



Timber Potential of a Secondary Forest with *Araucaria* in Brazilian Atlantic Forest: Implications for Small-Scale Management

Leandro Correa Pinho¹ · Daisy Christiane Zambiasi² · Mário Dobner Jr.³ · Alexander Christian Vibrans⁴ · Alexandre Siminski¹ · Vinicius Costa Cysneiros¹ 

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Abstract

Despite a three-decade-long prohibition on the harvesting of *Araucaria angustifolia* and other timber species in the Atlantic Forest, the conservation status remains critical, as evidenced by the ongoing illegal exploitation, deforestation, and habitat fragmentation. This underscores the need to develop and implement effective strategies to reconcile the use of forest resources with the maintenance of their ecosystems and associated ecosystem services. This study assessed the timber potential of a secondary forest fragment with *Araucaria* by characterizing the composition, forest structure and timber stocks, while accounting for timber and stem quality. Fifty tree species were sampled, 72% of which have some timber use and 19% of which have high quality timber. The average timber stock was $177.6 \text{ m}^3 \text{ ha}^{-1}$, with *Araucaria angustifolia* standing out, accounting for $28 \text{ m}^3 \text{ ha}^{-1}$, mainly in high-quality commercial stems. Two forest types were identified within the studied area: a diversified forest and a high stock forest, representing two groups of sampling units with marked differences in timber quality and stocks. The highest quality stock was concentrated in the commercial ($dbh > 50 \text{ cm}$) and pre-commercial ($30 \leq dbh \leq 50 \text{ cm}$) classes. *A. angustifolia* and *Nectandra megapota mica* stood out for providing high-quality timber and for being dominant commercial species. The results revealed the need for differentiated management practices between forest types. These practices should prioritize the sustainable use of dominant commercial species and the use of lower-quality stems for secondary products. The results indicate that small-scale management, associated with silvicultural treatments, could contribute to integrating conservation and income generation in secondary forests, promoting the maintenance of ecosystem services.

Keywords Subtropical Atlantic forest · Threatened ecosystem · Timber stocks · Dominant commercial species · Small-scale forestry

Introduction

Over the last five centuries, the Brazilian Atlantic Forest has experienced economic cycles based on the predatory exploitation of its natural resources. This has resulted in serious structural and functional consequences, including the simplification of forest structure, loss of biodiversity, disruption of regeneration processes, and the weakening of key ecosystem services. The Mixed Ombrophilous Forest (MOF) or Araucaria Forest, one of the phytophysionomies of the Atlantic Forest Biome (IBGE 2012), has experienced a significant reduction in extent and fragmentation of its remaining areas (Zorek et al. 2024). Within MOF, the intense logging of native species, especially *Araucaria angustifolia* (Bertol.) Kuntze, has favored the expansion of agricultural frontiers by converting natural areas into agricultural lands, forest plantations, and livestock farms (Bertoldo et al. 2014). Due to the repeated occurrence of these impacts, the forest also faces challenges related to climate change and intensified land use, with poorly protected and ecologically disconnected remnants (Bernadinis et al. 2023), formed mainly by fragments of secondary forests within private properties (Fantini et al. 2019).

In response to the drastic reduction of forests, extensive legislation has been implemented in recent decades in order to control the use of natural resources in the Atlantic Forest (Silva et al. 2017; Stevanato et al. 2022) and the MOF (Zorek et al. 2024). The commercial use of timber from *A. angustifolia* natural populations is prohibited (IBAMA Ordinance No. 37, 1992; CONAMA Resolution No. 278, 2001), and the species is considered "critically endangered" on the IUCN Red List (Thomas 2013) and "endangered" on the National List of Endangered Flora Species (MMA 2014). Nevertheless, despite prohibitions of logging and timber use for over three decades, the species' situation remains concerning, with continuous reduction of its natural habitat, reduction of commercial plantations, and insufficient natural regeneration in the few remaining areas (Eisfeld et al. 2020; Bernadinis et al. 2023; Hess et al. 2024).

Despite legal restrictions on its use, *A. angustifolia* timber remains one of the threatened species' most illegally traded in Brazil (Brandes et al. 2020). Its situation underscores two key points: first, the consistent demand for Atlantic Forest timber (Evangelista 2021); and second, the ineffective protection strategy for curbing the illegal logging of endangered species (Wendling and Zanette 2017; Eisfeld et al. 2020). Thus, there is a continued need for research aimed at implementing new strategies to ensure the conservation of forest resources and maintenance of their ecosystem services (Fantini et al. 2016; Bedrij et al. 2022), followed by a discussion of their effective implementation.

Native tree species play a crucial role in biodiversity conservation and ecosystem functioning (Delavaux et al. 2023). Maintaining them is fundamental to ensuring ecological balance, the resilience of forest ecosystems, and the provision of ecosystem services (Liang et al. 2016). Therefore, the commercial use of these species requires technical and scientific approaches that guarantee the maintenance of forest resources without compromising their regenerative capacity (Andrae et al. 2018; Britto et al. 2019; Fantini et al. 2019).

In Brazil, the legal strategy for using native timber forest resources is sustainable forest management (SFM). SFM is defined as managing natural vegetation to

obtain economic, social, and environmental benefits while respecting the support mechanisms of the managed ecosystem (Brasil 2012). Unlike conventional, predatory exploitation, SFM balances the use of forest resources with the conservation of natural habitats, acts as a sustainability mechanism, producing goods and services while guaranteeing the perpetuity of forest ecosystems (Brandt et al. 2016; Péllico Netto 2020). Although SFM is included in the Brazilian Forest Code (Brasil 2012), it is vetoed by the Atlantic Forest Law in the area where the biome occurs (Brasil 2006), under the prerogatives of high fragmentation and insufficient scientific knowledge to guarantee the sustainability of commercial management (Veto No. 1,164 of December 22, 2006). However, several studies have demonstrated that SFM can be an effective conservation strategy while simultaneously promoting income generation (e.g., Malhi et al. 2022; Zuidema and Zwerts 2022; Putz 2025).

Some studies have been conducted in experimental forest management areas in southern Brazil and northern Argentina (e.g., Oliveira et al. 2018; Britto et al. 2019, 2022; Likoski et al. 2021, 2022; Bedrij et al. 2022). However, it remains unclear which parameters should be evaluated for proper small-scale forest management planning, particularly in Mixed Ombrophilous Forest fragments. In this context, this study aimed to (i) assess the timber potential of a secondary forest fragment, by characterizing the composition, forest structure and timber stocks and (ii) investigate the stem and timber quality for commercial use. Finally, we propose to discuss the main implications for the implementation of SFM, as an alternative approach to conservation, use and valuation of secondary forests with *A. angustifolia*, providing an integrated assessment of timber stocks and stem quality to support small-scale management decisions.

Material and Methods

Study Area

The study was conducted in a secondary forest fragment within the Mixed Ombrophilous Forest (MOF) area, situated in Curitibanos, Santa Catarina, southern Brazil. The central coordinates are 27.317239° S and 50.712712° W (Fig. 1). The study area is located within the Experimental Forest Area (AEF), which belongs to the Federal University of Santa Catarina (UFSC). According to the Köppen classification, the region's climate is of the Cfb type, classified as temperate, humid, mesothermal with no dry season (Alvares et al. 2013); with mild summers and harsh winters with severe frosts, an average annual temperature of 16 °C, an average annual rainfall of 1500 to 1700 mm, and an average relative humidity of 80%. The gently undulating terrain is formed by lithic Neosols and Cambisols with varying degrees of stoniness (EMBRAPA 2004). The AEF covers 42 ha, 27.1 occupied by MOF. A total of 8.3 ha was used to assess the timber potential (Fig. 1), excluding all Permanent Preservation Areas (PPA), where timber forest management is prohibited by law (Brazil 2012).

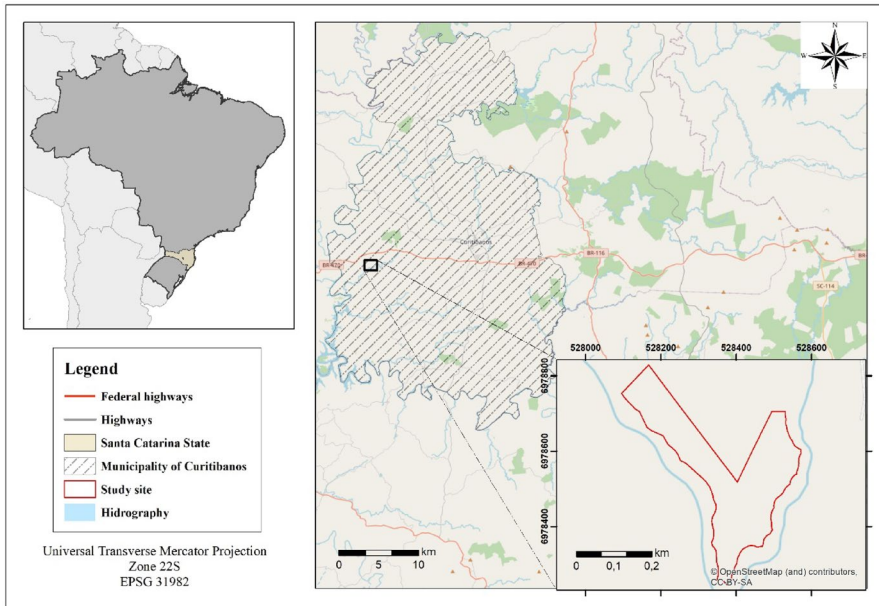


Fig. 1 Geographical location of the study area and the municipality of Curitibaanos, Santa Catarina, southern Brazil

Data Collection

The fixed-area sampling method was used to conduct the forest and phytosociological inventories, as well as to evaluate the composition, structure, and distribution of the timber stock. Sampling units were randomly selected to avoid overlap with roads and open areas without forest cover. Nine permanent rectangular sampling units (SU) measuring 2000 m² each (50 m × 40 m) were allocated in the study area, for a total sampled area of 1.8 ha, i.e., 21.7% of the forest area passive to forest management, excluding the permanent protection areas (PPA) along watercourses. The inventory was conducted in February 2023.

After installing the sampling units, all trees with diameter at breast height (*dbh*) > 10 cm were numbered with metal tags, measured, and identified to the genus or species level. The *dbh* was measured at 1.3 m above the ground using a diametric tape. Tree species were identified in the field by a specialist. From the individuals where identification was not possible in the field, botanical material was collected for later checking in specialized botanical collections. Each sampled tree was visually assessed for stem quality, health, sociological position, and the presence of vines. Trees were then classified according to the criteria described in the Supplementary Material (Supplementary Information I; Table S1). Dead individuals were excluded from the analysis.

The stem heights (*sh*) and total heights (*th*) of all *A. angustifolia* trees were measured using a Haglöf VL4 Vertex laser hypsometer according to the criteria detailed in Supplementary Information II. For the other broadleaf species, we measured the

heights of all emergent trees with a crown above the canopy, all trees with high-quality stems, and a completely random sample of 20% of the other trees. Bifurcated, broken, and excessively crooked trees were excluded from these measurements.

Dendrometric Estimates

Allometric models were adjusted based on the measured heights to estimate the stem and total heights of broadleaf species that were not measured. The procedures for fitting, evaluating, and selecting the height models are described in detail in Supplementary Information II (Tables S2 and S3, Figs. S1 and S2). The selected models were used to estimate the stem height (Eq. 1) and total height (Eq. 2) of the broadleaf species. We then estimated the stem volume of each sampled tree using the equations of Costa et al. (2022) for *A. angustifolia* (Eq. 3) and those of Vibrans et al. (2015) for the other broadleaf species (Eq. 4).

$$sh = 2,506.dbh^{0,415} \quad (1)$$

$$th = 7,638 + 0,188.dbh \quad (2)$$

$$v = 0,000053 \times dbh^{2,129} \times sh^{0,7267} \quad (3)$$

$$\ln\left(\frac{v}{1000}\right) = -17,96 + 0,96 \times \ln(cbh^2) + 0,76 \times \ln(sh) \quad (4)$$

where: *dbh*, diameter measured at 1.3 m above the ground, cm; *sh*, stem height, m; *th*, total height, m; *cbh*, circumference measured at 1.3 m above the ground, cm; *v*, stem individual volume, m³.

Timber Quality-Based Species Classification

The species were classified in terms of commercial timber quality based on the proposal by Zambiasi et al. (2021) and the wood densities obtained from Oliveira et al. (2019). The timber quality classification was supplemented by a comprehensive literature review (see Supplementary Information III). All sampled species were categorized in terms of timber quality (TQ) as low, medium, or high, as well as non-commercial. Each tree was also categorized in terms of stem quality (SQ) as straight, slightly crooked, crooked, or broken or defective. The criteria for classifying species in timber quality and trees in stem quality are described in detail in Supplementary Information III.

Forest Structure Assessment

To analyze the forest structure, the averages of dendrometric variables of diameter ($\overline{dbh}$, cm), stem height ($\overline{sh}$, m), and total height ($\overline{th}$, m) were calculated. Additionally, the values of the structure variables of tree density (N, trees ha⁻¹) and basal area (G, m² ha⁻¹) were calculated. To describe species diversity and evenness, the Shannon

diversity index (H') and Pielou evenness index (J) were also estimated. The forest structure analysis was supplemented by evaluating the diameter distribution of the trees using fixed *dbh* class intervals of 10 cm. Trees were classified according to their potential size for harvesting into two classes: commercial ($dbh \geq 50$ cm) and pre-commercial ($30 \leq dbh < 50$ cm), following the reduced-impact logging criteria (Putz et al. 2001). Commercial trees are eligible for harvesting, while pre-commercial trees form the remaining stock with potential for future harvest cycles. The diversity and equability calculations were carried out using the *vegan* package (Oksanen et al. 2015) in the R software environment (R Core Team 2023).

Sample Units Clustering

Since management recommendations for natural forests should be specific to each type of forest (Brasil 2006), we used dendrometric (*dbh*, *sh*, and *th*), structural (N and G), diversity (H' and J), and timber stock (V) characteristics to categorize the sample units in the study area between different forest types. We carried out cluster analysis using the *K-means* algorithm with the *factoextra* package (Kassambara and Mundt 2020), adopting $k=2$, based on a priori management-oriented criteria to distinguish sampling units with present versus future potential for sustainable forest management. We applied principal component analysis (PCA) to organize the sample components of variation using the *FactoMineR* package (Lê et al. 2008). Differences in forest structure (N and G), diversity (H' and J), and timber stocks (V) between forest types (sampling unit groups) were evaluated using the nonparametric Mann–Whitney U test ($\alpha=0.05$). All analyses were performed using R software (R Core Team 2023).

Timber Potential Assessment

The timber stock (V , $m^3 \text{ ha}^{-1}$) was calculated from the stem volume (v_i) of each individual tree, which was estimated for all sampled trees using Eqs. 3 and 4. Based on these estimates, the timber stock was calculated per sampling unit and analyzed by forest type, species, stem quality class, timber quality class, and diameter class. This analysis aims to explore the potential for commercial use and guide sustainable management practices appropriate to the forest fragment.

Assessment of the Potential for Forest Management

To simulate forest management in the study area, only commercial species with the highest importance value (VI), which is the sum of the relative values of density, dominance, and frequency, was calculated for all the sampled species, were considered (Zambiasi et al. 2021). Species with the highest VI values, which together accounted for 50% of the total VI , were classified as dominant (Finegan 1996). The timber stock of these species was then assessed by diameter class and stem quality to identify possible commercial uses and timber utilization.

Results

Composition, Structure and Timber Stock

The sampled area presented 1132 trees, and 1216 stems belonging to 50 tree species and 29 botanical families. Of the sampled species, 36 (72%) have some timber use. Seven were classified as high quality, 13 as medium quality, and 16 as low quality (see Table S4). Additionally, 14 species were classified as non-commercial, meaning they are not used for timber. Eight species had low timber quality and six had non-commercial timber, but both supplied non-timber forest products (i.e. seeds, fruits or barks). The average tree size, species diversity, forest structure, and timber stock varied between sampling units (Table 1). Diameter ranged from 19.3 to 23.1 cm and average stem height ranged from 11.1 to 12.1 m. Considering only commercial species, the largest diameter was 106 cm; the greatest total height, 28.6 m; and the greatest stem height, 17.1 m. Regarding diversity, the Shannon (H') and Pielou (J) indices were between 2.25 and 2.66 and between 0.73 and 0.86, respectively. These values indicate moderate diversity and suggest a relatively uniform distribution of species abundance. The forest structure variables, density and basal area, as well as timber stock, exhibited the greatest variability. Tree density (N) ranged from 425 to 765 trees ha⁻¹, basal area (G) ranged from 20.9 to 38.3 m² ha⁻¹, and timber stock (V) ranged from 114.5 to 242.2 m³ ha⁻¹. These values reflect marked structural heterogeneity between the sampling units in the study area.

Sample Units Clustering

The sample units clustering in two distinct groups indicated the presence of two forest types in the study area, as revealed by cluster and principal component analyses (PCA) (Fig. 2). The first group is characterized by greater species diversity and evenness (H' and J), while the second group defined as forests with the greatest stock and higher average for dendrometric variables (*dbh* and *th*), with significant differences

Table 1 Summary of dendrometric variables ($\overline{dbh}$ and $\overline{th}$), forest structure (N and G) and diversity (H' and J) and stock (V) per sampling unit (SU)

SU	$\overline{dbh}(\text{cm})$	$\overline{th}(\text{m})$	N (N ha ⁻¹)	G (m ² ha ⁻¹)	V (m ³ ha ⁻¹)	H'	J
1	20.6	11.7	480	23.3	131.3	2.564	0.829
2	19.3	11.1	585	24.0	135.5	2.663	0.849
3	21.9	12.1	500	35.0	221.5	2.538	0.862
4	20.0	11.9	660	29.2	174.2	2.255	0.730
5	20.6	11.8	765	38.3	242.2	2.632	0.799
6	20.2	11.6	755	34.6	204.1	2.443	0.816
7	21.1	11.5	610	31.8	184.6	2.634	0.852
8	23.1	12.0	425	31.5	190.7	2.297	0.828
9	20.0	11.1	535	20.8	114.5	2.525	0.843
Mean	20.8	11.6	591	29.8	177.6	2.506	0.823
Standard deviation	1.16	0.34	125	5.98	43.24	0.15	0.04
CV%	5.59	2.92	19.75	20.05	24.32	5.85	4.85

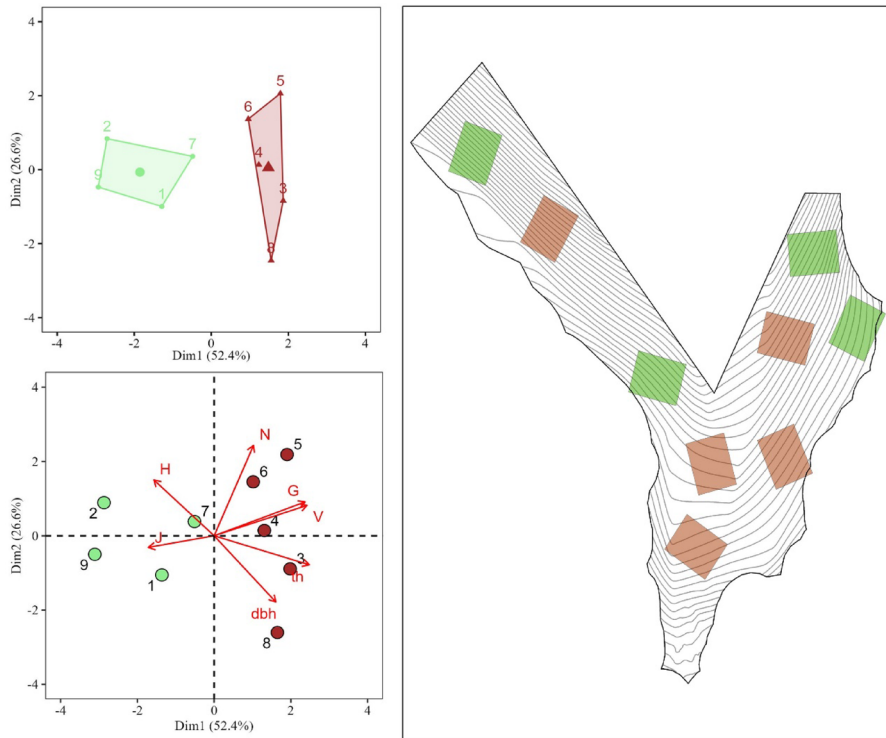


Fig. 2 Clustering and location of the sampling units in the study area. In green are the sampling units in diversified forest (FD) and in brown in high stock forest (FAE)

($P < 0.05$) in forest structure (G), and timber stock (V) (Supplementary Information IV; Table S5). These forest types were referred to in this study as diversified forests (DF) and high-stock forests (HSF). The sample unit groups by forest types were used to assess the stock and timber potential of forest fragment.

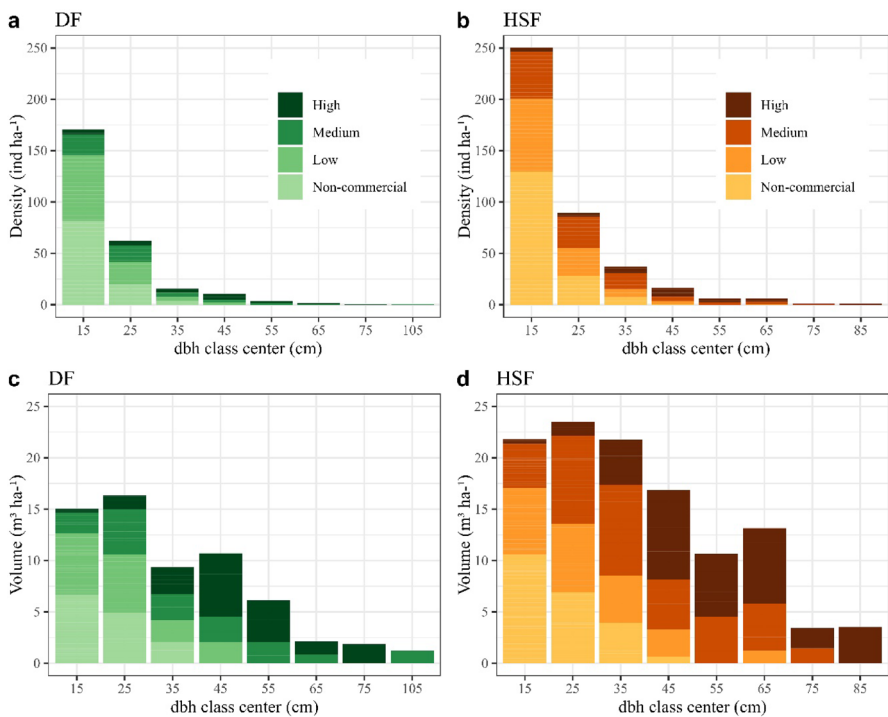
Distribution of Timber Stock

Considering the timber and stem quality classes (sums in Table 2) and the main commercial species (Supplementary Information IV; Tables S6, S7, and S8), most of the timber stock was contained in the HSF ($114.7 \text{ m}^3 \text{ ha}^{-1}$). The stock was also substantially higher in the HSF for the commercial diameter classes ($dbh \geq 50 \text{ cm}$), with a volume of $30.7 \text{ m}^3 \text{ ha}^{-1}$ (Figs. 3 and 4). When considering the timber commercial quality, the largest stock of high-quality was concentrated in the pre-commercial ($30 < dbh < 50 \text{ cm}$) and commercial ($dbh > 50 \text{ cm}$) classes in DF (Fig. 3). The same pattern was evident in HSF, with volumes of 8.7 and $18.9 \text{ m}^3 \text{ ha}^{-1}$ for the pre-commercial and commercial classes, respectively. Regarding the quality of the stems (Fig. 4), the largest stocks of high-quality stems were found in the intermediate diameter classes, from 20 to 60 cm in DF ($17.1 \text{ m}^3 \text{ ha}^{-1}$) and from 30 to 70 cm in HSF ($26.6 \text{ m}^3 \text{ ha}^{-1}$). In general, the lowest timber stocks were found in non-commercial

Table 2 Timber stock ($\text{m}^3 \text{ha}^{-1}$) by timber and stem quality in the diversified (DF) and high stock forests (HSF)

Forest type	Timber quality	Stem quality			
		High	Medium	Low	Total
DF	High	10.6	5.8	1.4	17.7
	Medium	6.3	5.5	3.8	15.6
	Low	4.1	8.1	3.6	15.8
	Non-commercial	1.7	6.3	5.7	13.7
	Total	22.7	25.7	14.5	62.8
HSF	High	23.4	8.6	1.8	33.9
	Medium	4.2	15.3	17.6	37.2
	Low	3.4	10.5	7.7	21.6
	Non-commercial	1.7	12.5	7.9	22.1
	Total	32.8	46.9	35.0	114.7

The highest values are highlighted in bold

**Fig. 3** Tree density (a, b) and timber stock (c, d) by diameter class and timber quality class (TQ) for diversified forests (DF; in green) and high stock forests (HSF; in brown)

species and low-quality stems, which were only more prevalent in the smallest diameter classes ($\text{dbh} < 30 \text{ cm}$), with $29.1 \text{ m}^3 \text{ha}^{-1}$ and $25.2 \text{ m}^3 \text{ha}^{-1}$, respectively.

Potential Timber Species

Based on the established criteria for assessing forest management potential, the most dominant commercial species were *Lithraea brasiliensis*, *Campomanesia xan-*

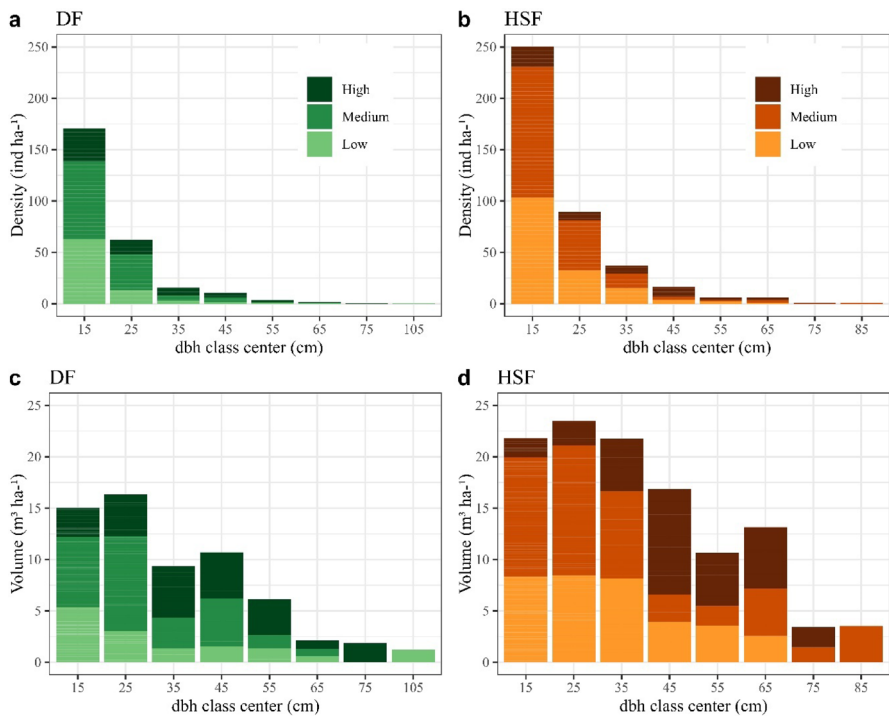


Fig. 4 Tree density (**a, b**) and timber stock (**c, d**) by diameter class and stem quality class (SQ) for diversified forests (DF; in green) and high stock forests (HSF; in brown)

Table 3 Timber stock of dominant species with potential for forest management

Dominant species	VI (%)	Timber quality	N (N ha ⁻¹)	V (m ³ ha ⁻¹)
<i>Lithraea brasiliensis</i>	7.49	Medium	50	20.4
<i>Campomanesia xanthocarpa</i>	7.42	Low	74	12.3
<i>Araucaria angustifolia</i>	7.39	High	29	28.0
<i>Myrcia palustris</i>	6.91	Non-commercial	64	9.6
<i>Cinnamodendron dinisii</i>	5.86	Non-commercial	47	10.3
<i>Banara tomentosa</i>	5.19	Non-commercial	49	5.8
<i>Clethra scabra</i>	4.99	Low	39	11.5
<i>Nectandra megapotamica</i>	4.46	High	12	12.2

thocarpa, *A. angustifolia*, *Clethra scabra*, and *Nectandra megapotamica* (Table 3). Three of the eight most dominant species did not have commercial-quality timber and were not included in this analysis. *A. angustifolia* showed the greatest potential for timber management, providing the largest timber stock (28 m³ ha⁻¹) and high-quality stems in all diameter classes, especially in the commercial (12.2 m³ ha⁻¹) and pre-commercial (9.3 m³ ha⁻¹) classes (Fig. 5a, b). Although *N. megapotamica* has high-

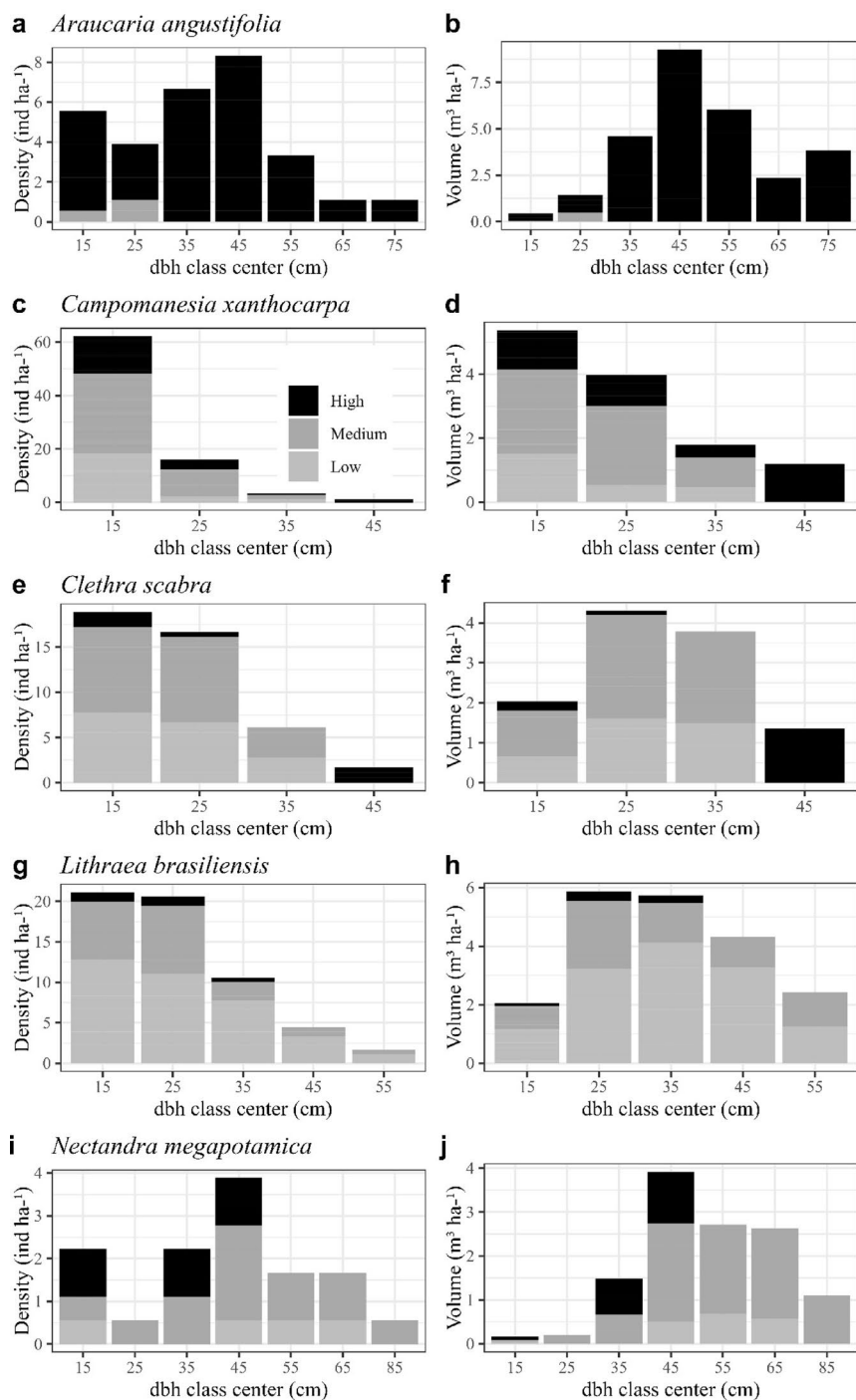


Fig. 5 Tree density (left panels) and timber stock (right panels) by diameter class and stem quality class (SQ) for the dominant commercial species. High quality: black; Medium quality: dark grey; and Low quality: light grey

quality timber, the quality of individuals classified in commercial classes decreased ($6.4 \text{ m}^3 \text{ ha}^{-1}$). These classes are predominantly made up of low- and medium-quality stems (Fig. 5i, j). On the other hand, *L. brasiliensis* showed low potential for trees of commercial size ($2.4 \text{ m}^3 \text{ ha}^{-1}$) and a predominance of low-quality stems in all diameter classes (Fig. 5g, h). Two dominant commercial species did not reach commercial size ($\text{dbh} > 50 \text{ cm}$), *C. xanthocarpa* (Fig. 5c, d) and *C. scabra* (Fig. 5e, f). But both showed timber potential in the pre-commercial classes (2.9 and $5.1 \text{ m}^3 \text{ ha}^{-1}$, respectively).

Discussion

In this study, we evaluated the timber potential of a secondary forest fragment with *A. angustifolia*. We did so by analyzing the volumetric stock and taking into account the timber commercial quality per species, as well as the stem quality per tree. We found that most species have potential for commercial timber use. However, substantial variations in stock and timber quality were observed between species and forest types, underscoring the need for locally adapted and species-specific management practices and diversified timber products to enhance the management of secondary forests with *A. angustifolia*. Additionally, this study presents a replicable approach for sustainable use in MOF fragments, by providing an integrated assessment of timber stocks and stem quality to support small-scale management decisions.

Distribution of Timber Stock

Of the species sampled, 36 had some commercial timber use (72% of total species richness), which is a lower absolute number but a higher relative proportion than that reported by Zambiasi et al. (2021) for secondary forests in southern Brazil (103 species; 51%). However, 45% of the commercial species in this study were of low quality, 36% were of medium quality, and only 19% were of high quality, which is characteristics of impoverished forests (Dawkins 1958; Osmaston 1968). Unlike the dominance of commercial species observed by Zambiasi et al. (2021), three of the eight dominant species in this study are non-commercial, and only *A. angustifolia* and *N. megapotamica* supply high-quality timber. In general, the average timber stock ($177.6 \text{ m}^3 \text{ ha}^{-1}$) was higher than the reference values of $86.2 \text{ m}^3 \text{ ha}^{-1}$ found for Santa Catarina (SFB 2018) and $97.1 \text{ m}^3 \text{ ha}^{-1}$ for *A. angustifolia* forests specifically (Vibrans et al. 2013). This finding reinforces the timber potential of the study area.

The variations in species diversity, forest structure, and timber stock observed in our sample plots reflect the forest's stand history (Zambiasi et al. 2021), exposure to the edge effect, and the site's usage history. These factors resulted in two distinct forest stand types. This has implications for management practices since most of the volumetric stock and commercially sized trees were contained in the HSF. This difference in stocks is typical of successional forests (Puc-Kauil et al. 2024), including in MOF, where total and *A. angustifolia* stocks are substantially higher in older forests (Vaz et al. 2022). The increased availability of high-quality timber in HSF aligns with the dynamics of timber stocks in secondary forest chronosequence, where

successional advancement favors species of greater commercial value (Zambiazi et al. 2021). In our study, however, non-commercial species and low-quality stems were only expressive in the smallest diameter classes ($dbh < 30$ cm).

Potential for Small-Scale Management

When analyzed individually, *A. angustifolia* emerged as the most promising species for timber management. Although it is not abundant in the forest fragment, it has the largest stock due to the size of its trees in both DF and HSF. This peculiar characteristic of forest fragments with *A. angustifolia* is independent of forest stand type and successional age (Vibrans et al. 2022), giving the species high timber potential (Costa et al. 2020; Cysneiros et al. 2023). Although several studies have demonstrated the management potential of *A. angustifolia* in secondary forests (Hess et al. 2018; Longhi et al. 2018; Costa et al. 2020), the use of its timber is controversial due to its threatened status and the current fragmentation of the Atlantic Forest. In this context, studies highlighted the need for a more conservationist approach to achieve the sustainable exploitation of species. This approach involves combining a larger minimum cutting diameter, lower harvesting intensity, and extended cutting cycles, primarily to maintain its genetic viability (Roque et al. 2023). However, the economic viability and technical suitability should be evaluated for the species, considering its biological and silvicultural characteristics. This underscores the ongoing need for discussions that promote strategies to enhance the regeneration, survival, and growth of this species, as well as maintaining its associated ecosystem services.

Although forest management does not affect species diversity, it can impact the abundance of individual timber species (Naves et al. 2020). In the present study, however, harvesting trees in the commercial class ($dbh > 50$ cm) would provide high-quality timber while ensuring the retention of a considerable number of superior pre-commercial trees ($30 \leq dbh \leq 50$ cm) for *A. angustifolia*. Harvesting trees in commercial classes ($dbh > 50$ cm) would also provide medium-quality timber for *N. megapotamica* and could boost its natural regeneration by opening canopy gaps (Pommerening et al. 2024). The species *L. brasiliensis*, *C. xanthocarpa* and *C. scabra* have the lowest potential for commercial trees ($dbh > 50$ cm) and a predominance of lower-quality stems in all diameter classes. This limits their use to supplying timber for secondary purposes. *C. xanthocarpa* and *C. scabra* did not reach commercial size but showed timber potential in the pre-commercial classes. Given that size pattern reflects a species-specific characteristic, differentiated management strategies, particularly regarding the minimum cutting diameter (Sist et al. 2003; Sontag et al. 2025), are recommended for these species. Additionally, these results highlight the need for silvicultural treatments to maintain or improve the commercial quality of forests, from regenerating individuals to commercially sized trees.

The analysis of the timber potential in the forest fragment raised two implications for small-scale forest management (Fig. 6). Firstly, the forest has the potential to produce high-quality timber for commercial use, and a large volume of timber of lower quality and with crooked stems was found that could be used for secondary purposes and for smaller pieces. Using this timber can help to reduce the pressure to extract high-quality species and stems, while also promoting the structural improvement of

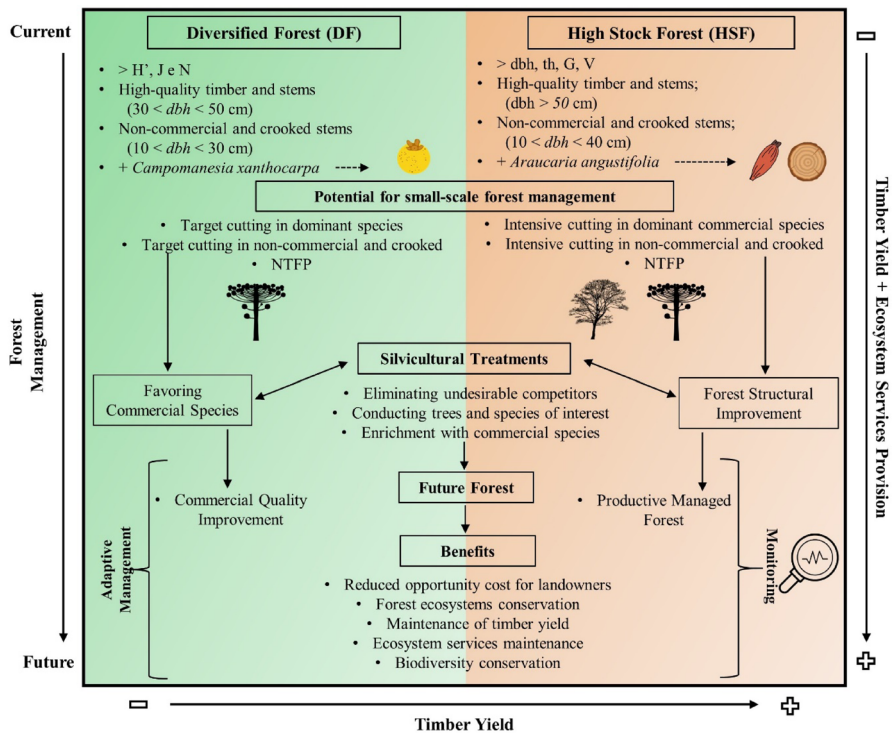


Fig. 6 Results and implications for small-scale forest management in secondary forests with *Araucaria angustifolia*

forests by removing inferior trees (Osmaston 1968; Pommerening et al. 2024). Furthermore, this practice can provide an additional source of income for smallholders, particularly when combined with low-impact management techniques such as selective and reduced-impact logging. Secondly, among the dominant and non-commercial species, 14 were classified as providing some kind of non-timber forest product (NTFP), demonstrating the forest's potential to provide multiple products. In this context, NTFPs can represent a way of diversifying production and income, making forest management more competitive in the short term and integrated with forest conservation (Guariguata et al. 2010). Here, we highlight the potential of the *C. xanthocarpa* and *A. angustifolia* species as sources of edible fruit and seeds, the *C. dinisii* species as a source of bark, and the *Drymis brasiliensis* species as a source of medicinal leaves and bark (see Table S4).

General Implications

The potential timber waste in secondary forests due to legal impediments to forest management represents an opportunity cost for landowners and conservation efforts (Zambiasi et al. 2021). Managing these forests can generate income and reduce pressure on remaining natural forests (Fantini et al. 2019), thereby avoiding forest land conversion for other land uses. An alternative use for these forests would be to selec-

tively fell trees followed by silvicultural treatments (Zambiasi et al. 2021; Pommerening et al. 2024). This is one of the strategies for reduced-impact logging (RIL) to management of natural forests (Putz et al. 2001; Bedrij et al. 2022). Although forest management is often mistakenly associated with deforestation, when planned effectively, it involves the selective removal of a limited number of trees without profoundly altering the forest's structure (Zuidema and Zwerts 2022). Accordingly, well-managed forests can be 'ecologically more energetic' than unmanaged forests, harboring more animal species, for example, and showing higher net primary productivity (Malhi et al. 2022), characterizing functional and diverse forest ecosystems (Zuidema and Zwerts 2022). Thus, these forests have a high potential to provide ecosystem services. For example, they can provide opportunities in the voluntary carbon market, which can leverage financial resources (Bonfim et al. 2022), making forest management more integrated with conservation.

Clearly, silvicultural treatments are needed to prevent the degradation of the Subtropical Atlantic Forest (Bedrij et al. 2022). However, our results indicate that management practices in secondary forests should be tailored to each specific forest type (Fig. 6). For example, the focus for HSF would be on sustainably using the available timber stock, promoting structural renewal and maintaining productivity, with cuts aimed at the dominant commercial species; in contrast, the focus for DF would be on light interventions that prioritize maintaining diversity and growing commercial species (Peña-Claros et al. 2008; Puettmann 2011; Zambiasi et al. 2021). However, targeted cuts and the elimination of competitors or undesirable individuals, as well as the favoring of superior individuals, would be desirable in both the DF and HSF. These silvicultural decisions should be grounded in the ecological, biological, and structural characteristics of the dominant species, avoiding uniform harvesting criteria and reinforcing the need for differentiated, site- and species-specific management strategies (Sist et al. 2003; Schöngart 2010; Pinto et al. 2021; Sontag et al. 2025).

Due to the characteristics of rural properties and the rugged terrain in our study area, managing secondary forests could efficiently integrate income generation and conservation, emerging as a land use alternative for small rural landowners (Fantini and Siminski 2016). It is important to emphasize that strict criteria, such as RIL practices, are essential for ensuring the effectiveness of sustainable forest management (Putz et al. 2001, 2008; Smith et al. 2006), as are long-term studies for understanding the dynamics of managed forests (Bedrij et al. 2022). However, logging can only be justified if it maintains biodiversity and the provision of ecosystem services in managed forests, as well as the supply of timber for future cycles (Bedrij et al. 2022). In this context, continuous monitoring of managed forests is crucial for adaptive management, depending on the temporal response of the forest to the interventions made (Zambiasi et al. 2021).

The current state of forest with *A. angustifolia* emphasizes the requirement for additional conservation measures, such as expanding the protected areas (Zorek et al. 2024) and ecosystems restoration (Bernadinis et al. 2023). Including native timber species of high commercial value and species that supply non-timber forest products in forest restoration projects is an effective strategy for increasing the efficiency of these conservation measures (Krainovic et al. 2023, 2025). This reduces the opportunity cost by introducing the prospect of future financial returns. This also applies

to the enrichment of degraded and/or exploited forests, an important conservation and management strategy which aims to improve forests in future by including rare, commercially valuable species (Piotto et al. 2020; Pinto et al. 2021). In this context, favoring species of interest through the management of natural regeneration can also be an attractive alternative (Fantini et al. 2017; Siminski et al. 2021; Zambiazzi et al. 2021), in line with current legal restrictions on the Atlantic Forest.

Conclusion

The timber stock varied according to the quality classes, with a predominance of medium and high-quality timber and stems, while low quality and non-commercial timber were only frequent in the smallest diameter classes. Most of the high-quality timber and stem volume was concentrated in high-stock forests, especially associated with *A. angustifolia*, a threatened species that still provokes discussions about strategies for its conservation and management. The timber potential assessment also highlighted the importance of applying silvicultural treatments to improve the forest quality by favoring commercial species. Overall, these results underscore the need for differentiated management strategies among species and forest types, prioritizing the sustainable use of dominant commercial species while directing lower-quality stems toward secondary products.

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Data Availability Data of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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Authors and Affiliations

Leandro Correa Pinho¹ · Daisy Christiane Zambiasi² · Mário Dobner Jr.³ · Alexander Christian Vibrans⁴ · Alexandre Siminski¹ · Vinicius Costa Cysneiros¹ 

✉ Vinicius Costa Cysneiros
vinicius.cysneiros@ufsc.br

Leandro Correa Pinho
pinho.ef@gmail.com

Daisy Christiane Zambiasi
daisyzamb@gmail.com

Mário Dobner Jr.
dobnerjr@gmail.com

Alexander Christian Vibrans
acv@furb.br

Alexandre Siminski
alexandre.siminski@ufsc.br

- ¹ Programa de Pós-Graduação em Ecossistemas Agrícolas e Naturais, Departamento de Agricultura, Biodiversidade e Florestas, Universidade Federal de Santa Catarina - UFSC, Rodovia Ulysses Gaboardi, Km 03, Curitibanos, SC 89520-000, Brazil
- ² Programa de Pós-Graduação em Agroecossistemas, Departamento de Fitotecnia, Universidade Federal de Santa Catarina - UFSC, Rodovia Admar Gonzaga, Florianópolis, SC 134688034-000, Brazil
- ³ Florestal Gateados, Rodovia SC 390, Km 204, Campo Belo do Sul, SC 88580-000, Brazil
- ⁴ Programa de Pós-Graduação em Engenharia Florestal, Fundação Universidade Regional de Blumenau - FURB, Rua São Paulo, 3250, Blumenau, SC 89030-000, Brazil