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# GROWTH MODELS FOR *Araucaria angustifolia* (BERTOL.) KUNTZE IN DIFFERENT ECOLOGICAL GRADIENTS IN THE STATE OF SANTA CATARINA

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**Resumo**

*Modelos de crescimento para Araucaria angustifolia (Bertol.) Kuntze em diferentes gradientes ecológicos no estado de Santa Catarina*. O crescimento de um ou mais indivíduos em uma floresta é variável com as condições bióticas e abióticas do ambiente. Diante disso, o objetivo deste artigo foi obter estimativas de idade e crescimento da *Araucaria angustifolia* em diferentes gradientes de altitude de ocorrência da espécie e identificar os pontos de culminação em área basal. O estudo abrangeu três áreas com Floresta Ombrófila Mista no estado de Santa Catarina, considerando diferentes altitudes de ocorrência da espécie. Foram coletadas amostras não destrutivas de 226 árvores, sendo 76, 73 e 77 árvores nas áreas 1, 2 e 3, respectivamente, e com isso analisado os anéis de crescimento. Utilizando as séries cronológicas, foram ajustados modelos de crescimento diamétrico, permitindo a obtenção das curvas de incremento corrente anual e incremento médio anual. Na área 1, a idade máxima das amostras foi de 174 anos, na área 2, foi de 170 anos e, na área 3, foi de 42 anos. O incremento médio anual para as áreas 1, 2 e 3 foram de 0,33 cm, 0,51 cm e 1,01 cm, respectivamente. A araucária consegue atingir um potencial elevado de crescimento por estar em melhores condições de desenvolvimento (solo, nutrientes, luz...).
*Palavras-chave:* Floresta de Araucária. Dendrocronologia. Altitude.

**Abstract**

The growth of one or more individuals in a forest is variable with the biotic and abiotic conditions of the environment. Therefore, the objective of this article was to obtain the age and growth estimates of *Araucaria angustifolia,* in different altitude gradients of occurrence of the species, and to identify the culmination points in the basal area. The study covered three areas with Araucaria Forest in Santa Catarina state, considering different altitudes of occurrence of the species. Non-destructive samples were collected from 226 trees, 76, 73 and 77 trees in areas 1, 2 and 3, respectively. Using the time series, diametric growth models were adjusted, allowing to obtain the curves of current annual increment and average annual increment. In area 1, the age range of the samples was 174 years, in area 2, it was 170 years and in area 3, it was 42 years. The average annual increment for areas 1, 2 and 3 were 0.33 cm, 0.51 cm and 1.01 cm, respectively. Araucaria manages to reach a high growth potential when it is in better development conditions (soil, nutrients, light…).
*Keywords:* Araucaria forest. Dendrochronology. Altitude.

## INTRODUCTION

The response of the tree species to changes in the environment allows variations in temperature, humidity, light, etc., to be registered in the growth rings. When the trees develop under similar conditions over a period of years, they end up showing synchronism in the variation of the width of their growth rings (FRITTS, 1976).

Dendrochronology is the science that studies growth rings, and from it, it is possible to know the situations of trees and populations. Dendrochronology helps to understand the structure and dynamics of native forests (MATTOS *et al.*, 2011), as the data obtained by this technique provide important information about the tree growth, such as knowledge of favorable years for growth and the more limiting (FRITTS, 1976).

In places with different altitude conditions, the behavior of the climate influences the structure of the forest. The wind, present in higher altitude areas, can cause stress on trees, causing them to spend more energy on mechanical support, at the expense of growing in height (LAWTON, 1982).

Species diversity and forest stature decrease with increasing altitude in tropical mountains. In addition, other physiognomic features, such as leaf characteristics, also change with altitude (GENTRY, 1988).

Scientific rigor for the application of dendrochronology is essential to ensure that the data are consistent and can be applied in various ecological analyzes of the forest (MIRANDA *et al.*, 2018b). Procedures such as cross dating allow the identification of false rings and missing growth layers, eliminating these sources of errors in the growth series (GROENENDIJK *et al.*, 2017).

To know the maximum diameter growth potential of a given species, it is important to know the growth of trees free of competition, aerial or underground. Furthermore, in order to propose the management of forests and forest populations, with a view to production sustainability, it is important to know not only the volumetric growth of wood, expressed by the increase in diameter and height and by the modification of the form factor, but also the growth and changes in the shape of the crown (DURLO *et al.*, 2004).

Until the beginning of the 20th century, *Araucaria angustifolia* (Bertol.) Kuntze dominated the landscapes of southern Brazil, where it covered a good part of the Southern Plateau. This species is the main element of the Araucaria Forest (KOCH; CORRÊA, 2010).

Araucaria is a species that can live hundreds of years. Its age and growth dynamics can be determined by the growth rings that are formed in the trunk (KOCH; CORRÊA, 2010).

The objective of this article was to obtain the increments by diameter class, the age estimates, describe and model the growth of *Araucaria angustifolia* in different altitude gradients of occurrence of the species and identify according to individual tree the culmination points in the basal area. This information can be used as basis for the elaboration of future sustainable management plans, providing the maintenance and conservation of this species.

## MATERIAL AND METHODS

### Study area

The study was carried out in areas of natural *Araucaria angustifolia* forest located in three municipalities in the state of Santa Catarina. The choice of locations was made in the way that they covered different altitudes of natural occurrence of the species, as follows: Bom Jardim da Serra (Area 1, average altitude of 1,350 m, Latitude 28°20'31" S, Longitude 49°35'10 " W, average annual rainfall of 1,670 mm), Painel (Area 2, average altitude of 1,150 m, Latitude 27°53'57" S, Longitude 50°07'42" W, average annual rainfall of 1,125 mm) and São José do Cerrito (Area 3, average altitude 950 m, Latitude 27°42'40" S, Longitude 50°28'51" W, average annual rainfall of 1,570 mm).

The three areas are private rural properties and have a high density of *Araucaria angustifolia* distributed in clumps of forest remnants of Araucaria Forest (AF).

For the three areas, according to the Köppen classification, the climate is predominantly characterized as being of the Cfb type, temperate proper, constantly humid and without a dry season, with an average temperature of the coldest month below 18ºC (mesothermal) (ALVARES *et al.*, 2013).

### Data collect

The sample units containing the araucaria trees for data measurement were selected by a random sampling process, using the Bitterlich method, with basal area factor (BAF) 2. The sample sufficiency indicated the representative number of points in each 7 in Bom Jardim da Serra (area 1), 6 in Painel (area 2) and 6 in São José do Cerrito (area 3).

Dendrochronological samples were collected from 226 araucaria trees, 76 in area 1, 73 in area 2 and 77 in area 3, with two non-destructive samples (increment rollers) being collected from each sample tree with a 30 cm Pressler Auger. The first sample was taken at 1.30 m above the ground (diameter at breast height – DBH) and the second at 90º from the first, shifted by 10 cm. The collections were carried out in the year 2017.

The growth rings were delimited, counted and measured with the aid of a stereoscopic microscope and a ring measuring table (LINTAB 6.0 - Frank Rinn Distributors, Germany), coupled to a computer, and the thickness of the growth rings were accurately measured. of 0.01 mm. The increment data were recorded by the TSAP-Win Software and the growth series were dated by visual analysis and with the Cofecha software.

### Growth modeling

From the time series of growth obtained, growth models were adjusted (Table 1) by non-linear regression, using the PROC NLMIXED procedure in the SAS software, for each of the study areas.

In selecting the best regression model, the adjustment of each equation was taken into account, observing the statistical parameters of the standard error of the estimate - $S_{yx}$ (%), the Akaike (AIC) and Bayesian (BIC) information criteria and the waste analysis.

Table 1. Fitted diametric growth models for *Araucaria angustifolia* in three locations, in Santa Catarina state, Brazil.
Tabela 1. Modelos de crescimento diamétrico ajustados para *Araucaria angustifolia* em três locais, no estado de Santa Catarina, Brasil.

| Denomination of the equation | Model | Parameter restrictions |
|---|---|---|
| Gompertz | $DBH = \beta_0 e^{-\beta_1 e^{-\beta_2 t}}$ | $\beta_2 > 0$ |
| Johnson-Schumacher | $DBH = \beta_0 e^{-\frac{\beta_1}{t+\beta_2}}$ | $\beta_1 > 0$ |
| Lundqvist-Korf | $DBH = \beta_0 e^{-\frac{\beta_1}{t^{\beta_2}}}$ | $\beta_1 > 0$ |
| Logística | $DBH = \frac{\beta_0}{(1+\beta_1 e^{-\beta_2 t})}$ | $\beta_2 > 0$ |
| Monomolecular | $DBH = \beta_0(1-\beta_1 e^{-\beta_2 t})$ | $\beta_2 > 0$ |
| Schumacher | $DBH = \beta_0 e^{-\frac{\beta_1}{t}}$ | $\beta_1 > 0$ |

Note: DBH = diameter at 1.3 m from the ground, without bark; t = time elapsed until reaching the considered DBH (years); $\beta_0$, $\beta_1$, $\beta_2$ = parameters of the equations and "*e*", Euler number. Source: Burkhart; Tome (2012).

From the values obtained by the diameter growth curves, the values in basal area were calculated, and from the mean annual increment (MAI) and the current annual increment, (CAI) curves were derived.

From the MAI and CAI curves in basal area, the maximum values and the technical age of growth culmination were obtained, the point at which the intersection of the two curves occurs (BATISTA *et al.*, 2014), seeking to understand the population throughout the period of time.

## RESULTS

The time series reached periods of up to 174 years (Table 2). The sample with the highest DBH was observed in area 2 and the smallest diameter amplitude was obtained in area 1. The smallest average annual increment was recorded in area 1 and the largest one in area 3.

Table 2. Quantitative description of *Araucaria angustifolia* time series in three locations, in Santa Catarina state, Brazil.
Tabela 2. Descrição quantitativa das séries cronológicas de *Araucaria angustifolia* em três locais, em Santa Catarina, Brasil.

| | Area 1 | Area 2 | Area 3 |
|---|---|---|---|
| Interval of sample DBH (cm) | 12.7 – 55.1 | 18.3 – 88.2 | 11.6 – 59.8 |
| Maximum age of sampled trees (years) | 174 | 170 | 42 |
| Average anual increment in DBH, without bark | 0.33 | 0.51 | 1.01 |

Note: Area 1 = Bom Jardim da Serra; Area 2 = Painel; Area 3 = São José do Cerrito; DBH = diameter with bark at 1.30 m above the ground.

The gross increments of *Araucaria angustifolia* by diameter class, for the three areas, showed an initial trend of greater increment with reduction as the diameter increased (Figure 1).

Considering the statistical parameters (Table 3) and the distribution of residues, the monomolecular model was the one that showed the greatest adherence to the time series of *Araucaria angustifolia* for the three study areas.

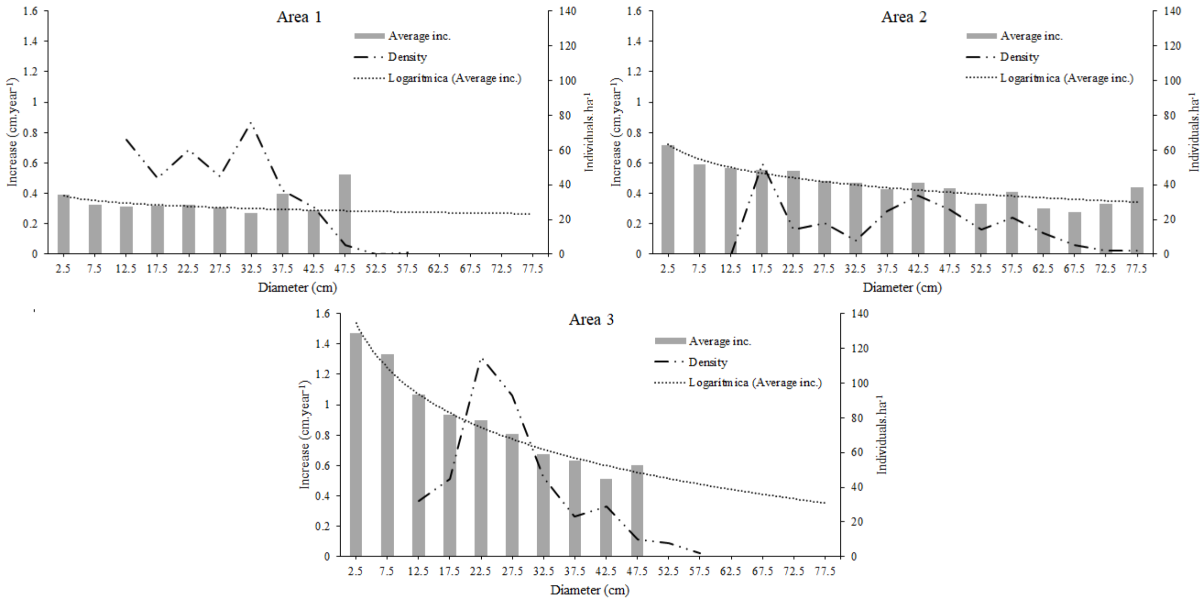


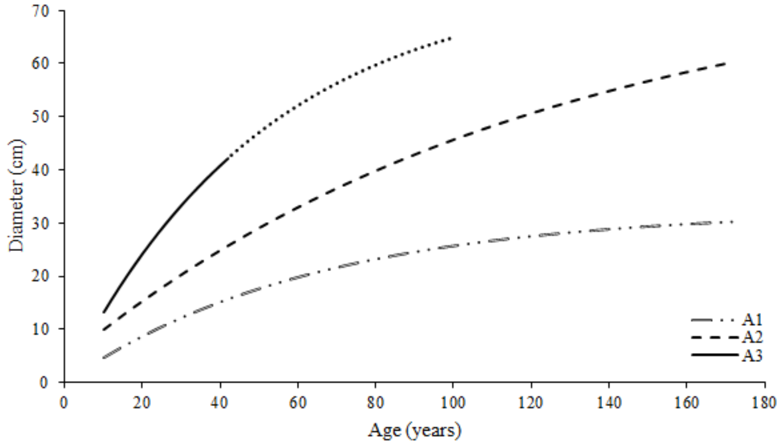

Figure 1. Average gross annual diameter increase, number of individuals per diametric class and respective trend lines for *Araucaria angustifolia* in three sites, in Santa Catarina state, Brazil.
Figura 1. Incremento bruto médio anual em diâmetro, número de indivíduos por classe diamétrica e respectivas linhas de tendência para *Araucaria angustifolia* em três locais, em Santa Catarina, Brasil.

Table 3. Statistical parameters and coefficients of the diametric growth models adjusted for *Araucaria angustifolia* in three locations, in Santa Catarina state, Brazil.
Tabela 3. Parâmetros estatísticos e coeficientes dos modelos de crescimento diamétrico ajustados para *Araucaria angustifolia* em três locais, em Santa Catarina, Brasil.

| Local | Model | Coefficients | | | Parameters | | |
|---|---|---|---|---|---|---|---|
| | | $\beta_0$ | $\beta_1$ | $\beta_2$ | $S_{yx}$ | AIC | BIC |
| A1 | Gompertz | 28.0053 | 2.2996 | 0.03229 | 36.5 | 35506 | 35533 |
| | Johnson-Schumacher | 41.201 | 54.8278 | 15.0796 | 36.3 | 35455 | 35482 |
| | Lundqvist-Korf | 88.5343 | 7.222 | 0.383 | 36.3 | 35458 | 35485 |
| | Logística | 26.644 | 5.6523 | 0.04803 | 36.7 | 35589 | 35615 |
| | **Monomolecular** | **32.3471** | **1.001** | **0.01581** | **36.3** | **35447** | **35473** |
| | Schumacher | 32.3404 | 27.8923 | - | 36.5 | 35669 | 35689 |
| A2 | Gompertz | 61.0001 | 2.0173 | 0.01959 | 35.3 | 34696 | 34722 |
| | Johnson-Schumacher | 84.0949 | 79.7273 | 26.5382 | 34.7 | 34519 | 34545 |
| | Lundqvist-Korf | 718.15 | 6.976 | 0.2002 | 34.2 | 34399 | 34425 |
| | Logistics | 57.9789 | 4.6305 | 0.02917 | 35.9 | 34858 | 34884 |
| | **Monomolecular** | **78.5098** | **0.9486** | **0.008195** | **34.6** | **34489** | **34515** |
| | Schumacher | 54.1459 | 26.7028 | - | 35.8 | 34828 | 34848 |
| A3 | Gompertz | 43.4466 | 2.6303 | 0.07604 | 29.0 | 11860 | 11882 |
| | Johnson-Schumacher | 77.6994 | 32.9819 | 8.5041 | 28.6 | 11808 | 11830 |
| | Lundqvist-Korf | 256.59 | 6.2231 | 0.3248 | 28.5 | 11790 | 11812 |
| | Logística | 38.5264 | 7.5901 | 0.129 | 29.5 | 11933 | 11955 |
| | **Monomolecular** | **75.6937** | **1.0024** | **0.0194** | **28.4** | **11784** | **11806** |
| | Schumacher | 45.8886 | 12.0484 | - | 29.0 | 11991 | 12008 |

Note: A1 = Bom Jardim da Serra; A2 = Painel; A3 = São José do Cerrito; $\beta_0$, $\beta_1$ and $\beta_2$ = adjusted coefficients; $R^2_{aj.}$ = adjusted coefficient of determination; $S_{yx}$ (%) = standard error of the estimate; AIC = Akaike information criterion; BIC = Bayesian information criterion. The equations with the best fit for each location are highlighted in bold. The coefficients were significant at a probability level of $p < 0.0001$.

In the growth in diameter in area 1, the asymptote was observed close to 28 cm, starting a period of lower growth after this diameter class. For area 2, it was possible to visualize this point close to being reached, but greater than 60 cm. In area 3, the measured diameters do not allow visualizing the asymptote, showing an ascending growth throughout the entire chronological series (Figure 2).

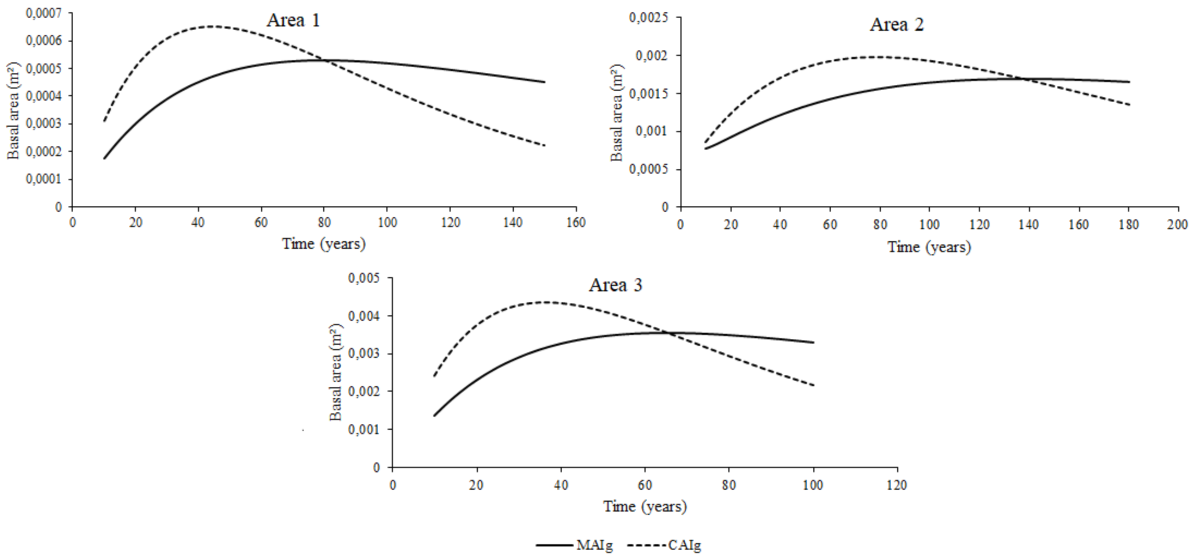



Note: A1 = Bom Jardim da Serra; A2 = Painel; A3 = São José do Cerrito; The dotted line indicates the projection of the growth equation for the data measured in A3.

Figure 2. Diametric growth models adjusted for *Araucaria angustifolia* in three locations, in Santa Catarina state, Brazil.

Figura 2. Modelos de crescimento diamétrico ajustados para *Araucaria angustifolia* em três locais, em Santa Catarina, Brasil.

The maximum CAIs observed by the increment curves for the basal area of the individual tree were reached in the three areas. Regarding the MAI in area 3, it was necessary to extrapolate the growth equation to obtain the estimated technical age of the growth completion (Figure 3).




Note: Area 1 = Bom Jardim da Serra; Area 2 = Painel; Area 3 = São José do Cerrito; MAIg = mean annual increment in basal area; CAIg = annual current increment in basal area.

Figure 3. Production curves in basal area for individual tree for *Araucaria angustifolia* in three locations in Santa Catarina, Brazil.

Figura 3. Curvas de produção em área basal para árvore individual para *Araucaria angustifolia* em três locais, em Santa Catarina, Brasil.

The maximization in basal area occurs at similar diameters (54.5 and 54.2) for areas 2 and 3, even with different increments (with time required more than double) showing a tendency for the species not to reach better performances after these diameters. The maximization in basal area of area 1 occurs at a smaller diameter (23.2) than the previous ones, suggesting environmental or competitive limitation may be influencing trees to reach larger diameters (Table 4).

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Table 4. Estimated ages and basal area of the diameters of technical stagnation and the maximum current annual increment for *Araucaria angustifolia* in three locations, in Santa Catarina state, Brazil.
Tabela 4. Idades e área basal estimados dos diâmetros em que ocorre o ponto de estagnação técnica do crescimento e o máximo incremento corrente anual para *Araucaria angustifolia* em três locais no estado de Santa Catarina, Brasil.

| Local | Growth culmination point | | | Maximum CAIg | | |
|---|---|---|---|---|---|---|
| | g (m²) | Age (years) | DBH (cm) | g (m²) | Age (years) | DNH (cm) |
| A1 | 0.0423 | 80 | 23.2 | 0.0206 | 44 | 16.2 |
| A2 | 0.2331 | 138 | 54.5 | 0.1227 | 79 | 39.5 |
| A3 | 0.2307 | 65 | 54.2 | 0.1131 | 36 | 38.0 |

Note: A1 = Bom Jardim da Serra; A2 = Painel; A3 = São José do Cerrito; g = basal area; DBH = diameter at 1.3 m from the ground; Growth culmination point = crossing of current annual increment and average annual increment curves in the basal area of individual tree; Maximum CAIg = maximum annual current increment in basal area of the individual tree.

## DISCUSSION

The presence of distinct growth rings in *Araucaria angustifolia* samples is consistent with what was observed in the literature. According to Mattos *et al.*, (2011), araucaria presents clearly visible growth rings, which facilitates the counting of age. As a result, dendrochronological studies with this species are increasingly frequent in the literature (CURTO *et al.*, 2017; HESS *et al.* 2018b; LAMBRECHT *et al.*, 2019, among others).

The largest age intervals found in areas 1 and 2 are similar to most areas of natural forests of *Araucaria angustifolia* (KOCH; CORRÊA, 2010). In area 3, the low age range of the samples (42 years) indicates that it is a young natural area. Possibly, the seeds that were in larger groves dispersed and started colonization of a new area nearby.

According to Klein (1960), *Araucaria angustifolia* is a pioneer species, invasive of the natural grasslands that occur in its geographic distribution area. By consulting satellite images from past periods, it was possible to verify that the location of area 3 was installed in an area where it was previously grass or agriculture field. This colonization guaranteed, due to the growing spacing between the trees, a dynamics of tree growth similar to planting areas.

The mean annual increment (MAI)  in the diameter obtained in area 3 was the highest among the three areas, probably because the individuals until the moment of measurement did not have to compete for space and light for their development. Thus, this area presented the culmination point of growth in basal area in a shorter time when compared to the others. This confirms that different locations may present different growth patterns for the same species.

The annual increment in area 1 was the smallest among the three studied areas. However, it was similar to the study carried out in a neighboring municipality, in São Joaquim, with 0.34 cm year$^{-1}$ (HESS *et al.*, 2018a).

The great divergence in relation to the average annual increments obtained demonstrates the need not to generalize information about the species. The species' growth pattern is different between locations, reaching very discrepant values, such as the MAI values found in the literature (Table 5).

Table 5. Mean annual increment of *Araucaria angustifolia* in natural forests of Santa Catarina State, Brazil.
Tabela 5. Incremento médio anual de *Araucaria angustifolia* em florestas naturais no estado de Santa Catarina.

| Local | Altitude (m) | IMA (cm year$^{-1}$) | Author |
|---|---|---|---|
| Bom Jardim da Serra (A1), SC | 1,350 | 0.33 | Current work |
| Painel (A2), SC | 1,150 | 0.51 | Current work |
| São José do Cerrito (A3), SC | 950 | 1.01 | Current work |
| São Joaquim, SC | 1,166 | 0.34 | Hess *et al.* (2018a) |
| Painel, SC | 1,123 | 0.69 | Hess *et al.* (2018a) |
| Lages, SC | 1,200 | 0.71 | Hess *et al.* (2018b) |
| Urupema, SC | 1,259 | 0.90 | Hess *et al.* (2018a) |
| São Joaquim, SC | 1,352 | 0.45 | Loiola *et al.* (2019) |
| São Joaquim, SC | 1,352 | 0.69 | Loiola *et al.* (2019) |

Apparently, the highest increments observed in areas 2 and 3 are not explained by altitude, since in area 1 (1,350 m altitude) the MAI was 0.33 cm year$^{-1}$.

The differentiated growth pattern (Figure 2) strengthens the indication that management guidelines for natural araucaria forests must be adapted to the individual characteristics of the species in each place of interest. Generalized guidelines, for example, may pose a risk to the sustainability of the forest management (BRAZ; MATTOS, 2015; FORTINI *et al.*, 2015).

The three areas showed an initial tendency to increase in the analysis by diameter class. However, it was possible to verify that in area 1, the increment of the last class with individuals stood out from the other values, and this can be explained by the fact that they are the largest individuals in the area and with easy access to the upper canopy, having available light and better conditions for its growth (Figure 1).

The variation in growth in trees of the same species can be a consequence of many factors, such as genetic characteristics (MIRANDA *et al.*, 2018a), climate (D`OLIVEIRA *et al.*, 2017), or differentiated access to the resources necessary for their growth during the different stages of life, such as the effect of competition, where access to light can be differentiated for each tree (LE BEC *et al.*, 2015; ROZENDAAL *et al.*, 2015; CANETTI *et al.*, 2016). These factors justify the standard deviations of growth in the different diameter classes.

According to Alder (1992), individuals from the smallest classes in tropical forests are generally under competition, growing more slowly. As they develop, they have more access to light and their growth rate increases, declining in the major classes as a function of age. However, for this study this pattern was not verified, since the smallest classes showed the greatest increment. This may indicate less competition in the past at the beginning of stand population formation.

Such a pattern of greater increment in the initial classes was also observed by Lambrecht *et al.* (2019) for araucaria in natural forest in the northwestern region of Rio Grande do Sul state, and by Curto *et al.*, (2017) in plantations of the species. This behavior can be attributed to the fact that the initial development of the species is favored in open environments (PALUDO *et al.*, 2011), which suggests that a significant part of the individuals studied here, mainly in area 3, initially developed in an area of low density, such as clearings or grasslands.

## CONCLUSIONS

- The difference in the growth pattern between the areas indicates that araucaria can reach a high anual increment, indicating better conditions of development.
- Differences in growth patterns in each area underscore the importance of studying each site individually.
- Different increment maximizations in basal area can be similar in diameter, but with a large difference in time required.
- Considering the araucaria forests increment as the same value can lead to errors in the quantification of the forests growth potential.
- The set of analyzes on the growth of araucaria in different areas will serve as a basis for simulations of the population growth, allowing the elaboration of management parameters that guarantee its sustainability.

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