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ORIGINAL ARTICLE – Forest Management

Tree slenderness and stability of Brazilian pine in a secondary forest

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Abstract

The aim of this study was investigating the factors that render *Araucaria angustifolia* trees less stable in secondary forests to support the species conservation strategies. Nine plots were allocated in a Mixed Atlantic Forest where, buckling damage was observed among Araucaria's trees. Then stability was evaluated using the tree slenderness coefficient (TSC), considering TSC ≥ 80 as the critical stability threshold of buckling and breakage. Generalized additive models were fitted to describe variations in TSC in response to tree and plot characteristics. The tree-level characteristics DBH, TH, and canopy position significantly influenced the TSC, as well as competition with larger trees at plot-level. Slenderness decreased with tree size and increased with light competition, with small trees under competition having TSC values beyond the critical stability threshold. Therefore, to maintain more resistant and stable stands, small trees under intense competition should receive more attention and be favored in thinning procedures.

Keywords: Stem damage, Buckling, Breakage, Tree size, Competition.

1. INTRODUCTION

Araucaria angustifolia (Bertol.) Kuntze is southern Brazil's most ecologically, economically, and socially important tree species. The mixed Atlantic Forest or Araucaria Forest is mainly characterized by the presence and abundance of *A. angustifolia* trees (Castro et al., 2020). This species has high-quality wood for civil construction and paper production, but due to its classification as Critically Endangered, cutting *A. angustifolia* trees is prohibited by law (IUCN, 2021).

This prohibition led to a denser occupation of *A. angustifolia* in natural and managed landscapes, which has hindered its natural regeneration both naturally, through the shading produced by the closed canopy, and purposely, through the actions of landowners (Danner et al., 2012; Eisfeld et al., 2020; Hess et al., 2021). Currently, *A. angustifolia* wood production relies on a few commercial stands in southern Brazil (IBÁ, 2023). At the same time, cultivation for seed production (pinhão) has become an important economic strategy tied to its conservation (Carpanezzi, 2023).

Climate-related disturbances, such as strong windstorms and their impacts on forests, have received growing attention from forest managers (Hernandez et al., 2020), because offer multiple risk including non-negligible effects on tree stability (Wang et al., 2023). Studies have shown high susceptibility of conifers (Nykänen et al., 1997) and denser forest stands (Cremer et al., 1982) to wind and storm damage. This includes the Araucaria mixed forest, which is subject to strong storms produced by cyclones (Liebsch et al., 2021).

However, in sites prone to severe storms, forest managers can prescribe practices that improve tree- and stand-level stability (Wonn & O'Hara, 2001). In this context, the tree slenderness coefficient (TSC), or tree height:diameter ratio, has been historically used as an indicator of tree- and stand-level vulnerability to storm damage (Nykänen et al., 1997; Wonn & O'Hara, 2001) as well as a measure of tree stability variation along environmental gradients (Wang et al., 2023).

This study aimed to investigate the factors that lead to less stable *A. angustifolia* trees in a secondary forest. For this, we evaluated variations in TSC in response to tree- and plot-level characteristics. First, we evaluated the effects of tree size and canopy position, then we evaluated the effect of stand competition on TSC variation. Given the legal restrictions, the study aims to understand the factors that affect the tree stability of the species to support conservation strategies.

2. MATERIAL AND METHODS

2.1. Study area and data collection

The study was performed in a 21.7-hectare secondary Araucaria mixed forest located in the municipality of Curitibanos, Santa Catarina state, in southern Brazil (-27.317239°, -50.712712°). The fragment is monitored annually for a long-term study to evaluate the growth dynamics of Araucaria forests. The local climate is defined as subtropical humid (Cfa) according to the Köppen-Geiger classification, with regularly distributed rains, mean annual precipitation of 1600 mm, and mean air temperature of 16º C (Alvares et al., 2013), with harsh winters and severe frosts. The soils are primarily Litholic Neosols and Cambisols. In the preliminary inventory, buckling damage was observed among *A. angustifolia* trees (Figure 1). Buckling is known to decrease stability and increase the risk of breakage in trees (Wonn & O'Hara, 2001), which motivated this research.

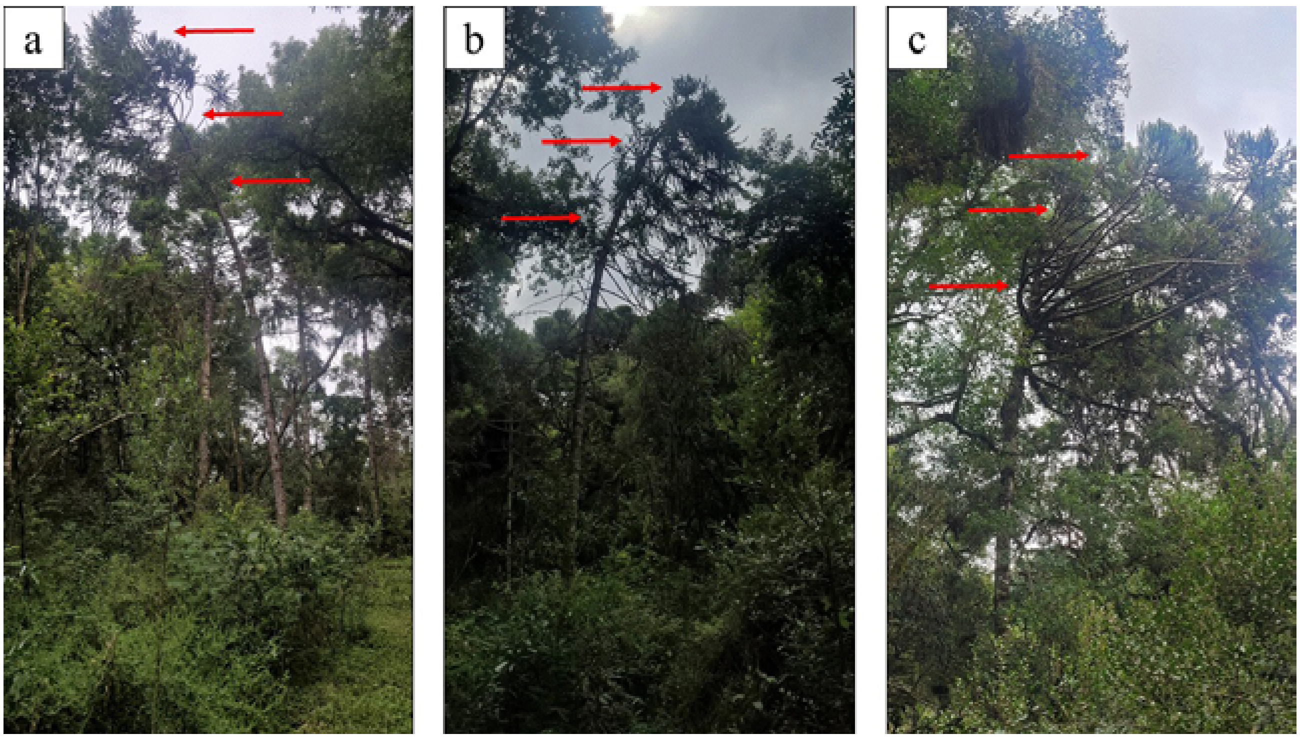

Figure 1. Buckling *A. angustifolia* trees in the study site.

Nine forest plots of 50 x 40 m (0.2 ha) were allocated in the study area, resulting in 1.8 ha of total area sampled. In each plot, all trees with a diameter at breast height larger than or equal to 10 centimeters (DBH ≥ 10 cm) were measured and identified. Other than the DBH, the total heights (TH) of all *A. angustifolia* sampled trees (n = 54) were also measured with a Vertex Haglof hypsometer, encompassing a broad range of tree sizes (Table 1). Subsequently, these trees were visually classified into canopy position categories to describe light competition: emergent (1), dominant (2), subdominant (3), and suppressed (4).

Table 1. Summary of the allometric variables measured in the sampled *A. angustifolia* trees.

Variable	Mean	Min	Max	SD	CV %
DBH (cm)	37.09	10.03	70.98	15.47	41.73
TH (m)	17.74	10.40	24.70	3.10	17.46
TSC	56.49	30.15	133.56	23.90	42.31

DBH: diameter at breast height; TH: tree total height; TSC: tree slenderness coefficient; SD: standard deviation; CV: coefficient of variation.

In each plot, we calculated basal area (G; m² ha^{-1}) as a descriptor of tree cover and competition. To use this variable as a measure of stand-level competition, we subtracted from the plot basal area the individual cross-sectional area of each target tree (Eq. 1), since one tree does not impose competition upon itself (Cysneiros et al., 2022). Subsequently, we calculated the competition index BAL (Eq. 2), which consists of the sum of the basal area of all trees larger than the target tree in the plot.

$$G = \sum_{j \neq i}^{n_p - 1} g_j \quad (1)$$

$$BAL = \sum_j g_j \text{ if } g_j > g_i \quad (2)$$

Where *i* is the target tree, *j* are competitor trees, *g* is the individual cross-sectional area, and n_p is the number of trees in the plot.

2.2. Data analysis

To evaluate tree stability, we calculated the tree slenderness coefficient (TSC; Eq. 3), considering TSC ≥ 80 as the critical stability threshold of buckling and breakage (Wonn & O'Hara, 2001).

$$TSC = TH * \left(\frac{100}{DBH}\right) \quad (3)$$

Where TH is tree total height in meters and DBH is diameter at breast height in centimeters. Generalized additive models (GAM) (Wood, 2006) were fitted to describe TSC variations according to tree- (DBH and TH) and stand-level (G and BAL) characteristics. The model fits were assessed by the percentage of explained variance (DE%), Akaike information criterion (AIC), coefficients significance as per the F-test, and graphical analysis of residuals. Kruskal-Wallis tests were used to test if TSC is affected by canopy position (categorical variables with 4 levels) and the Dunn post-hoc test to test if the trees subject to more intense light competition – located in the lower strata – are less resistant due to higher TSC. All analyses were conducted in R version 4.3.3 (R Core Team, 2023).

3. RESULTS

The tree-level characteristics diameter at breast height (DBH), tree total height (TH), and canopy position significantly influenced the tree slenderness coefficient (TSC) (Table 2; Figure 2). Tree slenderness decreased with increasing DBH and increasing TH (Figure 2b, c) and increased towards the lower canopy positions (Figure 2a). Most of the trees with smaller stature (DBH < 20 cm and TH < 15 m) and located in the lower strata (subdominant and suppressed) were beyond the critical stability threshold, indicating higher vulnerability to damages such as buckling and breakage. Only one tree from the dominant (2) category presented low resistance and stability (Figure 2a).

Table 2. Generalized additive model (GAM) fits of the tree slenderness coefficient (TSC) against tree- and plot-level predictors.

Level	Predictor	Parameter	Estimates	p-value	DE%	AIC
Tree	DBH	intercept	107.18	< 0.001	78.3	418.5
		s(DBH)	-1.366	< 0.001		
	TH	intercept	149.52	< 0.001	46.2	467.6
		s(TH)	-5.244	< 0.001		
Plot	G	intercept	58.51	0.004	0.21	501.1
		s(G)	0.062	0.918		
	BAL	intercept	23.38	< 0.001	73.1	430.1
		s(BAL)	10.95	< 0.001		

DBH: diameter at breast height, cm; TH: tree total height, m; G: stand basal area, m² ha^{-1}; BAL: basal area of larger trees index; DE: deviance explained.

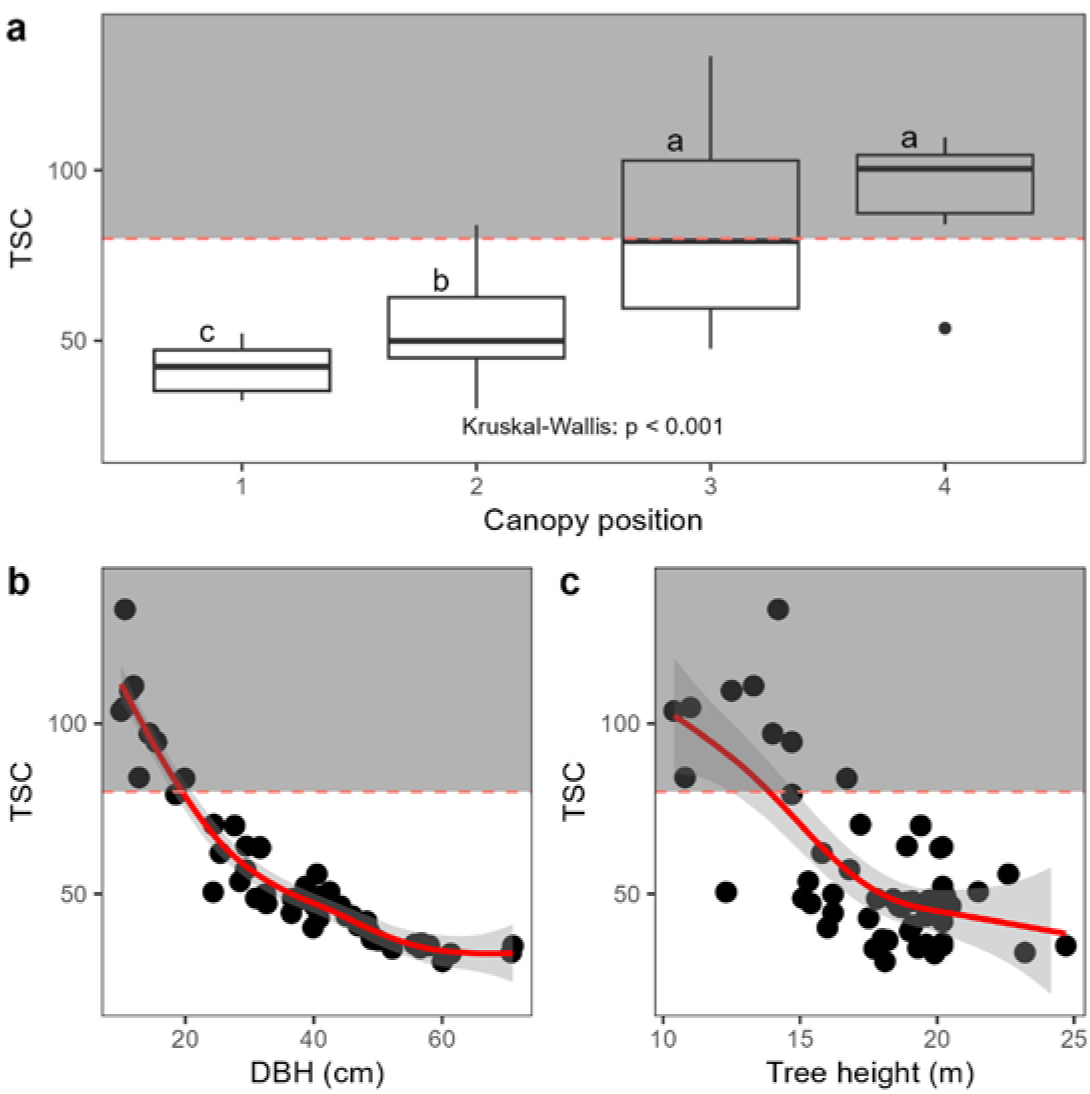

Figure 2. Variation of the slenderness coefficient of *A. angustifolia* trees relative to tree-level characteristics: (a) canopy position, (b) diameter at breast height, and (c) tree total height. Shaded areas delimited by dashed red lines represent the most critical stability regions. Different lowercase letters (a) indicate significant differences according to a Dunn test (α = 0.05). Solid red lines with a shaded band represent the GAM fits with confidence intervals (b, c).

Among the plot-level characteristics, only competition with larger trees (BAL index) significantly influenced the TSC (Table 2), with increasing slenderness associated with increasing competition (Figure 3b). However, only trees under strong competition with larger trees in the stand (BAL > 4) had TSC values beyond the critical stability threshold. Conversely, larger trees undergoing less competition (BAL ~ 0) showed the highest stability. Among the predictors evaluated, the highest explanatory power was provided by DBH (highest DE% and lowest AIC), followed by BAL and TH (Table 2). These variables provided efficient and non-biased models of TSC variation (Figure S1, S2 and S3).

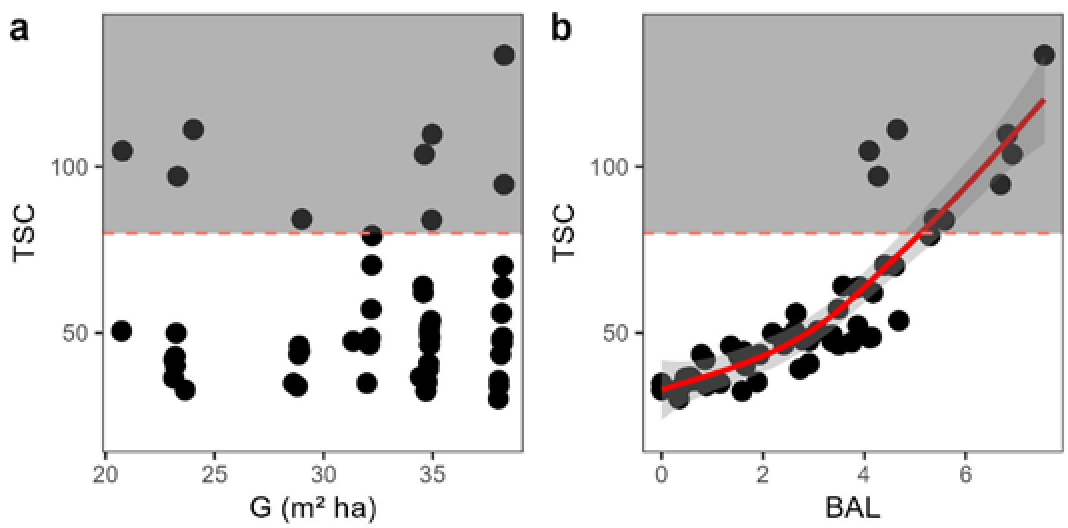

Figure 3. Variation of the tree slenderness coefficient of *A. angustifolia* relative to plot-level competition: (a) basal area of the stand and (b) basal area of the trees larger than the target tree. Shaded areas delimited by dashed red lines represent the most critical stability regions. The solid red line with a shaded band represents the GAM fit with its confidence interval (b, c).

4. DISCUSSION

In general, smaller and younger trees have higher TSC due to competition for space (Wang et al., 1998) and lower resistance due to a higher proportion of sapwood in the cross-sectional area (Sellin, 1994). Light competition across the different canopy strata also explains the higher slenderness of small-statured trees. While intermediate and suppressed trees tend to become slenderer and thinner for allocating more resources toward vertical growth due to light competition (Wonn & O'Hara, 2001), dominant and codominant trees do not undergo similar pressure for already occupying the canopy (Hess et al., 2021). This corroborates the inverse relationship between TSC and TH (Fig. 2c), whereby shorter trees, subjected to shading, become slenderer and, consequently, less stable. The high slenderness found in a single dominant tree (Fig. 2a), on the other hand, suggests that free growth (due to very wide spacing) may also lead to lower resistance of smaller trees.

Although denser forest stands are more likely to have low-resistance trees (Cremer et al., 1982), in the secondary Araucaria mixed forest studied here high stand basal area (i.e., stand cover) did not predict high TSC values among the target trees. We found that the least resistant trees occurred in all levels of stand cover sampled (Figure 3a). On the other hand, competition with larger trees significantly affected TSC. The larger and dominant trees exert strong competition on the smaller and suppressed trees (Wonn & O'Hara, 2001), negatively affecting their growth and allometry (Cysneiros et al., 2022). However, the fact that the BAL index is independent of distance and considers the largest trees in the whole plot can mask the effect of neighbor competition on the target trees (Orso et al., 2020). Lastly, these findings suggest that tree size and competition determine the slenderness and stability of *A. angustifolia* in natural forests.

The secondary forests are effective nature-based solutions (Griscom et al., 2017) that need to be managed to maximize their stability and provision of ecosystem service (Wang et al., 2023; Chazdon et al., 2016). In this context, thinning of undesirable competitors is the most recommended strategy for maintaining stable trees (Cremer et al., 1982; Wonn & O'Hara, 2001). These efforts should be especially directed at young *A. angustifolia* stands to favor the development of promising trees of smaller stature (Hess et al., 2021). Thinning of competing species procedures can even improve production and facilitate the collection of *A. angustifolia* edible seeds (pinhão) (Danner et al., 2012; Carpanezzi, 2023). However, more research is needed to determine, for example, the minimum and maximum spacings to avoid the development of unstable trees.

5. CONCLUSION

The results show that *A. angustifolia* slenderness decreases with tree size and increases with competition with larger trees. The smaller trees undergoing intense competition – especially from larger trees – showed lower resistance to damage. Therefore, these trees should receive more attention in natural and managed ecosystems toward the maintenance of more resistant and stable stands. Aligned with legal cutting restrictions, practices beyond conservation, such as selective thinning of competing or undesirable species, can promote the healthy growth and stability of *A. angustifolia* trees, and consequently improve the species conservation strategies

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Eduardo Luz de Souza: investigation (supporting), methodology (supporting), resources (equal), visualization (equal), writing – original draft (supporting), writing – review & editing (equal).
Leandro Correa Pinho: data curation (supporting), investigation (equal), methodology (supporting), supervision (supporting), visualization (equal), writing – original draft (supporting), writing – review & editing (equal).
Allan Felipe Vuolo: formal analysis (supporting), investigation (equal), software (supporting), visualization (equal), writing – review & editing (equal).
Isabelle Roisin Soler Pereira: investigation (supporting), methodology (supporting), validation (supporting), visualization (supporting), writing – review & editing (equal).

DATA AVAILABILITY

The entire dataset supporting the results of this study is available on request from the corresponding author [Vinicius Costa Cysneiros]. The dataset is not publicly available as it is part of an ongoing project.

SUPPLEMENTARY MATERIAL

The following online material is available for this article:
Figure S1 - Analysis of residuals (upper graphs) and trends checking (lower graphs) for the GAM model with DBH.
Figure S2 - Analysis of residuals (upper graphs) and trends checking (lower graphs) for the GAM model with TH.
Figure S3 - Analysis of residuals (upper graphs) and trends checking (lower graphs) for the GAM model with BAL.

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