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ORIGINAL PAPER

Height-to-diameter ratios with temporal and dendro/morphometric variables for Brazilian pine in south Brazil

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Abstract Height-to-diameter ratios (HD) are an important measure of the stability, density and competition of forest stands. It reflects the vertical growth of the trees, the vulnerability of the forest canopy structure and influences volumetric production. HD ratios vary according to tree size, availability of resources for growth, stand density and species composition. Data were taken from 210 trees and a regression technique of generalized linear models for the HD ratio applicable for forest structure conservation was developed. The objective of this study was to model the HD ratios of dominant and co-dominant trees of *Araucaria angustifolia* according to morphometric, dendrometric, annual diameter increment, stand density, and age variables in three sites in southern Brazil. The results show that the HD ratio decreases with increasing age, crown area and basal area, and increases with stand density and annual diameter increment. Accuracy of the developed equations was demonstrated by the values of deviation, Bayesian and Akaike criteria. The results are of interest to forest managers since they make decisions about silvicultural operations. Growth continuity and forest production indicate that any intervention should be directed at younger trees of smaller sizes, and that one of the main management factors for stand stability and growth is the formation of the stand and its capture of light.

Keywords Forest management · Mixed forests · Conservation · *Araucaria angustifolia*

Introduction

Brazilian pine (*Araucaria angustifolia* (Bertol.) Kuntze) is one of the most common and economically important coniferous species in southern Brazil. It generates revenues from the sale of timber (when licensed for cutting) and of cones with edible seeds. It occurs in the Mixed Ombrophilous Forest. Cutting of Brazilian pine for forest management is prohibited by law (Brasil 2006, 2008; MMA 2008). Along with this management policy, the predominance of the species, (forming pure forests), is supported by factors such as its dominance in all stand strata and the reduction in diversity of other species. This predominance causes other factors such as competition (intra and inter-specific), impedes regeneration (due to canopy closure), increment reduction, commitment to maintain a future diameter structure with old-growth trees, and highest mortality (Beckert et al. 2014; Hess et al. 2018a, b; Silveira et al. 2018).

Therefore, research on forest planning is necessary for the elaboration of techniques and models of silvicultural interventions with an emphasis on sustainability, prediction of growth and yield, aiming at the conservation and maintenance of future forest structure and diversity. In mixed forests, it is not always possible to determine tree ages. Models for individual trees that use morphometric

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variables, competition indexes, height-to-diameter ratios (HD), mortality, ingrowth (trees that migrate between diameter classes), increment rings and the relationships between these variables are extremely important to evaluate growth, yield and sustainable interventions of management (Adame et al. 2008; Costa et al. 2016, 2018; Hess et al. 2016, 2018c; Minatti et al. 2016).

However, it is difficult to guarantee and demonstrate to environmental regulatory institutions the need to conserve of forest resources, particularly Brazilian pine. In this study, the objective is to evaluate and model HD ratios using morphometric variables such as diameter at breast height, diameter increment, and age, with the goal of contributing to the sustainable management of the Mixed Ombrophilous Forest.

The choice of the HD variable is because of its importance as an index of tree resistance to wind breakage and as a measure of tree stability, especially of conifers, and for the development of models that can predict these factors (Eguakun and Oyebade 2015). Variation in the HD ratio is a result of different environmental and growth conditions that each tree experiences. Individual HD values may be different for sites, classification, stands, tree age, root system, soil type and soil conditions (Schelhaas 2008), and depend on the position that the tree occupies in the forest strata. HD ratios help define competition, resource availability, exposure to stress, and individual tree capacity for growth and crown shape.

HD ratios are also important because, when competing with other trees, the primary ways to increase light-harvesting capacity is by increasing height, crown length, crown width, or all three (MacFarlane and Kane 2017). Investigation of HD ratios focus on competition (high density), growth, stability, wind damage and productive capacity (crown length and width).

The ecological success of a tree depends on its ability to capture and utilize light (Alves and Santos 2002). Thus the earlier the tree can join the canopy, the higher the absorption of photosynthetic radiation and greater its productivity in mixed forests (Forrester and Bauhus 2016; Forrester et al. 2018). It is, however, difficult to determine which canopy structure or crown architectural characteristics most strongly influence light-related species mixing effects (uneven-aged stands) and how these effects might differ between sites, species composition and stand ages.

The HD ratio is also a reflection of the horizontal and vertical structure in mixed forests. Vertical stratification should enable the foliage of each species to be distributed in complementary vertical profiles (Forrester et al. 2018). This can result from contrasting height dynamics, age and physiology, including shade tolerance. Horizontal stand structure can also influence light absorption. For example, a higher number of trees or a higher average tree size could increase the stand density in terms of leaf area and hence absorption of photosynthetically active radiation (Forrester et al. 2018).

Schelhaas (2008) concluded that in Douglas-fir–beech mixtures, silvicultural systems leading to low height-diameter (HD) ratios were most successful in avoiding damage. Low HD ratios were obtained in the system with low stand density and no thinning, and in the uneven-aged system, by systematically removing trees with the highest ratios during thinning. In particular, the uneven-aged system combined high timber production with low risk. The use of Douglas-fir–beech mixtures changed the competition pressure on Douglas-fir, and thus the HD ratio and wind risk. Management only had an indirect influence on HD ratios through the manipulation of stand density. However, in the uneven-aged stand, management also had a direct effect on HD ratios because they were the main selection criterion when stand density had to be decreased in a particular diameter class (Schelhaas 2008). Forest stands with relatively high HD values can still be stable if stand density is high enough because of mutual support and shelter of the individual trees.

Schelhaas (2008) conclusions serve as the basis for the hypotheses in this study, namely that HD ratios change with the dynamics of individual trees. This also addresses the questions: (1) which period of tree growth and development requires silvicultural treatments? (2) In which period should an intervention be applied to reduce the HD ratio and generate adaptive responses of stability, crown formation and growth? There is a need, therefore, to understand the behavior of the HD ratio with changes in tree dynamics (age, size, diameter increment and shape), aiming to identify optimum times for intervention in forest.

Therefore, the objective of this study was to develop HD ratio models according to the independent variables of age, annual diameter increment, crown area, density (number of trees) and basal area for dominant and co-dominant trees. Knowledge of the dynamics of the HD relationship is important for forest managers because it is a variable that can be used to diagnose periods for intervention in forest density, wind damage, stability and productivity.

Materials and methods

Description of the area

Data in this study were obtained from dominant and co-dominant trees at three sites, São Joaquim (SJQ), Urupema (URU) and Painel (PNL) with a Brazilian pine forest in

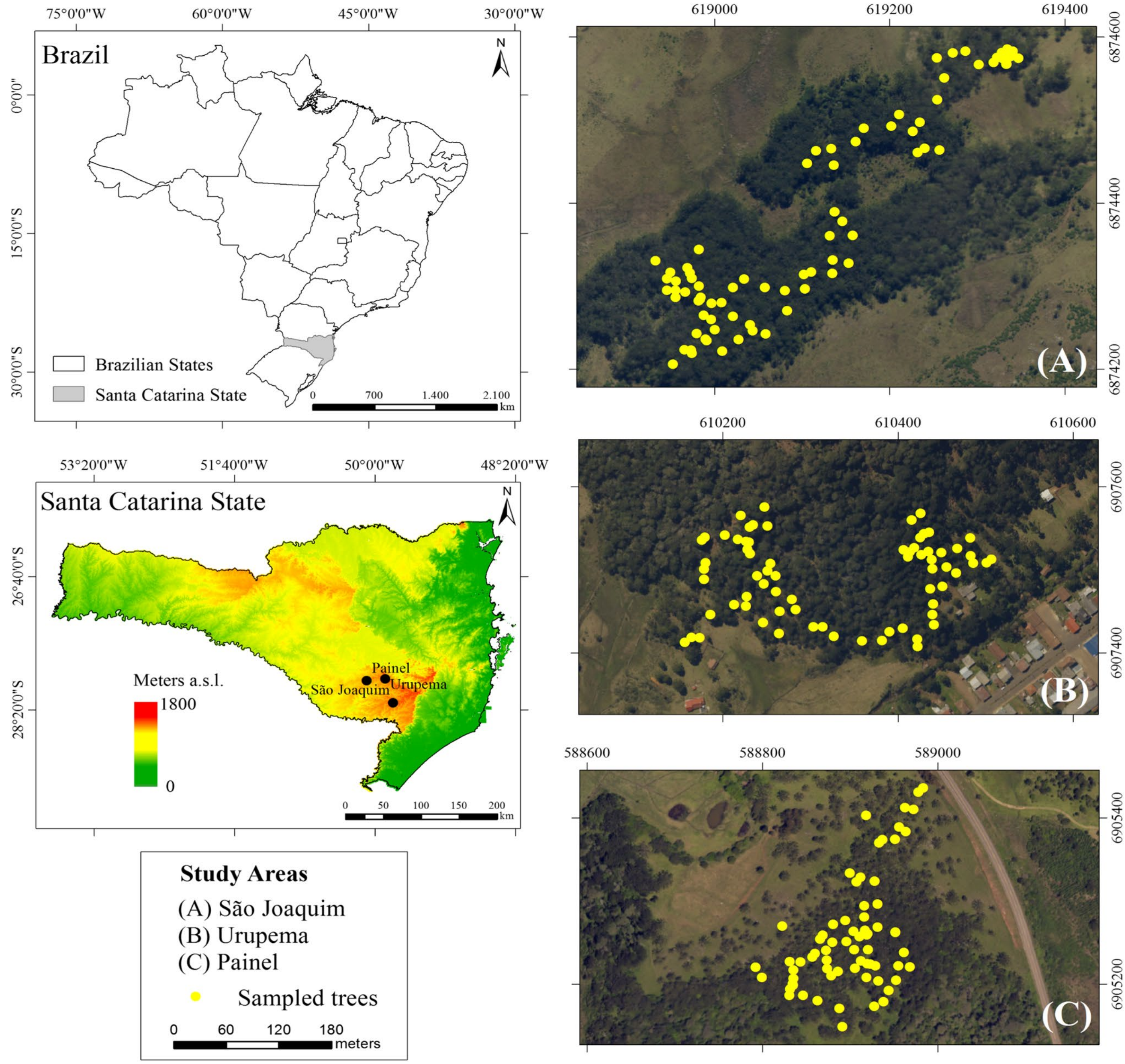

Fig. 1 Location of the three study areas used to determine height-to-diameter ratios

Santa Catarina, southern Brazil (Fig. 1). Dominant trees were those whose crowns reach the highest levels of the canopy, receiving direct sunlight from above and partially laterally; co-dominant ones with crowns just below the canopy and with average dimensions, have lateral competition and receive direct sunlight from above and sparsely laterally. Despite using three sites and trees with different ages, it was possible to classify dominant and co-dominant trees because the stands were unequal, presenting competition and development at different heights for each individual tree.

The location of the study sites is in the Mixed Ombrophilous Forest (MOF). Brazilian pine has characteristics of both a pioneer and a climax species, with individuals in all three strata of the forest. This reduces biodiversity of other tree species and favors the formation of araucaria-dominated forests.

On these sites, due to restrictive forest legislation, no silvicultural thinning take place in the first 20 years. The sites have similar characteristics with regards to species composition. The majority of species are late secondary species and, due to canopy closure by Brazilian pine, temperature increases and the breaking of seed dormancy are restricted. Thus, *Araucaria angustifolia* is between 57 and 60% of the spatial arrangement of the forest, while the other species are pioneer and secondary species with little commercial value.

All the study sites are characteristic of the Mixed Ombrophilous Forest biome, in which *Araucaria angustifolia* forms a very characteristic, sometimes continuous, cover, giving the impression that it is a single stratum. However, under the canopies of Brazilian pine, there are other species of trees and shrubs, herbs, epiphytes and lianas varying in abundance and size depending on location and stage of stand development (Sonego et al. 2007).

The region is Cfb climate according to Köppen classification, which is a constantly wet temperate climate without a dry season. In São Joaquim (SJQ), altitude is 1166 m a.s.l. with an average annual temperature 14 °C and precipitation of 1740 mm. At Urupema (URU), altitude is 1259 m a.s.l., average temperature is 13.7 °C and annual precipitation is 1722 mm. The altitude at Painel (PNL) is 1123 m a.s.l., average temperature is 15.3 °C and annual precipitation is 1543 mm (Alvares et al. 2013).

Database

A total of 210 trees, 70 at each site, were measured for diameter at breast height (DBH), total height (H) and four crown rays (cr) in the cardinal positions with the aid of a compass and a Trupulse hypsometer. Two increment cores/tree were extracted at opposite radii at DBH with a 30-cm increment borer (Assmann 1970). The increment cores were sanded and annual rings marked. Ring widths were measured with a Lintab-6 digital measuring with an accuracy of 0.001 mm, and is supported by software for time series analysis and presentation (TSAP-Win) (Schöngart et al. 2005).

The data set allowed for the analysis of HD ratios with variables in two moments. The first was for the data set (70 trees) measured in the present and its relationship with crown area (ca), basal area (gi) and density (N), Eqs. (1)–(3). The second was calculated from hindsight tree measurements from 210 trees, modeling HD ratios with age and annual diameter increment (id_{t-1}), both obtained at breast height.

Data analysis

Descriptive statistics for dendrometric and morphometric variables, annual diameter increment and age were obtained as well as crown area, basal area and density (number of trees).

$$ca = \pi * \overline{cr}^2 \tag{1}$$

$$gi = \frac{\pi * d^2}{40000} \tag{2}$$

$$\mathrm{N} = \frac{10000}{\mathrm{ca}} \tag{3}$$

where ca is crown area in m^2, $\overline{cr}$ mean crown radius in m, *gi* the individual basal area in m^2, *d* the DBH (cm) and N the number of trees per hectare

Data analysis was performed using the Time Series Analysis Program (TSAP-Win) with cross-dating procedure (Rinntech 2010). HD ratio data were subjected to analysis of covariance to test whether the slopes and levels differed significantly among the study areas (Kaps and Lamberson 2004), i.e., differences in HD patterns and capacity for height growth. HD ratios and their variability as a dependent variable were considered to explain particular aspects of the site, density and stability of trees, while annual diameter increment (id_{t-1}), age, crown area, basal area and number of trees were considered as continuous independent variables. Application of the model proposed by Kaps and Lamberson (2004), including the effect of local and simple linear regression, is shown in Eq. 4:

$$y_{ij} = \beta_0 + \tau_i + \beta_1 x_{ij} + \sum \mathrm{i}\beta_{2\mathrm{i}}(\tau * x)_{ij} + \varepsilon_{ij}, \quad i = 1, \ldots, a; j = 1, \ldots, \mathrm{n} \tag{4}$$

where y_{ij} is the observation *j* of group *i*; τ_i: group effect; β: regression parameters; x_{ij}: value of continuous independent variable for observation *j* of group *i*; $(\tau * x)_{ij}$: interaction of group *x* covariable; ε_{ij}: random error.

With annual diameter increment determined from the increment cores, it was possible to obtain diameter retreat until current age. With this data, height at each diameter (Eq. 5) (Hess et al. 2018e) was estimated and adjusted in previous studies for the species, and thus the HD ratios were calculated for each growth period of the sampled trees. The adjustment of the model had a deviation value of 22.2, Akaike's information criterion of 2093.3 and Bayesian information criterion of 2106.

$$\mathrm{h} = 7.4373 + 0.2077 * \mathrm{d} \tag{5}$$

where h is total height in m and d is DBH (cm).

For adjustments of the HD ratio models with crown area, basal area, number of trees ha^{-1}, age and annual diameter increment, the residuals (adjustment error) were submitted to regression conditioners (normality, homogeneity of variance and error independence). As the conditioners were not met, the models were adjusted by the regression of generalized linear models (GLMs) gamma distribution, identity link function and logarithm. The adjusted models were:

$$\text{HDs} = \beta_0 + \beta_1 * ca \quad (6)$$

$$\text{HDs} = \beta_0 + \beta_1 * gi \quad (7)$$

$$\text{HDs} = \beta_0 + \beta_1 * N \quad (8)$$

$$\text{HDs} = \beta_0 + \beta_1 * \text{age} \quad (9)$$

$$\text{HDs} = \beta_0 + \beta_1 * id_{t-1} \quad (10)$$

where HDs is height-to-diameter ratio, ca crown area in m^2, *gi* basal area (m^2), *N* is number of trees ha^{-1}, id_{t-1} is annual diameter increment cm.

Equations 6, 7, and 8 are for the current data for the seventy trees, 9 and 10 for retrospective analysis of the HD ratio with age and annual diameter increment. To evaluate the accuracy of the equations, the deviation, Akaike, Bayesian criteria, graphical analysis of the residuals and observed and estimated values were used. All analyses were processed in the Statistical Analysis System, SAS 9.2 (SAS Institute Inc. 2011). HD ratios with the variables of size, shape, increment and age were constructed to indicate tree behavior in the stand and to make inferences regarding the stability of trees, productive capacity and periods to propose silvicultural operations.

The graphical analysis of residuals (Figs. 2, 3) show homogeneity of the variance with no discrepant points. This indicates that the adjusted equations can be used to estimate

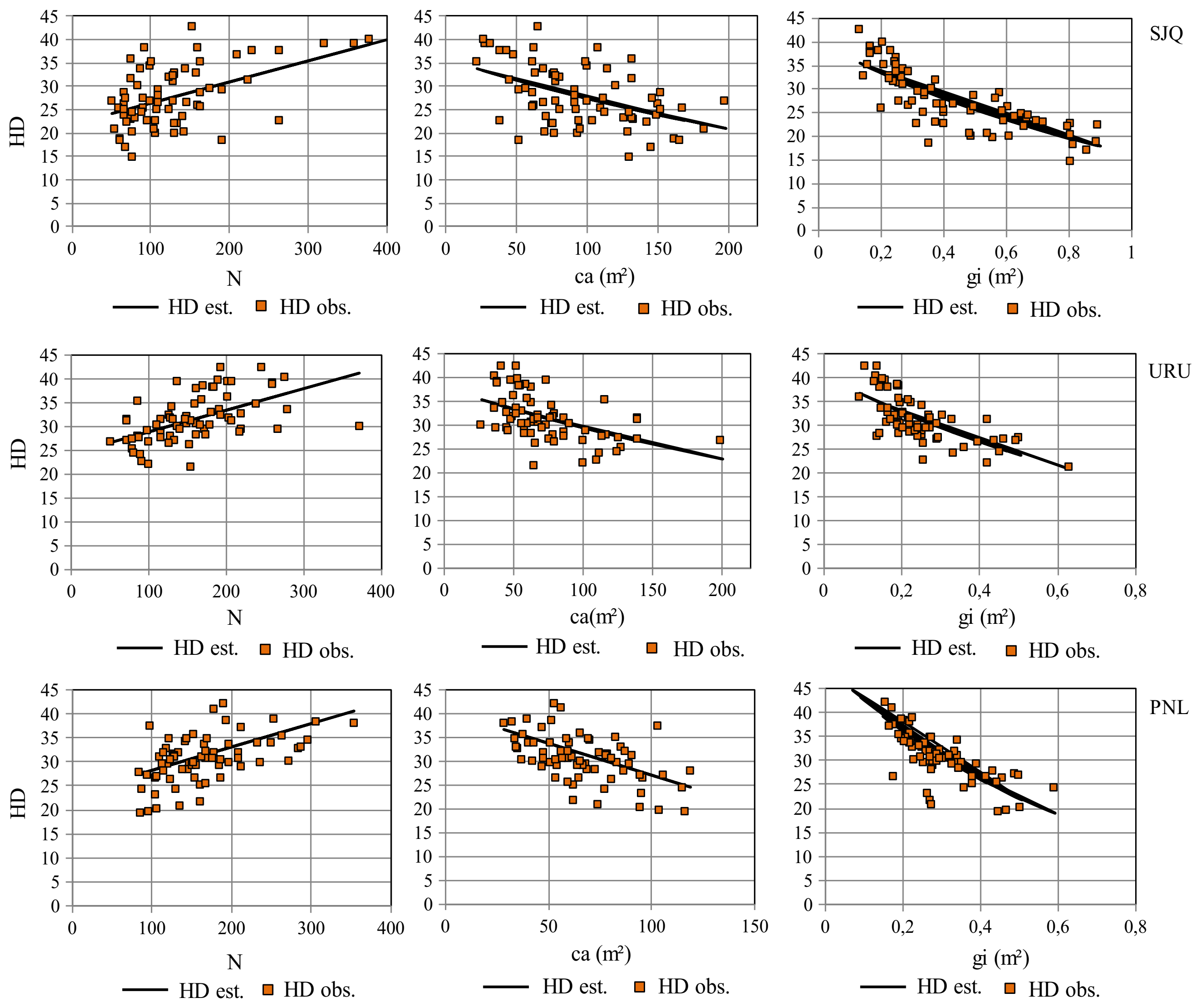

Fig. 2 Adjustment and accuracy of the HD ratio with density, crown area and basal area for dominant and co-dominant Brazilian pines at three sites in southern Brazil. HD: height-to-diameter ratio; N: number of trees (ha^{-1}); ca: crown area (m^2); gi: basal area (m^2); HD est.: estimated HD ratio; HD obs.: observed HD ratio; SJQ: São Joaquim; URU: Urupema; PNL: Painel

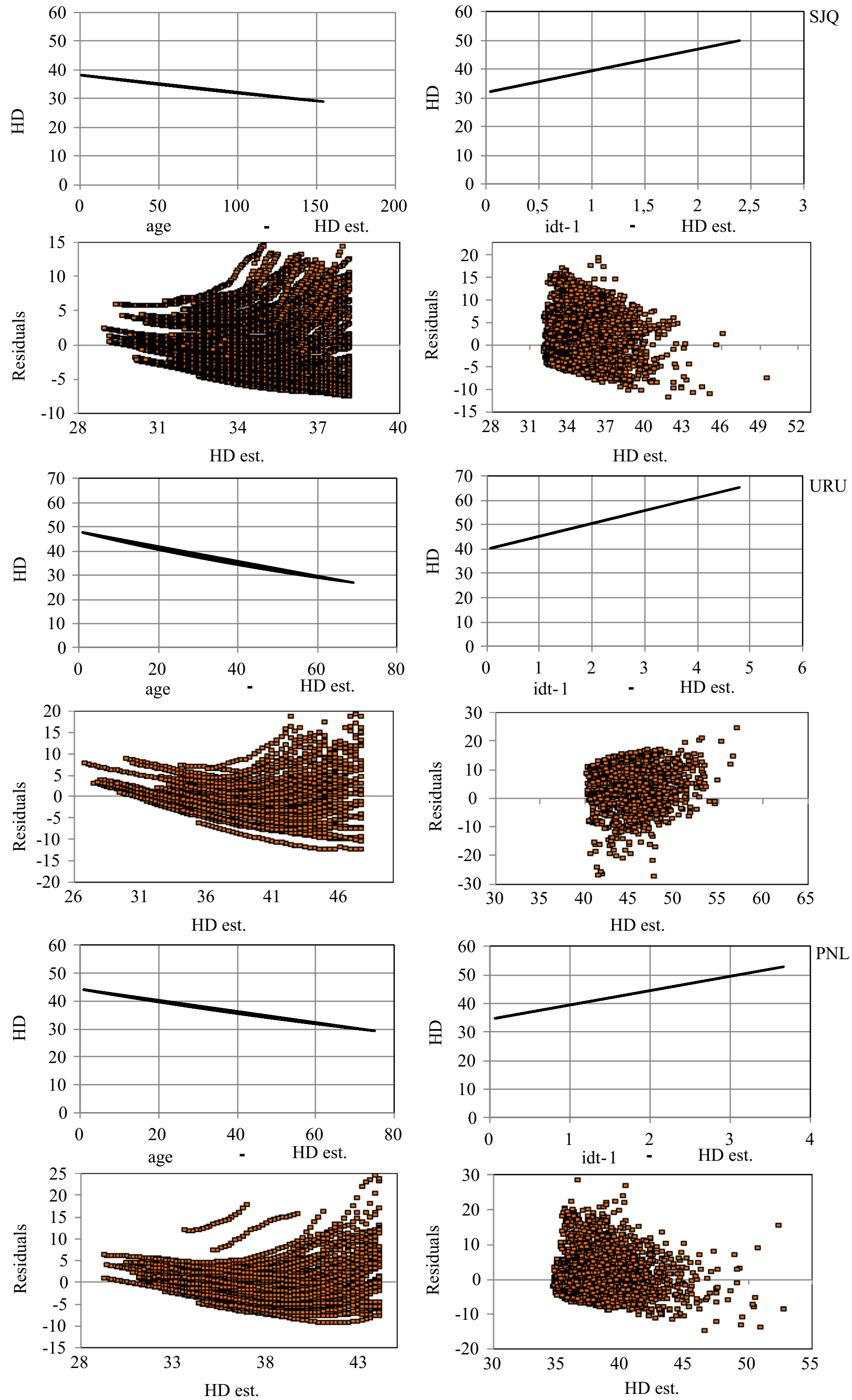

Fig. 3 Adjustment and precision (residuals graphical) of HD ratio change with age and annual diameter increment for dominate and co-dominant Brazilian pines; HD: height-to-diameter ratio; id_{t-1}: annual diameter increment; HD est: estimated HD ratio; SJQ: São Joaquim; URU: Urupema; PNL: Painel

HD ratios with precision as a function of the independent variables.

Results

Of the seventy trees sampled at the SJQ site, 27 were dominant and 43 co-dominant; there were 8 dominant and 62 co-dominant at the URU site and 17 and 53 at the PNL, respectively. The statistics for each variable (Table 1) show that SJQ had the highest averages for dendrometric variables and lowest HD ratios. This indicates that trees on this site are older and have stabilized their height growth.

Whereas at the URU site, trees have longer crowns, higher photosynthetic capacity, the largest annual diameter increment (Table 2), and the trees are not self-pruning. Competition is less and there is greater lateral space for crown growth. Smaller crown ratios of dominant and co-dominant trees is an ontogenetic or developmental feature of Brazilian pine, indicating that the tree reached maturity, growth stagnated and the crown developed an umbel shape.

This relationship is shown in Fig. 2, indicating that HD ratios decreased with increasing crown size and basal area, showing higher HD values as trees cease height growth. In relation to the number of trees, HD ratios increase with an increase in stand density, indicating competition and the need to reduce the number of stems.

Dendrochronology of the 210 trees allowed a retrospective analysis of the increment in diameter from age 24 to 150 years. The results showed that the width of the growth rings ranged from 0.03 to 4.79 cm a^{-1} and the mean annual increment 0.3 to 0.9 cm a^{-1} (sum of annual increment divided by age). The data show that growth on the SJQ site is stagnant and trees are older than on the other sites. Although the URU and PNL sites had higher average annual increments, Hess et al. (2018d) showed that, in the last 10 years, increment on all three sites decreased by 71% (SJQ), 49% (URU) and 62% (PNL), which means stagnation and the need for management intervention.

Table 2 Increment intervals and average diameter increment for 210 *Araucaria angustifolia* trees for the three study areas

Diameter annual growth rates	Study area		
	SJQ	PNL	URU
Minimum (cm $year^{-1}$)	0.036	0.068	0.069
Maximum (cm $year^{-1}$)	2.39	3.66	4.79
Average (cm $year^{-1}$)	0.34	0.68	0.90
Retrospective analysis (years)	60–153	34–68	24–62

SJQ, São Joaquim; URU, Urupema; PNL, Painel

The results show a correlation between HD ratios, annual diameter increment and age, making this relationship important for developing silvicultural operations. The results also indicate that when the HD ratio is stabilized at lower values, these individuals can be removed, allowing space for younger trees and maintaining the diametrical (horizontal) and vertical structure of the forest.

Bošela et al. (2014) commented on HD ratios with altitude, noting that trees with longer crowns and highly tapered stems at high altitudes, had lower HD ratios than trees at lower altitudes. They found high correlation and adjustment of the HD ratio with crown ratio. Other factors affecting the HD ratio were tree density, site and tree age.

Different ages characterize differences in tree development among sites, and are associated with resource availability for growth, as well as differences in HD ratios, density and competition.

The analysis of covariance for HD ratios, according to the dendro/morphometric variables, showed differences between levels (β_0 coefficient) and inclination (slope) of

Table 1 Dendrometric and morphometric variables for the total and dominant and co-dominant trees at the three sites

Study area	Minimum tree height (m)	Maximum tree height (m)	Average tree height (m)	Average dominant height (m)	Average co-dominant height (m)	Minimum diameter (cm)	Maximum diameter (cm)	Average diameter (cm)
SJQ	12.3	25.1	18.9	20.9	16.9	41.1	106.6	71.5
PNL	12.3	22.6	18.4	20.7	17.7	30.2	86.6	60.2
URU	11.5	22.8	16.9	20.8	16.4	34.4	89.4	54.8

Study area	Average dominant diameter (cm)	Average co-dominant diameter (cm)	Average HD dominant	Average HD co-dominant	Average ca dominant (m^2)	Average ca co-dominant (m^2)	Sample area (ha)
SJQ	82.9	64.8	29	26	104.9	90.5	4.1
PNL	64.4	58.9	32	31	77.1	63.5	4.3
URU	70.9	52.6	32	31	100.2	68.1	2.2

SJQ, São Joaquim; URU, Urupema; PNL, Painel; cr, crown ratio; HD, height-to-diameter ratio

Table 3 Coefficients and statistical criteria of fit models for dominant and co-dominant of Brazilian pine

Equation	b_{0*}	b_{1*}	D	AIC	BIC	FL
Site SJQ						
ca	3.5795	−0.0027	2.9	444.2	450.9	*G-ln*(μ)
gi	3.6883	−0.8833	1.3	385.7	392.5	*G-ln*(μ)
N	21.8821	0.0452	2.8	442.9	449.7	*G-μ*
age	3.6437	−0.0018	98.3	38,737.7	38,758.2	*G-ln*(μ)
id_{t-1}	31.9052	7.5537	109.2	39,458.8	39,478.8	*G-μ*
Site PNL						
ca	40.4651	−0.134	2.6	454.2	461.0	*G-μ*
gi	3.9151	−1.6309	1.3	405.8	412.5	*G-ln*(μ)
N	23.37	0.0487	2.7	456.7	463.5	*G-μ*
age	3.7323	−0.0055	43.7	20,844.3	20,862.9	*G-ln*(μ)
id_{t-1}	34.4479	5.0196	62.8	22,185.2	22,203.9	*G-μ*
Site URU						
ca	3.6321	−0.0025	1.2	397.3	403.9	*G-ln*(μ)
gi	3.7036	−1.056	0.8	369.7	376.4	*G-ln*(μ)
N	24.3368	0.0454	1.2	395.7	402.5	*G-μ*
age	3.8727	−0.0084	37.5	15,391.1	15,408.7	*G-ln*(μ)
id_{t-1}	39.9257	5.2889	58.1	16,527.2	16,544.8	*G-μ*

ca, crown area m^2; gi, basal area (m^2); N, number of tress (ha^{-1}); id_{t-1}, annual diameter increment (cm); D, deviation; AIC, Akaike information criterion; BIC, Bayesian information criterion; LF (*G-μ*), identity link function, gamma distribution; *G-ln*(μ), logarithmic link function, gamma distribution

*All coefficients significant at $p < 0.0001$

regression lines for HD ($p < 0.0001$) for each area, and the interaction between the independent variables and the site.

The adjustment of the models by the GLMs technique showed that the residuals have gamma distribution, identity link, and logarithmic function. Most of the equations showed a negative coefficient (b_1), indicating that, while the independent variable increased, the dependent variable decreased. The negative coefficient (b_1) was for crown area, basal area (Fig. 2) and age (Fig. 3). For the HD ratio with number of trees.ha^{-1} and annual diameter increment, the adjustment increased linearly (coefficient b1 positive), meaning that the higher the density and the annual increase in diameter, the greater the value of the HD ratio (Table 3).

The adjusted equations show that the HD ratio tends to stabilize with age, crown area, and basal area. This indicates that during this period, there was an increase in diameter due to greater growing space.

HD ratios were positively correlated with id_{t-1} (linear increase), indicating that annual diameter increment occurs parallel to height growth and initial growth in diameter. This continues to increase with time until the tree reaches the maximum support capacity of the growth curve since the tree stops height but not diameter growth. The negative correlation with age indicates that the trees established themselves in the vertical structure of the forest, reducing the HD ratio.

Discussion

This study highlights the importance of the HD ratio for the structure and conservation of species in a mixed forest. However, the HD variable alone may not be sufficient to predict the formation of forest structure, as processes in forest ecosystems are dynamic.

Therefore, the association of the HD ratio with crown area, basal area, stand density and diameter increment variables assists in understanding ecosystem dynamics over time and in modelling the use and conservation of the species. This study answered the hypotheses, by indicating the change of the HD relationship in time with dendrometric variables and silvicultural operations. Adjustment of the models identified a period in which thinning may be carried out based on the HD ratio. This period is important for stand stability, preventing tree damage and conserving forest structure, as well as an indicator for maintaining the growth rate.

The pattern of height and diameter increment is not the same throughout the life of the trees. Thus, HD ratios change from initial growth to maturity. The results show that HD ratios decrease as the independent variables (age, ca and gi) of dominant and co-dominant trees increase.

Lower HD ratios indicate that the trees have grown in diameter but stabilized height growth. HD values also relate to past competition, since the trees have higher values for this relation. The values are greater density of trees per area.

However, forest stands with relatively high HD ratios may still be stable if density is high enough because of mutual support and shelter amongst the individual trees (Schelhaas et al. 2007).

Our results show that there is a close relationship between the increase of the HD ratio with density and diameter increment, indicating that competition at the time of stand establishment can be a positive factor for growth.

Management decisions and silvicultural treatments influence the state of the forest and thus its susceptibility to windthrow (Schelhaas 2008). On highly exposed sites, a higher initial density is recommended. To control the relationship of HD ratios with thinning, this should be lower with the development of the stand.

Consequently, once the vertical structure of the forest was established, the trees displayed greater growth in other variables (shape, crown, and diameter), and HD ratios became smaller. This confirms that trees grow first in height and once their position is established in the canopy, they invest in growth in other variables.

However, this decrease in HD ratios does not occur abruptly, its highest value in younger trees, middle crown ratios and smaller diameters, as observed by Albert and Schmidt (2010) and Vieilledent et al. (2010). According to Bošela et al. (2014), the initial HD ratio increase with stand age is most probably related to competition stress in younger trees. Hence, trees invest more in height growth than in diameter to reach a position of dominance within a stand to capture enough sunlight.

The decrease in the HD ratio occurs as trees age, reducing height increment and increasing diameter increment as well as other variables. Dominant and co-dominant trees seek space in the upper canopy and once reached, growth of other variables (crown area, basal area), assumes more importance than height growth.

The increase in the HD ratios with increment shows that, in the early phases of stand development, trees are in competition for light and space in the vertical structure of the forest. This is the critical time for stability (wind damage), reduced competition, and continued growth. These results indicate that silvicultural operations should be carried out when the trees are in the inflection phase of the growth curve (Fig. 3) as they have the ability to overcome competition and maintain the rate of increment in diameter. Because the ratio HD and increment in diameter has higher values, the higher the growth efficiency and resource availability. We can also indicate that to inform about the stability of the tree the annual increment in diameter will be more accurate, since it indicates that trees under these conditions have the capacity to win the competition, better crown shape, photosynthetic capacity, carbon fixation, productivity and to compose the future structure of the settlement.

The results indicate that light and growth in height are factors that drive other morphometric and dendrometric variables so that trees overcome competition and occupy the canopy. Shape and size of the root system, climate, type and soil conditions are also important factors. Alves and Santos (2002) also verified that all variables related to crown shape and trunk diameter increased significantly with height.

The results in this study show that height growth is the first factor that the forest manager must identify in forests, i.e., the vertical structure is formed with the advance of the horizontal structure of the forest. After a number of years, silvicultural operations are needed to open the canopy so that regeneration can increase height and develop the forest structure so that seedlings are not suppressed by reduced light.

Forest management can use HD ratios as an indicator of silvicultural treatments using reference values of the variable or measurements of individual trees for stability to maintain growth and development. Monitoring the variable with tree density avoids competition and adequate availability of growth resources. HD ratios are to forest managers, showing that interventions for tree stability should be undertaken early, especially in high density stands.

Decrease of the HD ratio in older stands might be related to reduced height increments as a result attaining a dominant position within the stand and where crowns are no longer limited to sunlight and/or tree senescence (Bošela et al. 2014).

The results confirm that tree stability (HD ratio) is a key factor in the development and structural architecture of a tree, recognizing that the architecture is the arrangement of different parts in a hierarchy of growth units. It can be described by measurable traits such as height, crown width, height of first branch and allometric ratios between them, e.g. the height-to-stem diameter ratio (MacFarlane and Kane 2017).

In conjunction with tree architecture, the HD ratio provides information for understanding the development of forest structure dynamics, ecosystem functions (Jucker et al. 2015), and tree management (Pavlis et al. 2008). Trees are sufficiently adaptable to the ecological conditions of the site in order to develop. Fundamentally, in competition for light, trees build their stem, branches, height and crown arrangement to capture light energy (MacFarlane and Kane 2017).

Studies of the mechanical stability of trees have historically focused on height–diameter relationships as key functional traits. In competition with other trees, trees increase their light harvesting capacity by increasing height, crown length, crown width or all three. As stem growth near the base indicates overall growth and successful light capture (King et al. 2005), the ratio of height growth or crown expansion to stem thickening can be used as an expression of the requirement to harvest more light.

This corroborates the results of this study, as it indicates that the HD ratio was higher during the early stages of growth when dominant and co-dominant trees established themselves in the vertical structure of the stand. Once established, the HD ratio decreased and morphometric and dendrometric variables increased. This result is important for forest management since it highlights the investment in resources by the trees, and which ones should be removed and which should be left.

Therefore, trees under intense competition become thinner and have narrower crowns. Following the development of the HD ratio assists the forest manager in the formulation of silvicultural interventions and, consequently, in the best tree form, canopy, stability, growth, wind resistance, least damage and tree productivity. At this point, we can say that the phytosanitary condition of trees in a forest and their formation are directly related to the HD ratio.

As Brazilian pines may occupy all forest strata (pioneer up to the upper canopy), management of the HD ratio becomes even more important, mainly by proposing interventions in dominant and co-dominant trees. Because of the prohibition of management in Araucaria forests since the 1990s, these trees have occupied the canopy, preventing light penetration and the development of intermediate trees in the forest strata, thus compromising its future structure.

Silvicultural interventions that promote the arrangement of the vertical structure of the forest are important. For example, the highest growth in height of a tree in relation to the diameter is a natural chemical response to the restriction of light. Fundamentally, increasing height growth relative to diameter growth is a natural response to carbohydrate starvation caused by light deprivation (Barthélémy and Caraglio 2007). This increase in height presents a critical limit that, when achieved, may result in damage (wind breaking) of the stem and mortality (precarious development), and is related to the level of competition which represents a constant stress for the trees the stand (Lines et al. 2012; MacFarlane and Kane 2017).

Dominant and co-dominant trees are those that overcame direct competition and increased their rate of diameter increment, established in canopy and crown development Competition and higher HD ratios may be seen as a benefit to the growth and structure of the forest. However, there is a need to control the value of the HD ratio as well as forest density over time.

Models for HD ratios and their monitoring can be an inherent growth strategy that defines tree shape (stem) and its structural architecture. It expresses the nature and sequence of activities of the endogenous morphogenetic processes of the organism and corresponds to the fundamental growth program in which the entire architecture is established (Barthélémy and Caraglio 2007).

Therefore, by using the process of reiteration defined by Barthélémy and Caraglio (2007), the morphogenetic process by which the organism duplicates its own architectural unit, the manager can guide the forest in such a way that trees in a subsequent order of occupation of the upper strata will have the same characteristics as the current dominant and co-dominant trees. The fundamental interest of this concept resides on it regrouping all these phenomena into a coherent whole to bring about a common morphogenetic event.

Additionally, this concept is important for the structure and production of the forest, as well as to verify that HD ratios differ between sites, density, age, morphometric variables and period of growth, which produces more accurate results (Tsega et al. 2018). According to Zhang et al. (2014), the ratio between tree height and diameter is one of the most important elements of forest structure.

Conclusion

The models adjusted for the HD ratio and dendro/morphometric variables showed accuracy and can be used to verify changes that occur in tree development and for forest management. This study also shows that thinning operations should be in the initial periods of tree development when HD ratios are higher, ensuring the stability of the tree, improved growth rate, and vertical and horizontal structures of the forest.

The HD ratio is more important in the early years of stand development, especially in mixed forests, high-density stands, and with shade-intolerant species, since it is the period when trees compete, create stability and form the vertical structure of the forest. The highest HD values in the early years are consistent with smaller diameters at this time.

The results show that light and growth in height are primary factors in the formation of the structure and final growth of the forest, light being one of the resources that the forest manager can regulate.

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