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Competition Indices and Their Relationship With Basal Area Increment of Araucaria

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Abstract

Models that report the effect of competition are important for forest management since forests with higher levels of competition have lower increment rates, and their use is necessary to plan forest interventions. Thus, this study aimed to assess the effect of competition in the basal area increment of individual trees of *Araucaria angustifolia* (Bertol.) Kuntze in a natural forest. A total of 397 subject trees were measured, covering the diametric range. The dendrometric and morphometric characteristics of subject trees and their competitors were obtained, and 22 distance-dependent and distance-independent competition indices were calculated, in addition to increment cores extracted radially from the trunk at diameter at breast height. The relationship between models of periodic annual increment in basal area based on competition indices has allowed to obtain R^2 values of 0.425 and Syx% ≥ 50.2. The multivariate technique of principal component analysis has shown that three principal components explain 78.43% of total variation. The first component was responsible for explaining 52.95%, with similar eigenvector for 11 competition indices, evidencing that these models can be used to describe especies competition, although they show different variables and mathematical equations in calculations. Results show the importance of competition to predict increment of Araucaria in individual trees.

Keywords: quantification, tree growth, mixed ombrophilous forest

1. Introduction

One of the most important facts to simulate tree growth is to assess the effects of competition, *i.e.*, the influence of characteristics of the population where the tree is found. These characteristics can be measured through competition indices, which are algebraic relationships used to quantify the effect of higher or lower resource availability for a subject tree in relation to other competitor trees. The use of these competition indices has become an important tool for forest management worldwide (Pedersen et al., 2013).

It is possible to find in the literature competition indices with various complex ways of calculation, mainly the ones described by Gerrard (1969), Bella (1971), Arney (1973), Hegyi (1974), Ek and Monserud (1974), Glover and Hool (1979), Lorimer (1983), Corona and Ferrara (1989), Mugasha (1989), Rouvinen and Kuuluvainen (1997), Castagneri et al. (2008), among others. These competition indices can be divided into two classes: (a) distance-independent indices that use non spatial measurements, based on tree size distribution in a given area; (b) distance-dependent indices, in which competitors are identified based on their size and the distance in relation to the subject tree (Wimberly & Bare, 1996).

Index assessment and its influence on tree growth have been investigated by several authors (Daniels et al., 1986; Pukkala & Kolström, 1987; Holmes & Reed, 1991; Biging & Dobbertin, 1995; Álvarez Taboada et al., 2003; Corral Rivas et al., 2005; Castagneri et al., 2008; Contreras et al., 2011). Some studies report diameter increment modelling and basal area of individual trees of *Araucaria angustifolia* (Bertol.) Kuntze (Zanon, 2007; Chassot, 2009).

In some cases, when regression models are used, with a great variety of explanatory variables, multivaried statistics may be useful to reduce the number of variables without loss of understanding of the observed phenomenom. In this context, the Principal Components Analysis (PCA) aims at gathering most of the original information (variation) in a minimum number of factors for prediction purposes (Hair et al., 2009), and this analysis reduces the data to be analysed, especially when they consist of a great number of inter-related variables (Jobson, 1992). With this analysis, the first components responsible for most variation of original data are determined, and they can be used to summarize data with little loss of information (Everitt & Dunn, 2010). In summary, it is necessary to calculate the variance-covariance matrix, or correlation matrix, finding eigenvalues and eigenvectors, in order to determine the principal components, and, finally, write the linear combinations, which will be the new variables, or principal components, being each principal component a linear combination of all original variables, mutually independent, and they will retain, in order of estimation, most variation from the initial data (Gotelli & Ellison, 2011).

In view of the above, the present study aimed to assess the effect of competition on the periodic annual increment in basal area of individual trees of *Araucaria angustifolia* (Bertol.) Kuntze in a natural forest, as a way to help in activities of silvicultural interventions of this species. The specific objectives were: (a) characterize tree growth and its relationship to distance-dependent and distance-independent competition indices; (b) adjust statistical models to describe the periodic annual increment in basal area according to competition indices; and (c) apply the multivariate technique of principal component analysis (PCA) in competition indices, aiming to interpret the influence of each index on the composition of data variation.

2. Material and Methods

Trees growing under competition in a natural forest were sampled in the municipalities of Lages (SC) and São Francisco de Paula (RS). The climate in these municipalities is humid subtropical according to Köppen classification, without a dry season and with temperate summer (Cfb) (Alvares et al., 2013). Location and climate characteristics of the studied places are indicated in Table 1.

Table 1. Location and climatic characteristics of the studied areas

Municipality	Latitude	Longitude	Altitude (m)	MAT	MAP
Lages	-27°48′	-50°19′	987.0	15.2	1684.7
São Francisco de Paula	-29°26′	-50°35′	854.0	15.0	2016.4

Note. MAT = Mean Annual Temperature, in °C; MAP = Mean Annual Precipitation, in mm.

In Lages, the study was carried out in a private rural property with 83.5 hectares of araucaria forest, 30km from the municipality seat, in the Central Plateau of Santa Catarina. In the forest, 28 species were identified according to the survey for the Forest Management Plan, in 1999 (Table 2), in which is presented that 10 species express 82.9% of the total importance value index (IV), whereas other 18 species represent 17.1%. In São Francisco de Paula the study was performed in São Francisco de Paula National Forest (FLONA-SFP), 27 km from the municipality seat, in the Campos de Cima da Serra region, northeast Rio Grande do Sul. In the araucaria forest, trees belonging to the plots (1546; 1537; 1539; 1543 and 1545) of the Brazilian Long-Term Ecological Research (LTER) were sampled. A total of 74 species were identified in the studied fields, 10 species had higher importance value index (IV), 71.4% from the total, and the other 64 species represented 28.6% (Table 2).

Table 2. Horizontal phytosociological analysis: density, dominance, frequency and importance value index of the sites studied in the Araucaria forest

N	Local	Scientific name	RD	RDo	RF	IV
1	Lages, SC	*Araucaria angustifolia* (Bertol.) Kuntze	30.5	34.0	19.2	27.9
2		*Ocotea* spp.	27.2	29.6	13.7	23.5
3		*Sapium glandulosum* (L.) Morong	5.4	4.4	8.9	6.3
4		*Piptocarpha* sp.	4.5	3.5	8.9	5.6
5		*Lamanonia ternata* Vell.	5.7	5.6	2.7	4.7
6		*Lithraea brasiliensis* Marchand	2.9	2.7	6.8	4.2
7		*Styrax leprosus* Hook. & Arn.	3.7	3.5	2.7	3.3
8		*Myrsine umbellata* Mart.	2.9	2.2	3.4	2.9
9		*Ilex brevicuspis* Reissek	1.4	1.2	4.8	2.5
10		*Myrceugenia euosma* (O.Berg) D. Legrand	1.5	1.3	3.4	2.1
... 28		Outras spp.	14.2	11.9	25.3	17.1
		Total	100.0	100.0	100.0	100.0
1	São Francisco de Paula, RS	*Araucaria angustifolia* (Bertol.) Kuntze	26.2	67.6	15.4	36.4
2		*Blepharocalyxsalicifolius* (Kunth) O.Berg	8.1	5.2	7.8	7.0
3		*Casearia decandra* Jacq.	7.7	1.7	7.5	5.6
4		*Sebastiania brasiliensis* Spreng.	7.3	1.4	7.0	5.2
5		*Ilex paraguariensis*A. St.-Hil.	4.1	1.8	5.1	3.6
6		*Matayba elaeagnoides* Radlk.	3.9	2.2	4.4	3.5
7		*Ilex brevicuspis* Reissek	2.7	2.2	3.2	2.7
8		*Cryptocarya aschersoniana* Mez	2.9	1.5	3.4	2.6
9		*Nectandra megapotamica* (Spreng.) Mez	2.6	1.5	3.2	2.4
10		*Luehea divaricata* Mart. & Zucc.	2.7	1.5	2.5	2.2
… 74		Outras spp.	31.8	13.4	40.5	28.6
		Total	100.0	100.0	100.0	100.0

Note. N = number of species; RD = relative density, in %; RDo = relative dominance, in %; RF = relative frequency, in %; IV = importance value index, in %; NI = no identify.

A total of 397 subject trees of *Araucaria angustifolia* (Bertol.) Kuntze distributed in diameter classes were intentionally selected within the natural forest, aiming to obtain sample trees in the whole diametric range, taking into account the smallest class core of 10cm, and intervals of 10cm between diameter classes. The intentional selection of trees is justified by the need to assess the inherent characteristics of each individual. Araucaria trees in competition were named 'subject tree', and the neighbouring trees were named 'competitor trees'. From the 397 subject trees, 308 (77.6%) were measured in Lages, SC; the other 89 trees (22.4%) were measured at FLONA in São Francisco de Paula, RS.

The criteria to select competitor trees in relation to the subject tree was based on crown dimensions, and consequently tree height assessed regarding capacity to compete for light and growth space. The neighbouring trees with contact between crowns in a 360° turn from the subject tree were considered competitors. When the competitor tree was taller or shorter than the subject tree, with no contact between crowns, it was not selected, since the aim was to select trees with effective competition. Due to the high dominance of *Araucaria angustifolia* (Bertol.) Kuntze in the studied sites, subject trees were influenced by intraspecific competition (Table 2). Thus, when considering contact between crowns, the selection criteria of competitor trees may be represented by the Equation (1):

$$dist_{ij} < (rci + rcj) \quad (1)$$

Where, $dist_{ij}$ = horizontal distance between subject tree (i) and competitor tree (j); rci = radius of crown of subject tree (i) in meters; rcj = radius of crown of competitor tree (j) in meters. The crown radius of trees (cr) was calculated dividing by half the value obtained for the crown diameter model (cd) based on the DBH for Lages, SC: cd = 1.3149 + 0.2112·DBH; R^2 = 0.838; Syx % = 13.7%, and São Francisco de Paula, RS: cd = 0.8947 + 0.2032·DBH; R^2 = 0.853; Syx % = 15.4%.

Diameter at breast height (DBH), total height (h), crown insertion height (cih), and 8 crown radii in the direction of the cardinal points: north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), and northwest (NW), were measured for each subject tree and their respective competitors. Crown insertion height was determined as the height from ground level to insertion of live crown. Diameter was measured with diametric tape, in centimeters, and horizontal distances ($dist_{ij}$) and height were measured with Vertex IV hypsometer, in meters, both with declivity corrected, as well as the crown radii, with accuracy down to centimeters. Crown diameter (cd) was determined by doubling the root mean square of the eight crown radii (mcr). The crown horizontal projection area (CHPA) of araucaria trees was calculated considering the circular shape as $CHPA = \pi \cdot mcr^2$.

The calculated competition indices considered the dimensional variables between subject trees (i) and their respective competitors (j): diameter at breast height (DBH), horizontal distances (dist), basal area of individual tree (g), height (h), crown diameter (cd), crown horizontal projection area (CHPA), potential crown horizontal projection area for araucaria ($CHPA_{pot}$), crown overlap area (COA), and mean crown radius (mcr) (Table 3).

Table 3. Competition indices evaluated for *Araucaria angustifolia* (Bertol.) Kuntze in natural forest

Indices	Equations	Variables	Source
CI1	$= DBH_i^2 \cdot n \Big/ \left(\sum_{j=1}^{n} DBH_j^2 \right)$	DBH	Daniels et al. (1986)
CI2	$= \sum_{j=1}^{n} \left(DBH_j^2 / DBH_i^2 \right)$	DBH	Corona and Ferrara (1989)
CI3	$= \left(\sum_{j=1}^{n} DBH_j \right) \Big/ DBH_i$	DBH	Lorimer (1983)
CI4	$= \left(\sum_{j=1}^{n} DBH_j \Big/ DBH_i \right) \Big/ n$	DBH	Mugasha (1989)
CI5	$= \sum_{j=1}^{n} \left[DBH_j / (DBH_i \cdot distij) \right]$	DBH, dist	Hegyi (1974)
CI6	$= \sum_{j=1}^{n} \left[DBH_j / \left(DBH_i \cdot distij^{0.5} \right) \right]$	DBH, dist	Hegyi (1974), modified
CI7	$= \sum_{j=1}^{n} \left[\left(DBH_j / DBH_i \right)^2 / distij \right]$	DBH, dist	Rouvinen and Kuuluvainen (1997)
CI8	$= \sum_{j=1}^{n} \left(DBH_j / distij \right)$	DBH, dist	Rouvinen and Kuuluvainen (1997)
CI9	$= \sum_{j=1}^{n} g_j$	g	BAL modified
CI10	$= \sum_{j=1}^{n} \left(h_i / \bar{h}_j \right)$	h	Glover and Hool (1979)
CI11	$= \sum_{j=1}^{n} \left(DBH_i^2 h_i / \overline{DBH_j^2 h_j} \right)$	DBH, h	Glover and Hool (1979)
CI12	$= \sum_{j=1}^{n} \left[\left(h_j / h_i \right) \text{arctang} \left(h_j / distij \right) \right]$	h, dist	Rouvinen and Kuuluvainen (1997), modified
CI13	$= \sum_{j=1}^{n} \text{arctang} \left[\left(h_j - h_i \right) / distij \right]$	h, dist	Pukkala and Kolström (1987)
CI14	$= \sum_{j=1}^{n} \left[cd_j / \left(cd_i \cdot distij^{0.5} \right) \right]$	cd, dist	Hegyi (1974), modified
CI15	$= \sum_{j=1}^{n} \left[CHPA_j / (CHPA_i \cdot distij) \right]$	CHPA, dist	Álvarez Taboada et al. (2003)
CI16	$= \sum_{j=1}^{n} \left[CHPA_j / CHPA_i \right]$	CHPA	Castagneri et al. (2008)
CI17	$= \sum_{j=1}^{n} \left[CHPA_j h_j / CHPA_i h_i \right]$	h, CHPA	Castagneri et al. (2008)
CI18	$= \sum_{j=1}^{n} \left[CHPA_j h_j / CHPA_i h_i \right] / distij$	h, CHPA, dist	Castagneri et al. (2008)
CI19	$= 100 \sum_{j=1}^{n} \left[COA_{ij} + CHPA_{pot} \right] \Big/ CHPA_{pot}$	$CHPA_{pot}$, COA	Arney (1973)
CI20	$= \sum_{j=1}^{n} \left[COA_{ij} / CHPA_i \right]$	CHPA, COA	Gerrard (1969)
CI21	$= \sum_{j=1}^{n} \left[\left(COA_{ij} DBH_j \right) / \left(CHPA_i DBH_i \right) \right]$	DBH, CHPA, COA	Bella (1971)
CI22	$= \sum_{j=1}^{n} \left[COA_{ij} \left(mcr_j h_j / mcr_i h_i \right) \right] \Big/ CHPA_{pot}$	h, mcr, $CHPA_{pot}$, COA	Ek and Monserud (1974)

Note. DBH = diameter at breast height, in cm; dist = horizontal distances, in m; g = basal area of individual tree, in m^2; h = total height, in m; cd = crown diameter, in m; CHPA = crown horizontal projection area, in m^2; $CHPA_{pot}$ = potential crown horizontal projection area for araucaria, we used the equation: $cd_{pot} = 4.8601 + 0.2038 \cdot DBH$ (Costa, 2015), therefore: $CHPA_{pot} = \pi\ (cd_{pot}/2)^2$, in m^2; COA = crown overlap area, in m^2; mcr = mean crown radius, in m; subject tree (i); competitor tree (j).

The calculation of crown overlap areas (COA) between subject tree (i) and each competitor (j) was performed through an algorithm developed in Visual Basic language for Microsoft Excel™ 2013 spreadsheet editor. For this purpose, the equation of crown overlap areas presented by several authors (Lee & Gadow, 1997; Gadow, 2003; Álvarez Taboada et al., 2003) was programmed, the algorithm was adapted to situations in which CHPA were secants to one another, internally and externally disjoined; and crowns that could be externally and internally tangent and concentrically disjoined were verified, however not found in any of the 1560 analyzed trees.

The periodical increment was established annually in the last five years through growth rings measured in increment cores sampled radially from the trunk with Pressler borer. Two increment cores were removed from each tree, but due to the difficulty to quantify increments of individuals in high competition, fieldwork had to be repeated when necessary to collect new increment cores from the same tree. The periodic annual increment in basal area of each tree was calculated by the Equation (2):

$$PAIg = (g - g_5)/\mathrm{t} \qquad (2)$$

Where, PAIg = periodic annual increment in basal area, in cm^2/year; g = basal area of individual tree at the end of the period, in cm^2; g_5 = basal area of individual tree in the beginning of the period, in cm^2; t = number of assessed years: for the present study, the period of the last five years was established, according to what is indicated for this type of model (Hasenauer, 2006; Pretzsch, 2009).

To assess the influence of competition (CI) in the periodic annual increment in basal area (PAIg) of the subject tree, the nonlinear alometric model was adjusted by Equation (3):

$$PAIg = \beta_0 CI^{\beta_1} + \varepsilon \qquad (3)$$

Where, PAIg = periodic annual increment in basal area, in cm^2 $year^{-1}$; CI = competition indices; β_0 and β_1 = estimated regression coefficients; ε = residual error.

All the statistics were processed in the Statistical Analysis System (Sas, 2004). Data were characterized through descriptive statistics and adjusted models were assessed regarding coefficient of determination (R^2), standard error of estimate percentage (Syx%), F value, and its probability in the analysis of variance. The principal components analysis was used to reduce the number of variables, verify the influence of the 22 competition indices in the principal components, and their importance in relation to total data variation.

3. Results and Discussion

The calculation of competition indices (Table 3) for the 397 subject trees allowed to charachterize each one with the analysis of descriptive statistics (Table 4). Values of coefficient of variation for the 22 competition indices oscillated within a range of 17.0% and 650.2% indicating high dimensional variability (DBH, horizontal distances, heights, basal areas, crown diameters, crown horizontal projection areas, crown intersection areas) of subject araucaria trees and each of their competitors. Negative values of CI13 occurred when the height of the subject tree was smaller than that of their competitor. The minimum value of 100.0 for CI19 and zero for CI20, CI21, and CI22 resulted from nine subject trees whose crowns were assymmetric, leading to the decrease of mean crown radius in the calculation, and reducing this value until there was no crown intersection, contradicting the results found in fieldwork.

Table 4. Statistical summary of competition indices calculated for *Araucaria angustifolia* (Bertol.) Kuntze sampled in natural forest

Variable	Minimum	Q1	Mean	Median	Q3	Maximum	CV%
PAIg	1.82	8.63	18.30	14.51	24.89	80.19	69.7
CI1	0.0032	0.0129	0.0219	0.0171	0.0254	0.1717	84.1
CI2	0.2756	2.9939	7.6037	5.5728	9.9499	49.0338	90.2
CI3	0.5250	2.9270	4.8242	4.4493	6.3861	14.9270	51.1
CI4	0.4259	0.8893	1.3154	1.1675	1.6056	4.1888	45.5
CI5	0.0802	0.4588	0.9084	0.7682	1.1875	6.6738	74.4
CI6	0.2297	1.2094	2.0071	1.7875	2.5896	7.6860	55.5
CI7	0.0527	0.4706	1.4511	0.9231	1.7761	16.2760	119.0
CI8	1.8000	19.8475	29.9132	29.5466	39.0074	82.0129	45.7
CI9	0.0076	0.3774	0.7182	0.6923	0.9996	2.5379	60.2
CI10	0.3265	0.8661	0.9672	0.9605	1.0546	1.6606	17.3
CI11	0.0343	0.3102	0.9514	0.6114	1.2117	8.2041	108.1
CI12	0.6888	3.4579	4.9677	4.7188	6.4183	11.2471	43.6
CI13	-4.8905	-0.6872	0.2270	0.2359	1.1765	4.4658	650.2
CI14	0.1504	1.2267	1.9826	1.8226	2.5088	6.3517	53.1
CI15	0.0227	0.4438	1.4023	0.9251	1.6887	12.0646	116.5
CI16	0.1857	2.9447	7.5925	5.6378	8.5478	54.2230	98.3
CI17	0.1881	2.9177	8.9063	6.0036	10.6166	90.0655	114.0
CI18	0.0229	0.4564	1.6517	0.9486	1.9035	16.9717	129.8
CI19	100.0	308.2	440.0	433.7	564.6	1205.1	45.7
CI20	0.0	0.4357	0.9888	0.9433	1.4492	3.1824	65.5
CI21	0.0	0.4743	1.4442	1.0333	1.9936	7.8866	94.4
CI22	0.0	0.1761	0.7056	0.5130	1.0370	3.1804	93.8

Note. PAIg = periodic annual increment in basal area, in cm^2 $year^{-1}$; [CI1 … CI22] = competition indices; Q1 = first quartile; Q3 = third quartile; CV% = coefficient of variation.

By adjusting the regression model (3), a relationship was found between the models of periodic annual increment in basal area and the 22 competition indices calculated for araucaria trees (Table 5). Results evidenced that all equations showed regression, and increment in basal area at individual tree level reached values of up to 0.425 for R^2 and Syx% ≥ 50.2.

Table 5. Estimated coefficients and adjustment and precision statistics of periodic annual increment models in basal area (PAIg) in function of competition indices (CI) for *Araucaria angustifolia* (Bertol.) Kuntze in natural forest

CI	Coefficients		Std. Er.	Value t	Prob.>|t|	R^2	Syx%	Value F	Prob.>F
CI1	β_0	113.9954	17.0998	6.67	<0.0001	0.227	61.0	597.3	<0.0001
	β_1	0.4613	0.0404	11.41	<0.0001				
CI2	β_0	33.4093	1.1734	28.47	<0.0001	0.368	55.1	776.3	<0.0001
	β_1	-0.3936	0.0256	-15.35	<0.0001				
CI3	β_0	34.0032	1.7326	19.63	<0.0001	0.224	61.1	594.3	<0.0001
	β_1	-0.4595	0.0410	-11.20	<0.0001				
CI4	β_0	20.3166	0.5335	38.08	<0.0001	0.402	53.6	832.0	<0.0001
	β_1	-1.0229	0.0659	-15.52	<0.0001				
CI5	β_0	15.0501	0.6092	24.70	<0.0001	0.292	58.3	671.4	<0.0001
	β_1	-0.4574	0.0358	-12.76	<0.0001				
CI6	β_0	22.8504	0.6355	35.96	<0.0001	0.280	58.9	655.9	<0.0001
	β_1	-0.4936	0.0390	-12.64	<0.0001				
CI7	β_0	16.2088	0.5425	29.88	<0.0001	0.418	52.9	858.8	<0.0001
	β_1	-0.4022	0.0248	-16.24	<0.0001				
CI8	β_0	45.9523	7.1428	6.23	<0.0001	0.070	66.9	463.6	<0.0001
	β_1	-0.2843	0.0497	-5.72	<0.0001				
CI9	β_0	17.5660	0.7510	23.39	<0.0001	0.009	69.1	422.2	<0.0001
	β_1	-0.0723	0.0355	-2.04	0.0425				
CI10	β_0	19.1023	0.5564	34.33	<0.0001	0.321	57.1	708.4	<0.0001
	β_1	2.1793	0.1537	14.18	<0.0001				
CI11	β_0	21.0590	0.5275	39.92	<0.0001	0.425	52.6	873.2	<0.0001
	β_1	0.4407	0.0270	16.32	<0.0001				
CI12	β_0	30.5181	2.3364	13.06	<0.0001	0.085	66.3	474.3	<0.0001
	β_1	-0.3535	0.0548	-6.45	<0.0001				
CI13	β_0	12.5849	0.6417	19.61	<0.0001	0.147	50.2	261.5	<0.0001
	β_1	-0.2126	0.0311	-6.84	<0.0001				
CI14	β_0	22.4605	0.6610	33.98	<0.0001	0.223	61.1	594.1	<0.0001
	β_1	-0.4499	0.0410	-11.22	<0.0001				
CI15	β_0	16.5609	0.5638	29.37	<0.0001	0.336	56.5	729.2	<0.0001
	β_1	-0.3621	0.0252	-14.37	<0.0001				
CI16	β_0	32.2109	1.2560	25.65	<0.0001	0.293	58.3	672.8	<0.0001
	β_1	-0.3711	0.0278	-13.36	<0.0001				
CI17	β_0	32.4127	1.1222	28.88	<0.0001	0.350	55.9	748.3	<0.0001
	β_1	-0.3638	0.0241	-15.07	<0.0001				
CI18	β_0	16.7209	0.5428	30.80	<0.0001	0.391	54.1	812.7	<0.0001
	β_1	-0.3630	0.0227	-15.98	<0.0001				
CI19	β_0	31.7654	11.8255	2.69	0.0075	0.005	69.2	420.0	<0.0001
	β_1	-0.0922	0.0628	-1.47	0.1430				
CI20	β_0	17.9658	0.6642	27.05	<0.0001	0.026	68.2	432.5	<0.0001
	β_1	-0.0850	0.0275	-3.09	0.0021				
CI21	β_0	18.0675	0.6219	29.05	<0.0001	0.111	65.1	492.8	<0.0001
	β_1	-0.1442	0.0214	-6.75	<0.0001				
CI22	β_0	16.8927	0.7290	23.17	<0.0001	0.053	67.2	450.7	<0.0001
	β_1	-0.0925	0.0207	-4.48	<0.0001				

Note. [CI1 … CI22] =competition indices; Std. Er. = standard error; β_0, β_1 = estimated regression coefficients; R^2 = coefficient of determination; Syx% = standard error of the estimate in percentage; Prob.>|t| = probability of significance for the t value; Prob.>F = probability of significance to F value.

Regardless of the high variability in the relationship between basal area increment and competition indices (Table 5), the results found are in accordance with studies performed with other species (Shi & Zhang, 2003; Castagneri et al., 2008). The relationship can be improved when aggregated to independent variables such as DBH (Contreras et al., 2011), crown attributes, basal area and density of stand (Corral Rivas et al., 2005). For araucaria trees, variance of basal area increment was studied based in dendrometric and morphometric variables, showing improvement in the description of species growth (Costa et al., 2015). However, the inclusion of other independent variables that characterize the present dimensions, site quality, crown dimension variables, and the effect of competition measured by an index has also improved the predictive performance of the model of basal area increment for araucaria in south Brazil (Costa, 2015).

According to the statistical criteria for adjustment (R^2) and accuracy (Syx%) used to assess the performance of models of basal area increment of araucaria (Table 5), the four best equations were selected through observed and estimated values based on competition indices CI4, CI7, CI11 and CI18 (Figure 1). The competition indices (Figures 1a, 1b and 1d) showed inversely proportional relationships to growth, *i.e.* as competition increased, there was a decrease of basal area increment of araucaria trees. On the other hand, CI11 was directly proportional to tree growth, showing that value increase reflects on lower influence of competitor trees on the subject tree.

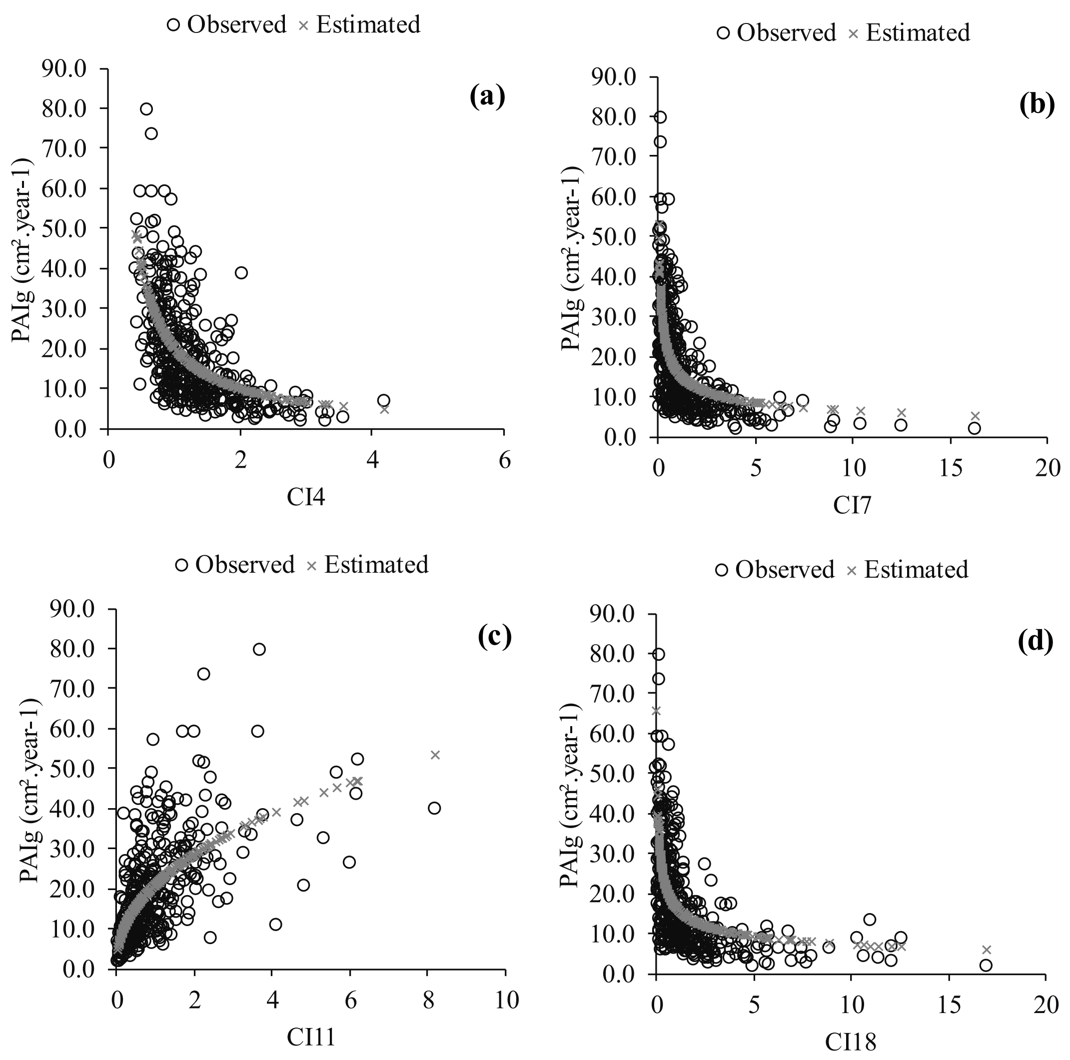

Figure 1. Observed and estimated values of periodic annual increment in basal area (PAIg) in function of competition indices; (a) CI4; (b) CI7; (c) CI11; (d) CI18; for *Araucaria angustifolia* (Bertol.) Kuntze sampled in a natural forest

The principal components analysis was efficient, reducing the number of variables, and allowing to identify that from the 22 indices calculated, the eigenvalue of the first component (Figure 2a) was 11.65, contributing with 52.95% of the total explained variance (Figure 2b). In the same relationship, the eigenvalue of the second principal component was 3.67, 16.68% of the total explained variance, and the third component showed cumulative total explained variance of 78.43% (Figure 2b). Thus, these three components were taken as examples since they explain most variability of the data observed.

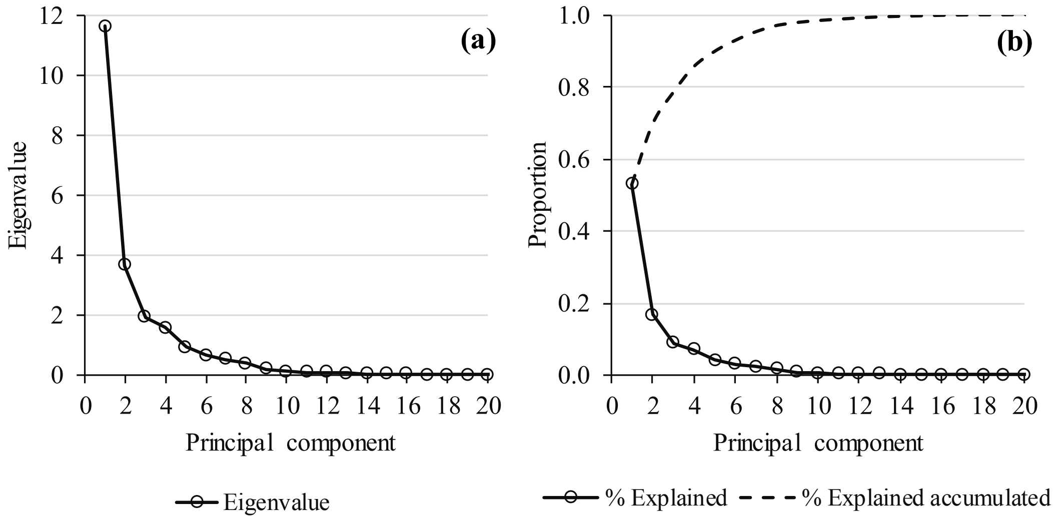

Figure 2. (a) Eigenvalue value in function of the principal component; (b) % of the proportion of explained and cumulative variance according to the principal component for *Araucaria angustifolia* (Bertol.) Kuntze sampled in a natural forest

The first component (PC1) explained 52.95% of the total data variance, whose eigenvectors were similar in 11 competition indices, varying between 0.23 and 0.27 (Table 6), approximately, confirming that although they showed different variables and mathematical equations used for the calculation, competition indices can be used to describe species competitiveness. When compared to the model adjustments (Table 5), it was found that these competition indices (included in PC1) show intermediary adjustments (R^2) and moderate accuracy (Syx%). In the second component (PC2), four indices stood out, with eigenvectors varying between 0.32 and 0.48, explaining only 16.68% of total variance of data. Based on the values of Table 6, competition indices in PC2 presented the lowest adjustments (R^2) and the highest errors (Syx%), as seen in Table 5. The third principal component (PC3) was responsible for 8.81% of total explained variance, being CI1, CI10 and CI11 the indices with the highest eigenvectors. Competition indices that were directly proportional to basal area increment of araucaria trees (Table 5) were grouped in this component.

Table 6. Eigenvectors of the main components (PC) for competition indices of *Araucaria angustifolia* (Bertol.) Kuntze sampled in natural forest

Indices	PC1	PC2	PC3
CI1	-0.1553	0.0843	**0.4780**
CI2	**0.2650**	-0.0495	0.0287
CI3	**0.2467**	0.1942	-0.0970
CI4	0.2166	-0.2853	-0.0518
CI5	**0.2545**	0.0210	0.1407
CI6	**0.2727**	0.1110	0.0300
CI7	**0.2522**	-0.0996	0.1528
CI8	0.1847	**0.3464**	0.0083
CI9	0.0605	**0.3241**	-0.3043
CI10	-0.1666	0.2294	**0.3895**
CI11	-0.1748	0.1792	**0.4357**
CI12	0.1572	**0.3872**	-0.1558
CI13	0.1808	-0.1971	-0.2638
CI14	**0.2688**	0.1096	0.1049
CI15	**0.2484**	-0.1283	0.2378
CI16	**0.2372**	-0.0867	0.1193
CI17	**0.2367**	-0.1284	0.1134
CI18	**0.2474**	-0.1610	0.2132
CI19	0.0807	**0.4820**	-0.0728
CI20	0.1884	0.1817	0.1479
CI21	**0.2436**	-0.0156	0.1383
CI22	0.1813	0.0783	-0.0080

Note. [CI1 … CI22] = competition indices; PC1, PC2, PC3 = principal components 1, 2 and 3.

The biological process that involves competition between trees is more complex than it may be described by only one mathematical competition index (Daniels et al., 1986). However, several competition indices are used to model tree growth and production (Burkhart & Tomé, 2012). In general, it is recommended to use competition indices that express the biological behavior of Araucaria trees, associated with the ease and convenience of field measurement and application in a natural forest.

4. Conclusion

Competition indices showed high variability, and when adjusted through regression techniques, they allowed to explain the variation of periodic annual increment in basal area in a moderate way, with high estimation errors.

The principal components analysis was efficient and allowed to find eleven potential competition indices to describe increment in basal area of araucaria trees.

The models assessed help to model growth of Araucaria trees together with independent variables that characterize tree size, crown vitality, site, among other factors.

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