the fits made for old-growth areas in this study, but is similar to the secondary forest areas. In the study by Costa *et al*. (2017), models with 11 qualitative and quantitative variables were applied to *A. angustifolia* in the states of SC and RS using the stepwise method, obtaining an R^2 of 0.5742 and S_{yx}% of 46, with lower fits than those found in the present study. These results reinforce the importance of including qualitative variables in the models to better represent the growth of the species, since models with simple inputs based only on quantitative variables, such as diameter and height, do not fully capture the complexity of the factors which influence the growth of *A. angustifolia*.

The studies discussed propose fits for modeling the growth of *A. angustifolia* over short periods, without fully considering the potential expression of this forest physiognomy. However, this study broadens understanding of the historical structure of the species, enabling an analysis of its growth over decades and its response to environmental changes. On the other hand, the fit accuracy could be improved with a greater number of samples, since growth ring analysis is subject to biases inherent to the methodology. Furthermore, considering the centennial life cycle of the species, an analysis period of 60 years may not be sufficient to capture the full complexity of the growth dynamics of *A. angustifolia*, making it essential to conduct studies covering increasingly longer periods. Finally, it is essential to expand the analyses to different locations in order to understand how distinct environmental gradients influence the growth variation of the species and thus improve the representativeness of the developed models.

CONCLUSION

It is concluded that:

- Old-growth *A. angustifolia* forests had more stable growth (1.9 – 11.5 cm) than secondary forests (2.1 – 16.4 cm) due to fewer disturbances, but secondary forests had larger growth rates;
- Regression fits were more accurate in the long term (30-60 years) in old-growth forests and better in the short term (10-30 years) in secondary forests;
- The mean BAI was similar between old-growth forests (0.380-0.423 m²) and secondary forests (0.142 – 0.189 m²), with less variation in old-growth forests;
- The stepwise method showed that five variables were ideal for modeling growth, with the addition of a new variable resulting in insignificant gains, and with its removal the fit did not present a good result when compared previously;
- Understanding the growth of *A. angustifolia* over time improves decision-making for management and conservation of the species, allowing integration of past and future analyses in defining more effective strategies.

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