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Sustainability Assessment of Araucaria Forest Remnants in Southern Brazil: Insights from Traditional Forest Inventory Surveys

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Abstract: Precise estimates of dendrometric and morphometric variables are indispensable for effective forest resource conservation and sustainable utilization. This study focuses on modeling the relationships between shape (morphometric), dimension (dendrometric) and density (N) to assess the sustainability of forest resources. It sheds light on the current state of site characteristics, reproduction, and the structure of *Araucaria angustifolia* trees at selected forest remnants across multiple sites in Santa Catarina, Southern Brazil. Individual trees and their dendrometric variables, such as the diameter at breast height (d), height (h), crown base height (cbh), annual periodic increment (API) in growth rings, and morphometric variables, including four radii of the crown in cardinal directions, were evaluated. These measurements allowed us to calculate various morphometric indices and crown efficiency, enabling the assessment of both vertical and horizontal structural conditions. Statistical analysis confirmed a positive relationship of the crown volume (cv) and crown surface area (csa) with the crown length (cl). Conversely, the crown efficiency, density, increment rate, and reproductive structure production declined. These morphometric relationships emphasize the complex dynamics within these forest ecosystems, irrespective of the chosen site, indicating that horizontal and vertical forest structures have stagnated and have been characterized by limited change in the last ten years. Such results raise concerns about sustainability, highlighting the need for proper conservation measures and sustainable forest management practices. Our findings underscore the need for substantial adjustments in the structure and dynamics of the forest, particularly on selected rural properties where this tree species is abundant, to ensure long-term sustainability.

Keywords: forest conservation; sustainability variables; forest structure; diversity

1. Introduction

The intricate relationship between sustainability and forest management has deep historical roots, dating back to the pioneering work of von Carlowitz in 1713, which later found its place in forestry science. Sustainable Forest Management (SFM) represents a holistic framework underpinned by a comprehensive set of principles and practices meticulously crafted to ensure the enduring well-being and vitality of a forest. This approach seamlessly harmonizes the preservation of forests' long-term health and viability with the imperative of meeting the needs of both present and future generations [1].

SFM requires intensive forest inventory surveys, wherein a set of dendrometric and morphometric variables are collected. Subsequently, models can be generated to show the relationships among these variables, characterizing the chosen forest stand development [2,3]. Interestingly, the concepts of conservation and sustainability in such forest management protocols are guided by specific legislation and supervised by international organizations [4–6]. Oliveira et al. [7] and Pukkala et al. [8], through experiments under SFM, emphasized the importance of focusing on the structure retrieved by dendrometric and morphometric variables.

In this study, we evaluate the current conditions of Araucaria angustifolia (Bertol.) Kuntze in the Mixed Ombrophylous Forest (MOF) in Southern Brazil, including their dendrometric and morphometric variables. MOF holds particular socioeconomic, sociocultural, and environmental importance.

The absence of proper SFM protocols in selected MOF sites for more than four decades has affected structures, dynamics, growth rates, natural regeneration, and genetic adaptations to changes in environmental conditions [9,10]. Therefore, additional studies on the morphometry dimension relationship of trees are still necessary.

Roman et al. [11] reported the importance of understanding characteristics describing competition types, dynamics, functions, and forest ecosystem services, mainly for managing competition and supplying tree growth. Morphometric indices provided insights to reconstruct the optimal necessary space occupied by each tree, judge the degree of competition in a stand, and infer each tree's stability, vitality, and productivity [12,13].

In the past, several remnants of MOF suffered intensive and degradative exploitation, leading to very restrictive initiatives aiming for full conservation and neglecting any intervention. However, some previous studies have highlighted the importance of SFM initiatives in promoting forest sustainability [3,14–18].

Changes in the shape, size, structure, and dynamics of a forest can be natural or anthropogenic, altering the ecosystem's structure, resource availability, and tree composition. Human disturbances have the advantage of having a smaller impact, as there is control over scale and intensity, and they are also similar to natural disturbances [11,14]. In this sense, diversity usually increases with intermediate levels of disturbance [15,19–22].

As suggested, sustainability is not only about protecting nature but mainly about production since the first cannot exist without the second. Therefore, sustainability guarantees the continuity of a system, as opposed to the exclusive protection of nature, and supports local communities [18].

Recent studies have shown how crown morphometric information related to size and increment has been used, as responses are variable in models for growth, competition, and population dynamics [21], leading to the application of concepts for sustainability. The imperative use of crown information is viable as it serves as an indicator of the tree's vigor and photosynthetic capacity, and factors that affect its growth, and consequently its structure and dynamics, as well as expressing the species' current conditions compared to the past of the species' development [22,23]. Beginning recently, this information can also be obtained with remote sensing images.

Integral to the sustainability of forest management is a profound understanding of temporal dynamics essential for preserving critical factors and processes. As suggested by Montigny [24], silvicultural treatments are indispensable for fostering structural diversity, including canopy layers and spatial irregularity, to enhance biodiversity. Notably, tree crown dimensions, encompassing growth, carbon sequestration, shading, filtering, and wind resistance, play a pivotal role in this context, correlating with a tree's physical footprint and physiological functions [25]. Plant growth rates, influenced by factors governing resource capture and utilization efficiency [26], hinge on growth efficiency as a measure of tree vigor, with leaf area serving as an indicator of occupied growing space [27].

A comprehensive grasp of crown dynamics is imperative for the sustainability of forest management, as it underpins models encompassing dynamics, structure, diversity, stability, productivity, and diversity. Collectively, these models mirror the expression of ecosystem functions and services. Notably, tree crown dynamics constitute the most prominent structural facet in forest growth [28]. Growth directly responds to silvicultural interventions and changes in crown shape, structure, leaf area [29,30], crown length and width, and mantle [31].

Precise quantification of changes in the shape and size of trees are linked to the interference of management regimes and ensures the sustainability of trees and populations as resilient to dynamics. This is important for commercial plantations, but preferably in mixed forests, where it is only sometimes possible to obtain age and growth data for the wide species diversity.

This study verifies the need and viability of proposing SFM to maintain the sustainability of Araucaria forest remnants. Therefore, we aim to assess the relationship between form and dimension and model this variable within these ecosystems to assess their present conditions. By doing so, we aspire to offer valuable insights that can inform SFM practices and secure the future of these unique and ecologically vital forests.

In this regard, we established the following hypotheses: (1) *A. angustifolia* dominance is linked to unmanaged forest forms with a regular distribution pattern; (2) variations in interdimensional relationships correspond to changes in forest density and structure; and (3) these variations influence the formation of reproductive structures (male strobili).

2. Materials and Methods

2.1. Description of the Tree Species and the Study Area

A. angustifolia is a dioecious species, and it exhibits a conical crown during its youth and assumes an umbel shape in maturity. This tree species is characterized by cylindrical, straight trunks, evergreen aciculifoliate needles (leaves), and the production of edible seeds (pine nuts) in female reproductive structures [32–35]. The species successful dispersion is attributed to wind-borne pollen grains [36].

Our research was performed in six sites distributed in the municipalities of São Joaquim (SJQ), with a size of 4.1 hectares, Urupema (URP)—4.3 ha, Urubici (URUB)—5.2 ha, Painel (PNL)—2.2 ha, Bom Retiro (BRT)—5.8 ha and Lages (LAG)—84 ha, in the Santa Catarina State (Figure 1).

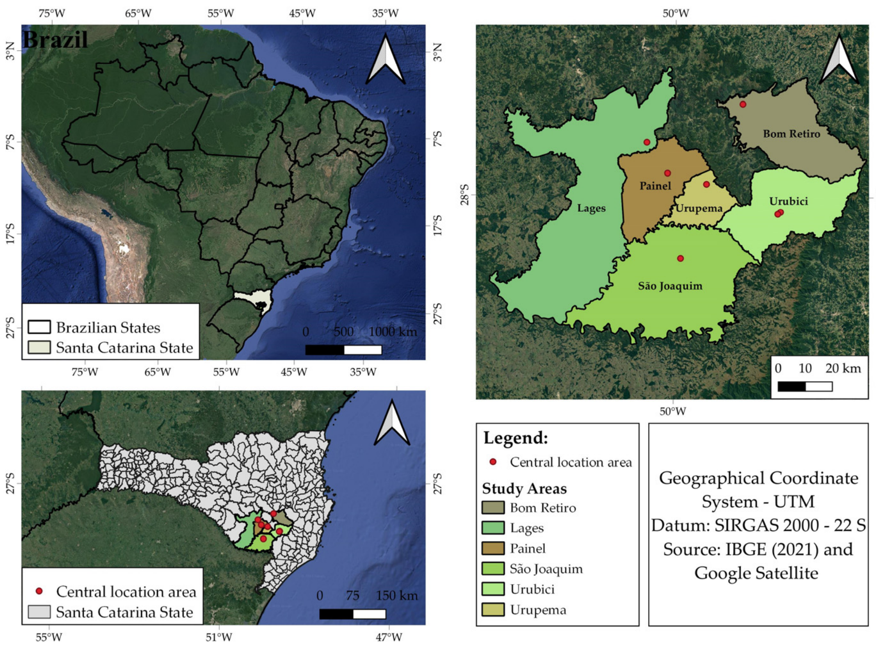

Figure 1. The geographic location of the study areas in the State of Santa Catarina. The (**upper right**) corner figure indicates the location of the Santa Catarina State (Southern Brazil). The (**bottom left**) shows the municipalities covered, and on the (**bottom right**), the locations of the sites sampled from 2010 to 2022.

All study areas were subjected to some degree of anthropization, leaving forest fragments, which reduced part of its diversity in species and genera [37]. In this way, the forest assumes the status of a regular forest with a predominance of *A. angustifolia* (Figure 2), and when it has other species in its structure, these are considered of minor economic value and purpose of use (pioneer, early secondary, late secondary), such as, for example, *Lithraea brasiliensis* (L.) Marchand, *Ocotea pulchella* (Nees & Mart.) Mez, *Sapium glandulosum* (L.) Morong, *Zanthoxylum rhoifolium* Lam; *Ocotea puberula* (Rich.) Nees, *Feijoa sellowiana* (O. Berg) O. Berg, and *Allophylus edulis* (A St. Hil.) Radlk., among others.

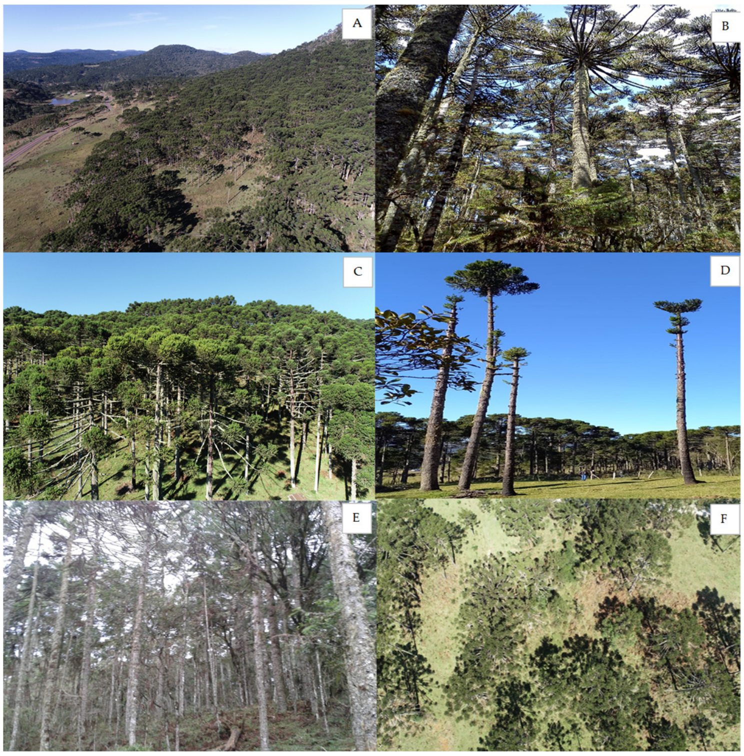

Figure 2. Ground and drone impressions of the current structure of the forest remnants with *Araucaria angustifolia* highlighting changes in land use (**A**), irrational exploitation of the forest in the past (**B**), a mixture of trees with pasture (**C**), pruning aiming to damage standing trees (**D**), insignificant visualization of natural regeneration (**E**,**F**), and generating risks to the sustainability of the ecosystem.

A Cfb temperate climate characterizes the region according to the Köppen classification, an altitude above sea level of 1140 m, average annual precipitation of 1641 mm, and yearly average temperature of 14.3 °C [38]. The current conditions of the forest remnants show a clear dominance of *A. angustifolia* trees in the area (see Figure 2A,C,E), areas altered by the use of livestock farming (Figure 2D,F), and forest remnants with lower diversity of other species (Figure 2A–F). Land owners' actions, such as thinning and burning branches, mainly on the border of forest remnants, also exist (Figure 2D). These areas also show an evident absence of natural regeneration (Figure 2E) due to the species dominance in the upper canopy strata. The selected forest remnants are also subjected to the overexploitation of edible seeds, compromising this resource's sustainability.

2.2. Data Mensuration

The sampling process used techniques to study individual trees at SJQ, URU, PNL, URUB and BRT sites (Figure 1). A total of 25 sample plots with a fixed area of 400 m^2 were considered in the LAG site. In LAG, these sample plots were established in 1999 and remeasured again in 2018, where all tree species with a diameter at breast height ≥10 cm were measured [37]. We adopted a systematic sampling design considering equidistant lines of 100 m and 50 m between plots. The individual tree method consists of a system of equations to simulate population dynamics for a period of time [39]. Each tree was considered a sample labeled and georeferenced using a measuring tape, topographic pole, fiberglass measuring tape, and handheld GNSS receiver.

Dendrometric measurements, including diameter at breast height (d), total height (h), crown base height (cbh), and four crown radii in cardinal directions (cr), were taken using a survey pole, leveling rod, measuring tape, and inclinometer. For all individual trees, in all sites, two increment rolls perpendicularly at the (d) height were extracted with the Presller method to determine the annual periodic increment in diameter (API_{d10}), considering a ten-year timeframe.

The timeframe of ten years was considered because longer times may not be significant for crown changes. However, besides considering the entire timeframe available in the increment rolls, the age at d height does not represent the absolute age of the chosen tree. The increment rolls were fixed in wooden boxes, dried, and sanded. After being marked, they were measured using the stereo microscope Lintab 6 and the software Time Series Analysis Program TSAP-Win with crossdating.

With the measurement of dendrometric variables, the morphometric indices, csa, cv, cl, annual increment in diameter API_{d10}, basal area IPA_g (%) and number of trees per hectare (Equations (1)–(6)) were calculated:

$$\text{csa} = \frac{\pi \times \text{cd}}{2} \times \sqrt{\text{cl}^2} + \frac{(\text{cd})^2}{2} \quad (1)$$

$$\text{cv} = \frac{\pi \times \text{cd} \times \text{cl}}{12} \quad (2)$$

$$\text{cl} = \text{h} - \text{cbh} \quad (3)$$

$$\text{API}_{\text{d10}} = {}^{(\text{ d} - \text{dt})}/_{\text{t}} \quad (4)$$

$$\text{IPAg}(\%) = \{[\text{g}_{\text{t2}} - \text{g}_{\text{t1}}/\text{g}_{\text{t1}}] \times 100\}/\text{t} \quad (5)$$

$$\text{N}/\text{ha} = 10{,}000/\text{csa} \quad (6)$$

csa: crown surface area (m^2); cd: crown diameter (m); cl: crown length (m); cv: crown volume (m^3); g: basal area (m^2); d: diameter at breast height (cm); h: height (m); cbh: crown base height (m); $APId_{10}$; annual periodic increment in diameter ($cm \cdot year^{-1}$); dt: diameter at breast height (cm) obtained from average of the two increment rolls at the beginning of the period; t: period of time considered; IPAg (%): annual potential periodic increment in basal area in %; g_{t2}: basal area at the end of the period; g_{t1}: basal area at the beginning of the period; t: time period in years considered; and N: potential number of trees per hectare.

The adjustment of the models of the relationship between the variables shape (cv, cl), size and shape (g, csa), density with size (N/ha, d) (Equations (7)–(10)), crown efficiency (CE), number of male strobili (ns) as a function of crown size (d) and efficiency (Equations (11)–(14)), as well as growth and production (Equation (15)) were carried out using the generalized linear model technique (GLM), which is an extension of the classic linear model [40]. The accuracy was assessed considering deviation, Akaike, and Bayesian criteria. Graphs were plotted to visualize the regression line on the observed values. All adjustments were processed in SAS (2004) Statistic Analysis System [41].

$$\text{cv} = \beta_0 + \beta_1 \times \text{cl} + \varepsilon_i \quad (7)$$

$$\text{csa} = \beta_0 + \beta_1 \times \text{cl} + \varepsilon_i \quad (8)$$

$$\text{g} = \beta_0 + \beta_1 \times \text{csa} + \varepsilon_i \quad (9)$$

$$^{\text{N}}/_{\text{ha}} = \beta_0 + \beta_1 \times \text{d} + \varepsilon_i \quad (10)$$

$$\text{CE} = \text{API}_{\text{d10}}/\text{csa} \quad (11)$$

$$\text{ns} = \beta_0 + \beta_1 \times \text{d} + \varepsilon_i \quad (12)$$

$$ns = \beta_0 + \beta_1 \times CE + \varepsilon_i \quad (13)$$

$$CE = \beta_0 + \beta_1 \times API_{d10} + \varepsilon_i \quad (14)$$

$$IPAg(\%) = \beta_0 + \beta_1 \times d + \varepsilon_i \quad (15)$$

csa: crown surface area (m^2); cd: crown diameter (m); cl: crown length (m); cv: crown volume (m^3); g: basal area (m^2); N/ha: number of trees per hectare; d: diameter at breast height (cm); $APId_{10}$; annual periodic increment in diameter ($cm \cdot year^{-1}$); CE: crown efficiency ($cm \cdot year^{-1}/m^2$); ns: strobili number; IPAg (%): annual potential periodic increment in basal area in %; and ε_i: random error.

The adjusted equations of the relationship between morphometric and dendrometric variables, which express the current conditions of the forest structure, were for the SJQ, URU, PNL, URB, and BRT sites. The site at LAG was used to determine the male reproductive structure, which forms the pollen and fertilizes the female tree, to determine the horizontal structure of the forest, density, dominance, frequency, and richness based on the Margalef, Menhinick, and Jentsch Mixture Quotient indices for the timeframe of 18 years.

As detailed in Demetrio et al. [42], the quantification of male reproductive structures (strobili) was measured for different diameters and obtained from drone images. The count was carried out through visual inspection and labeling of RGB images. Interestingly, to avoid counting the same strobilus twice, the images were taken following the cardinal directions (north, south, east, and west) and from the top of the tree, obtaining at least five images of each single tree. Male strobili were quantified in the same sample for two consecutive years, November 2019 and December 2020, when they became mature and visible in the images.

The adjustments allow for a description of the current conditions of the forest and reflect what happened in the past with this resource in terms of structure (density and dominance), species composition, growth, dynamics (tree morphometry), and crown efficiency.

The morphometric indices were subjected to analysis of covariance (ANACOVA) to test whether there is a difference in slope and level between the study areas [43], that is, differences in the shape and size patterns of the trees. The morphometric variables (cv, csa), size (g), density (N/ha), and their variability were considered dependent variables that explained the shape aspects. Meanwhile, cl, csa, d, and APId10 were considered continuous independent variables, and the sites were categorical independent variables.

3. Results

3.1. Characterization of the Forest Component

The total number of trees measured in all locations was 672, whose descriptive statistics of the dendrometric and morphometric variables measured in the forest inventory are shown in Table 1. The ANACOVA employed to assess the relationship between shape, density, and dimension variables revealed significant differences in the regression lines' intercept (coefficient b_0) and slope (b_1). The probability values for the study sites (site test) indicated a highly significant difference (Prob. < 0.0001). Similarly, the interaction terms for the cl* site, csa* site, d* site and API_{d10}* site also exhibited a significant probability value. Given the significance of covariance, separate equations were tailored for each site to account for and explain the variations in shape, size, and density observed at each specific site.

The results show that the SJQ, URU, URUB, BRT and LAG present similarities in the development of dendrometric and morphometric variables (Table 1). The exception occurred in the PNL site. The URUB and PNL site showed a discrepant average, first for the csa variable and the second for the N. This discrepancy in the csa variable indicates a tree that grew isolated and has a higher cd and cl (URUB), and, in terms of N, the PNL site had a higher density due to minor csa. As it is a measurement by individual tree, this variation was not removed from the sample, as it characterizes the species' ontogeny.

Table 1. Descriptive statistics of morphometric, dendrometric and density variables measured in the study to understand the structure and modeling of interdimensional relationships of *Araucaria angustifolia* in sites in southern Brazil.

Site		d	cd	cl	cv	csa	g	N
SJQ	max	106.6	16.6	10.9	32.4	276.8	0.89	368.4
	min	20.1	4.2	0.5	1.4	27.1	0.03	36.1
	mean	57.4	9.8	4.4	11.2	106.8	0.28	112.6
	sd	16.7	2.2	2.1	5.9	44.3	0.17	54.7
URU	max	89.4	15.9	13.1	36.0	253.3	0.62	447.5
	min	18.7	4.1	0.3	0.9	22.3	0.02	39.5
	mean	46.3	8.9	5.8	13.6	107.0	0.18	113.9
	sd	14.3	2.2	2.1	6.3	44.2	0.11	61.2
PNL	max	86.6	12.3	12.0	23.3	149.6	0.56	1145.9
	min	23.6	1.25	0.5	1.2	8.7	0.04	66.8
	mean	49.5	7.1	4.5	7.5	67.7	0.21	197.6
	sd	13.4	2.7	2.5	4.4	31.9	0.11	143.9
URUB	max	91.9	24.9	14.3	93.0	739.5	0.66	513.9
	min	12.9	4.6	1.4	1.7	14.5	0.01	13.5
	mean	37.4	10.0	6.3	19.1	147.3	0.13	111.3
	sd	14.4	3.5	3.5	15.4	111.5	0.10	90.7
BRT	max	75.4	18.9	7.4	33.9	324.6	0.45	227.4
	min	25.5	7.4	1.0	1.9	43.9	0.05	30.8
	mean	47.2	10.8	4.0	11.9	122.9	0.18	100.4
	sd	1.9	2.7	1.9	7.7	65.8	0.08	45.2
LAG	max	69.7	19.6	12.2	45.2	301.7	0.16	576.4
	min	16.4	4.7	2.7	4.4	17.3	0.001	33.1
	mean	40.1	9.6	6.9	17.6	80.2	0.03	188.3
	sd	9.0	3.3	2.2	9.3	59.7	0.03	124.3

max: maximum value; min: minimum value; mean: average value; sd: standard deviation; d = diameter in cm; cd = crown diameter in m; cl = crown length in m; cv = crown volume in m^3; csa = crown surface area in m^2; g = basal area in m^2; N = number of trees per hectare. SJQ: São Joaquim; URU: Urupema; PNL: Painel; URUB: Urubici; BRT: Bom Retiro and LAG: Lages.

In general, the structural analysis, that is, density by diameter class, showed that there is diameter concentration in the 30 to 60 cm d classes, indicating structural stability in *d* and other variables, as they presented equidistant variations from the mean value.

The remeasurement of the permanent plots shows that in 1999 there were a total of 430 trees/ha, 30 species and 18 botanical families and, in 2018, 570 trees/ha, 25 species and 17 families. Diversity indices also indicated a reduction, with Margalef's index decreasing from 4.78 to 3.78, Menhinick's from 1.44 to 1.04 and Jentsch's from 0.07 to 0.04 [37].

In 1999, 46% of the number of trees were *A. angustifolia* and in 2018 this reached 62%. The importance value of the species increased from 37.2% (1999) to 53.1% in 2018. The importance value of the species increased from 37.2% (1999) to 53.1% in 2018 (density, frequency and dominance) [37].

3.2. Structure, Growth, Form Dimension and Regeneration of the Araucaria Forest

The results show the formation of a regular distribution pattern (similar to a normal distribution) of the number of trees per diameter class (Figure 3A) and that the rate of potential periodic increase in the basal area decreased with increasing diameter (Figure 3B). There was a concentration of trees in the intermediate classes and a lower growth rate in those of smaller diameter (growth stagnation).

Increment roll measurements show that the species has an average annual increment in diameter for SJQ of 0.45 cm/year, URU 0.75 cm·year^{-1}, PNL 0.9 cm·year^{-1}, and LAG 0.56 cm·year^{-1}, and the number of years in the increment roll showed a retreat in years between 20 and 153 years [44].

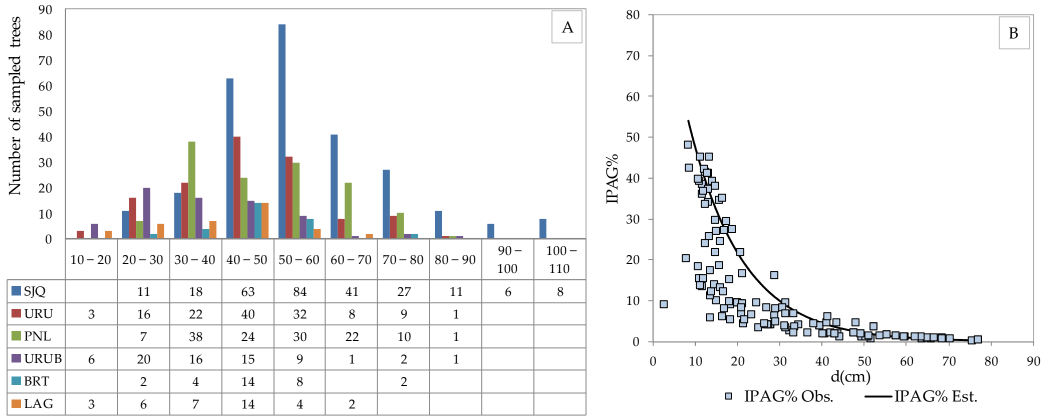

Figure 3. The characterization of the structural pattern of sites sampled in density and growth. (**A**) Trees sampled at the study sites, (**B**) periodic increment rate in basal area as a function of diameter.

At the LAG site, to differentiate the increment rate, the trees were divided into three diameter classes: C1 (10–29.9 cm), C2 (30–49.9) and C3 > 50 cm. The analysis of the increment for the three diameter classes showed that, for class C1, the mean annual increment in diameter was 0.54 cm·year^{-1}, for C2, the increment was 0.717 cm·year^{-1}, and for C3, 0.66 cm·year^{-1} [45].

In the SJQ, URU and PNL sites, for the last ten years of the increment rate, the results showed a decrease of 71% (0.51–0.15 cm·year^{-1}), 49% (0.96–0.49 cm·year^{-1}) and 62% (0.89–0.34 cm·year^{-1}) in the d increment rate. The increment in d accumulated over the last ten years exhibited a decreasing pattern, suggesting that the majority of sampled trees had already reached maturity [44].

Adjustments of this increment as a function of age revealed a negative b1 coefficient, signifying a decrease in the increment rate with age [44]. This suggests trees may have already reached their growth support capacity [44]. Both Table 2 and Figure 4 demonstrated accuracy in predicting the need for forest structure management and estimating the production of reproductive structures and crown efficiency.

Table 2. Precision statistics of the fit of the equations between shape, size and density in order to know the current structure and dynamics of the araucaria forest.

Site	Eq.	b_0 *	b_1 *	D	AIC	BIC	LF
SJQ	7	−0.2805	2.6439	14.4	1216.6	1227.5	*G-μ*
	8	56.4195	11.5695	35.5	2731.9	2742.7	*G-μ*
	9	0.1377	0.0013	80.7	−323.4	−312.6	*G-μ*
	10	5.2547	−0.0095	46.1	2828.7	2839.5	*G-ln*(*μ*)
URU	7	1.3476	0.2034	10.9	705	713.6	*G-ln*(*μ*)
	8	4.0251	0.1072	16.6	1310.5	1319.1	*G-ln*(*μ*)
	9	−2.786	0.0095	29.9	−304.4	−295.8	*G-ln*(*μ*)
	10	5.6796	−0.0215	14.9	1308.6	1317.2	*G-ln*(*μ*)
PNL	7	1.4752	1.3733	20.8	628.2	636.8	*G-μ*
	8	4.1156	0.0218	32.9	1282.1	1290.7	*G-ln*(*μ*)
	9	0.0446	0.0024	26.1	−286.1	−277.4	*G-μ*
	10	6.5288	−0.0265	24.5	1514.7	1523.3	*G-ln*(*μ*)
LAG	12	4.7573	0.0237	7.5	456.7	461.4	*G-ln*(*μ*)
	13	5.9724	−22.0764	9.9	466.9	471.7	*G-ln*(*μ*)
	14	−0.0004	0.0197	14.3	−269.8	−265.1	*G-μ*
SITES SJQ-URU-PNL	15	4.6481	−0.0784	33.5	708.6	717.3	*G-ln*(*μ*)

b_0 and b_1 = coefficients; * = Chi-square probability test, all coefficients—Pr > ChiSq< 0.0001; D = deviance; AIC = Akaike's information criterion; BIC = Bayesian information criterion; LF *G-μ* = indentity link function, gamma distribution; *G-ln*(*μ*) = logarithmic link function, gamma distribution.

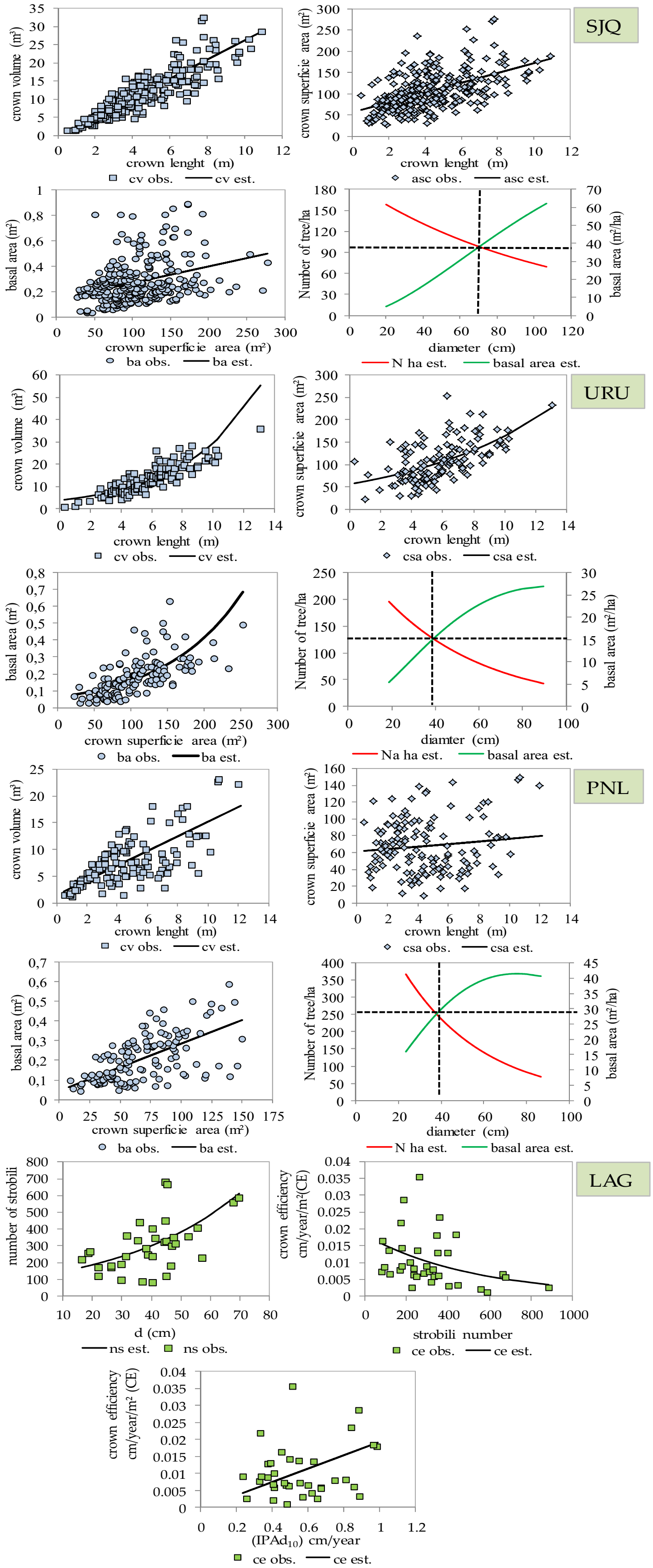

Figure 4. Expression of interdimensional shape–dimension–density relationships and reproductive structures (male strobili) with size, crown efficiency and increment. SJQ: São Joaquim, URU: Urupema, PNL: Painel and LAG: Lages.

Figure 4 shows the relationships between the variables of shape, size and density of the current structure of forest remnants and the connections between the formation of reproductive structures (male strobili), size, crown efficiency and increment.

The density and dimension ratio (depicted by the red line in Figure 4) exhibited an inverse relationship, suggesting that the number of trees decreases as dimensions increase, leading to greater production in basal area. The graphs represented by the red and green lines indicate that certain sites surpassed a basal area of 30 m^2/ha, signifying the dominance of the species in the forest. However, this dominance could pose a risk to structural dynamics and diversity if maintained for an extended period.

The sites of SJQ and URU showed a higher proportion and development of a crown structure, old-growth trees, higher age, and lower density. The PNL site showed higher density and lower plasticity for crown development.

Analysis of the formation of male strobili indicates that production increased, but up to diameters of 40–50 cm. The crown efficiency decreased as the number of strobili increased and increased with the increase in diameter. The lower efficiency with increased strobili formation shows that the physiological capacity, vigor, and formation of reproductive organs (strobili) decreased with the tree's age.

4. Discussion

Araucaria trees can exceed 150 years of age, maintaining either stable growth or experiencing reduction. However, relying on the self-regulation of forest structure entails a compromise in the supply of ecosystem goods and services, a condition that may only become apparent after three generations. The decline in growth is influenced by various abiotic and biotic factors, as explained by the Bertalanffy hypothesis, which expresses the rate of volume growth of an organism as the difference between constructive metabolism and destructive metabolism [39]. This decline has implications for the structure and dynamics of the forest ecosystem, emphasizing the necessity for silvicultural intervention to ensure the sustainability of the ecosystem.

The Forest Management and Growth Laboratory of the Forest Engineering Department of the State University of Santa Catarina, Lages, SC has conducted measurements of these forests and species for over 16 years. The results indicate several significant findings: normal distribution of dendro/morphometric variables (indicating structural standardization), a decrease in growth, the reduced formation of reproductive organs, the lower production of edible seeds, diminished monetary gain for rural producer families, limited regeneration of the species, a loss of diversity, allometry with a lower alpha index value, and increased competition, as reported in the literature [46–50].

The analysis by three diameter classes indicates that smaller diameter classes have a lower growth rate in unmanaged forests. If maintained for extended periods, this can lead to an irreversible effect, compromising the resumption of growth and, consequently, the future structure and sustainability of the forest.

Consequently, this structural stability compromises the development of the dynamics of the future structure and the relationships between shape, size and density of the forest. Araucaria dominates the upper stratum of the forest (largest csa). Due to its longevity, it reduces the entry of light and decreases the temperature below the canopy, harming the regeneration of MOF species, their diversity, ecological interactions and sustainability.

In this sense, the application of SFM contemplates the sustainable use of the ecosystem by communities and forest functions, as the relationships between the variables studied are positive and increase to a certain point in growth, allowing for sustainable production management. In other words, as the unit increases in x, the response in y grows asymmetrically and disproportionately, depending on the supply of resources (above or below ground) [51].

Compiling these results facilitates the generation of knowledge regarding the imperative need for the management of Araucaria Forests as a crucial instrument for the sustainability of this resource. The current conditions, as observed in these results and the forest field, indicate the formation of a regular structure, a lower increment rate, maturity, senescence, a diminished growth rate, lower natural regeneration, carbon sink status, and excessive exploitation of seeds. These factors are known to contribute to reduced genetic diversity. Additionally, the dioecy present in Araucaria represents an extreme mechanism to prevent self-crossing [52].

The reported results unequivocally affirm the tested hypotheses: conservation or the absence of management has a negative impact on sustainability, diversity, growth, structure, and the formation of reproductive organs. The dominance of the species results in the creation of a regular forest, where the complete occupation of the canopy impedes the recruitment of new species. This observation is evident in the current canopy surface area and volume dimensions and the interdimensional relationships between variables. Forests solely under a conservation regime (untouched) exhibit less diversity than those under a management regime, as the successional process is favored in the latter [53]. The phytosociological and species richness parameters corroborate the changes in the forest structure associated with the lack of intervention.

Crown parameters, recognized as morphometric indices, play a crucial role in ecology and forest management, aiming to sustain this vital resource [54]. These parameters not only influence tree growth and wood quality but also have direct implications for forest dynamics [55,56]. The development of a tree's crown shape is a direct response to its survival strategy [57], with the displacement and asymmetry of the crown serving to prevent competition from nearby trees [58].

Understanding the relationships between morphometric and dendrometric variables is crucial as a preventive measure for sustaining mixed forests structure, dynamics, diversity, and overall sustainability. Similarly, the formation of forest production, reproductive structures, and photosynthetic capacity relies heavily on the dimensions of the tree crown. In essence, managing the sustainability of forest resources encompasses the dynamics and maintenance of structure, growth rate, and the availability of resources and space.

The study results highlight that the forest's growth, dynamics, and structure significantly influence its sustainability. Larger size, increased volume, and a broader crown surface bring about modifications in crucial processes such as light entry, growth, and resource availability, shaping the forest structure over an extended period. An interesting aspect revealed in the analysis of the results is the observation that the changes influencing current crown measurements, size, and reproductive structure formation are no longer anthropogenic. This is evident in the absence of interference, particularly in terms of tree cutting, over a period approaching four decades.

Present anthropogenic interference primarily stems from livestock grazing, fruit cultivation, agriculture, and the overexploitation of pine cones [59]. This interference results in damage to regeneration, where few trees survive, and when present in greater numbers, they face competition and self-thinning, and sometimes succumb to mortality. These trends are underscored in the results, as sites exhibit a crown surface area ranging between 100 and 250 m^2, leading to canopy closure and adversely affecting processes in the ecosystem. Conversely, in other sites, although the crown surface is smaller, the density of trees increases.

The results from modeling interdimensional relationships highlight an optimal point between density and dominance (refer to Figure 4), representing a balance among processes, structure, and dynamics essential for the sustainability of the forest. Due to its longevity and dominance, the Araucaria species occupies all three strata in the forest. This association leads to the formation of old-growth forests, where productivity, regeneration, and the exchange of atmospheric elements with the environment decline in this phase [60–62].

While old forests may compromise sustainability due to the dominance of an aged species, leading to structural stability that affects the growth and future dynamics of the Araucaria forest, the preservation of older, larger forests with diminishing growth and limited regeneration poses a challenge for the future dynamics of the forest structure. The results also indicate that non-interventions contribute to a reduction in diversity.

This reduction is associated with specific species occupation and closure of the canopy. Heterogeneity, on the other hand, serves as a factor of adaptive complexity and enhances the capacity for social and environmental changes [63,64].

Larger and older trees also experience a reduction in efficiency and physiological capacity. Specifically in this study, Araucaria demonstrates a decline in the formation of reproductive structures, such as male strobili, pollen production, and the fertilization of female trees. This reduction, in turn, leads to a decrease in the production of cones and seeds. As highlighted in a study by Demétrio et al. [42], production has been progressively diminishing since 2017, and there is no legislative provision supporting the allocation of part of the production as a seed reserve. Consequently, all production is utilized and sold, posing a threat to the sustainability of the forest structure.

The forest canopy encompasses both horizontal and vertical structures, representing vital space, competition, the ontogeny of the species [65], and modifications in its allometry [66]. Interference in this dynamic is deemed necessary to optimize the growth and sustainability of the forest [67]. In this context, the results reflect past changes that elucidate the present conditions of the Araucaria Forest, enabling an evaluation of its structure and the prediction of future conditions in terms of productivity, diversity, and sustainable conservation [68].

Beltrán et al. [69] state that the increase in diameter is more significant in better sites and tree canopy class, while it decreases with tree age, directly impacting forest yield by reducing vigor [70]. Since this study aimed to use measures of density, growth, structure, efficiency, and regeneration to enable management actions for sustainability, these measures serve to comprehend the dynamics of the forest in light of potential future environmental changes [71].

Management and sustainability share a common objective, emphasizing the importance of maintaining structural heterogeneity. As a result, recent studies on forest structures have seen an expanded focus [72]. The structural complexity enhancement in stands is achieved through approaches such as natural regeneration, integrating different species, and increasing structural elements, including deadwood objects or habitat trees [73–75]. Strong evidence supports the notion that structurally complex forests exhibit higher resilience to disturbances, greater adaptability to environmental stressors, and increased biodiversity. Moreover, these forests are often at least as productive, if not more so, than their more homogeneously structured counterparts [76–78].

The positive response to the tested hypotheses reveals that volume, crown surface, and basal area exhibit an increase with dimensional growth. Additionally, density shows a decrease with increasing diameter, attributed to the fact that larger trees occupy more space. Therefore, tree growth is contingent upon resource availability, the proportion of acquired resources, and the efficiency with which those resources are utilized. Species interactions can influence each of these variables. These dynamic interactions undergo spatial and temporal changes as resource availability and climatic conditions fluctuate. Understanding these processes is crucial when designing and managing mixed-species stands and modeling them effectively [79].

The study unveiled the present conditions of the Araucaria Forest, revealing an asymmetrical allometry characterized by a greater slope and disproportionately higher growth values between organs, coupled with a decreasing increment rate. This development can be traced back to silvicultural approaches implemented four decades ago, which created and maintained the structural and compositional diversity of the population. The current state of the forest indicates structural stability, with an equal distribution of density across diameter classes. However, this equilibrium serves as an answer to the hypothesis of reduced formation of reproductive structures and, consequently, diminished regeneration of the species, thus falling short of providing the desired ecosystem function.

Hence, silvicultural actions become imperative, as described by Bauhus and Pyttel [80], involving the purposeful manipulation of forest structure, composition, and dynamics to ensure the provision of ecosystem services on a sustainable basis. This concept of a silvicultural system is crucial, as any alterations in tree crown morphology and canopy structure in interspecific versus intraspecific environments imply a modification in the trees space occupation, resource capture, and productivity. Of particular interest is a broader crown extension, indicating a reduction in competition and an increase in light interception [81]. Size growth and persistence become essential requirements for a tree to compete and maximize fitness under selective pressure in a forest stand.

Studies focusing on individual trees are valuable for comprehending methods of reducing competition, such as thinning, in conjunction with ecological concepts like complementarity and facilitation. These studies elucidate differences between dynamics, structure, and productivity [81,82]. Consequently, characteristics of individual trees can be extrapolated in the forest, and relationships between morphometric and dendrometric variables can be employed as a sustainable management model for species conservation.

5. Conclusions

The form–dimension–density and increment rate relations generate accuracy in the modeling of the forest dynamics, as well as the efficiency of the crown in the formation of reproductive structures. In this sense, sustainable management plans and decisions for conserving this important forest ecosystem in southern Brazil should be encouraged.

The reported results also show that conservation without implementing silvicultural management regimes puts the sustainability of the species, diversity, regeneration, productivity, and social losses of this important ecosystem at risk. The need to manage the forest structure is evident so that the forest ecosystem's dynamics and the set of goods and services continue to occur sustainably.

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