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# Competition indexes for individual *Pinus taeda* L. trees in non-thinned commercial stands

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**ABSTRACT:** The competition process in a forest plantation originates from the dispute for resources, which are essential for growth. Several indexes were proposed to assess competition for different species, but such studies for pine trees are scarce in the country. These competition indices are essential in the forest modelling process. Thus, the aim of this study was to assess competition indexes for a non-thinned *Pinus taeda* L. stand. Data from permanent sampling units in the Telêmaco Borba region, Paraná, Brazil, were used, and tree ages ranged from 3.4 to 21.4 years. Eight indexes were assessed with a Spearman correlation matrix with dendrometric and stand variables. Moreover, for each site class, the average trend of competition indexes by class diameter and age was analysed. There was no single index that correlated the most with all variables. For diameter, height and probability of mortality variables, the most correlated indexes were Glover and Hool, Lorimer, and Stage, respectively. The competition indexes have satisfactorily shown the average behaviour of competition in relation to age and site classes. The selection of a single index will depend on its use, being necessary specific tests according to purpose.

**Key words:** distance-independent indexes; intraspecific; Spearman correlation; tree modelling

# Índices de competição para árvores individuais em plantios comerciais de *Pinus taeda* L. não desbastados

**RESUMO:** O processo de competição em um plantio florestal é proveniente da disputa de recursos essenciais ao crescimento. Vários índices foram propostos para avaliar a competição de diferentes espécies, mas estudos desta natureza para pinus no país são escassos. Esses índices de competição são essenciais no processo de modelagem florestal. O objetivo foi avaliar índices de competição para árvores de um povoamento não desbastado de *Pinus taeda* L. Dados de unidades amostrais permanentes foram utilizados, de povoamento florestal localizado na região de Telêmaco Borba, Paraná, Brasil, com idade de 3,4 a 21,4 anos. Oito índices de competição foram avaliados por meio de uma matriz de correlação de Spearman com variáveis dendrométricas e do povoamento. Além disso, para cada classe de sítio, a tendência média dos índices de competição por classes de diâmetro e idade foi analisada. Não houve um único índice mais correlacionado com todas as variáveis. Para as variáveis diâmetro, altura e probabilidade de mortalidade, os índices mais correlacionados foram o de Glover e Hool, Lorimer e Stage, respectivamente. Os índices de competição demonstraram satisfatoriamente o comportamento médio da competição, em relação à idade e classes de sítio. A seleção de um único índice dependerá de seu uso, sendo necessário testes específicos conforme a finalidade.

**Palavras-chave:** índices independentes da distância; intraespecífica; correlação de Spearman; modelagem de árvore

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## Introduction

The competition between plants affects their ability to obtain resources, influencing mortality and growth patterns. Competition occurs when the availability of resources essential to growth is below the adequate level needed for trees in a forest stand. Water, light, and nutrients are some of the natural resources that plants compete for (Vatraz et al., 2018).

Although there are conceptual distinctions about competition, there is a consensus that trees compete for resources above and below ground surface, referring to the competition for light, water, and nutrients from the soil, respectively (Weiskittel et al., 2011). These same authors have pointed out other types of competition in forest areas regarding competitor species and symmetry of competitive interactions.

The effect of competition is usually expressed by a mathematical formulation commonly referred to as "competition index", which represents how much each tree is affected by its neighbour. Expressions used to quantify competition vary from simple formulations, which express the hierarchic position of a tree within the stand or sampling unit, to more complex indexes that express size, distance, and number of neighbouring trees (Burkhart & Tomé, 2012). Hierarchic position refers to the relationship between dimensions of the object tree and dimensions of average tree or dominant trees, for example.

Depending on the mathematical specification, competition indexes implicitly assume an asymmetric or a symmetric competition for resources between neighbouring trees. Competitive asymmetry refers to the advantage that larger trees have over smaller trees. On the other hand, symmetric competition implies that competitive effects of larger and smaller individuals are, to a certain extent, the same (Weiskittel et al., 2011).

A substantial part of competition indexes described in the literature can be divided into distance-independent or dependent (Kuehne et al., 2019). The former does not use spatial information directly, only tree size and number of trees within a given area; the distance-dependent indexes consider the relative locations of neighbouring trees within an area in addition to size and number (Contreras et al., 2011). There are also the semi-dependent indexes, developed for circular sampling units, which are especially restricted to trees closest to the object tree (Contreras et al., 2011) defined through a specific radius.

Distance-independent indexes do not require tree coordinates since they represent simple variable functions at stand and/or object tree dimensions level, in relation to the mean or maximum value for the stand (Burkhart & Tomé, 2012). Independent variables can represent the stand, an individual tree (Costa et al., 2018), or a combination of both. These indexes implicitly assume an asymmetric competition, reflecting mainly the competition for light (Burkhart & Tomé, 2012).

Several distance-dependent and independent competition indexes have been proposed, studied, and compared (Curto et al., 2020). Historically, several of these indexes were developed to predict growth in monospecific even-aged stands (Lorimer, 1983), in addition to mortality of individual trees. Various indices are used to describe density, stocking, and stockability, which are incorporated to varying degrees in growth models (Weiskittel et al., 2011). These indices represent important independent variables in forest modelling.

The main competition indexes used in modelling of individual trees can be found in the studies of Canetti et al. (2016), Costa et al. (2018), Lustosa Junior et al. (2019), and Curto et al. (2020). There is no consensus about the superiority of any index since the selection depends on the species and the conditions of the stand being studied (Curto et al., 2020).

Competition indexes have been successfully used in forest stands with more homogeneous conditions such as spacing, age and species, yet there are studies with this theme in native Brazilian forests. In Brazil, there are examples such as the studies of Martins et al. (2011) for clones of eucalyptus; Lustosa Junior et al. (2019) for species of a Semideciduous Seasonal Forest; Lambrecht et al. (2019) and Curto et al. (2020) for *Araucaria angustifolia* (Bertol.) Kuntze; Nascimento (2016) for commercial species from the Amazon Forest; Canetti et al. (2016) for *Podocarpus lambertii* Klotzsch ex Endl.; Orellana & Vanclay (2018) and Schons et al. (2020) for species from the Mixed Ombrophilous Forest in South Brazil.

Nevertheless, there is a lack of studies that approach the competitive condition and indicate more adequate competition indexes for species of the genus *Pinus* in the country, as well as the assessment of the behaviour of competition indexes in different sites and diameter classes. The hypothesis of this study is: distance-independent competition indexes can satisfactorily show the average behaviour of tree competition in relation to age and classes of site index? Therefore, the aim of this study was to assess and indicate distance-independent competition indexes for trees of a non-thinned *Pinus taeda* L. stand.

## Materials and Methods

The data used in this research are from permanent sampling units of a forest inventory conducted in non-thinned *Pinus taeda* L. stands, with initial planting space of 2.5 × 2.5 m, located in Telêmaco Borba, in the Campos Gerais region, Paraná, Brazil. The area has a slightly undulated relief, and the average altitude is 850 m. According to the Köppen-Geiger classification, the climate is Cfa, with average annual temperature 18.4 °C and average annual rainfall around 1,378 mm (Climate-Data.Org, 2021).

The sampling intensity was one sampling unit per hectare. Each sampling unit comprised 10 planting lines with 10 plants per line, totalling an average of 87 trees (CV = 11.7%) in each line. The remeasurements of these units occurred each one, two or three years. In each unit, the diameters at breast height (d) of all trees as well as total height (h) of the ten first trees were measured. Altogether, data from 1,135 sampling units were used, totaling 191,222 trees. The trees were distributed between the ages of 3.4 to 21.4 years, with 22, 35, 19, 13, 8, and 3% in classes 3 ⊢ 6, 6 ⊢ 9, 9 ⊢ 12, 12 ⊢ 15, 15 ⊢ 18, ≥ 18 years of age, respectively.

For this study, three site classes were established (class I: 30.5 m; class II: 25.5 m; and class III: 20.5 m) using the guide curve method, the Chapman-Richards model, and an index-age of 18 years, through the equation

$$h_{dom} = 41.224399\left(1 - e^{-0.0618321}\right)^{1.156161} \quad \left(S_{yx} = 9.5\%\right)$$

where $S_{yx}$, $h_{dom}$, and I are the standard error of the estimate (%), dominant height (m) and age (years), respectively. To obtain the estimates of total tree height, the generic hypsometric equation

$$h = e^{1.21133+0.01048S-6.34359d^{-1}+0.69040\ln I}$$

was used ($S_{yx}$ = 9.4%), where S is the site index (m), h, d, and I as described.

To assess the competitive status of the trees, distance-independent competition indexes were used (Table 1). The object tree was that whose competition index was calculated. The other trees of the sampling unit were considered competitors of the object tree.

Indexes IC.2, IC.7, and IC.8 tacitly assumed an asymmetric competition, reflecting the competition for light, mainly. The other indexes refer to the hierarchic position of the object tree within the sampling unit (Burkhart & Tomé, 2012).

Fallen and dead trees were disregarded since they are not competitors for other trees and are not part of the growth dynamics of the stand. For the chosen trees, the transversal area for each stem was calculated and subsequently added, resulting in the diameter equivalent to this transversal area (Dombroski & Pinto, 2019). In these cases, the total height corresponding to the highest stem was used.

**Table 1.** Distance-independent competition indexes assessed for individual trees of a *Pinus taeda* stand located in the Telêmaco Borba region, Paraná, Brazil.

| No. | Author/Source | Formulation |
|---|---|---|
| IC.1 | Stage (1973) - BAI (*Basal Area Index*) | $\left(d_i q^{-1}\right)^2$ |
| IC.2 | Stage (1973) - BAL (*Basal Area Larger*) | $\sum_{i=1}^{n} g_i$ |
| IC.3 | Daniels et al., (1986) - Modifications of the Glover & Hool index (1979) | $\left(d_i \bar{d}^{-1}\right)^2$ |
| IC.4 | | $h_i \bar{h}^{-1}$ |
| IC.5 | | $\left(d_i^2 h_i\right)\left(\bar{d}^2 \bar{h}\right)^{-1}$ |
| IC.6 | Lorimer (1983) | $\sum_{j=1}^{n} d_j d_i^{-1}$ |
| IC.7 | Tomé & Burkhart (1989) | $d_i d_{max}^{-1}$ |
| IC.8 | | $d_i d_{dom}^{-1}$ |

Where: IC - competition index; $d_i$ - diameter at breast height of the object tree (cm); $d_j$ - diameter at breast height of competitors trees (cm); $d_{max}$ - maximum diameter at breast height of the sampling unit (cm); $d_{dom}$ - dominant diameter, defined as the quadratic diameter of dominant trees in the sampling unit (cm); d - arithmetic mean value of diameters at breast height of trees in the sampling unit (cm); q - quadratic diameter of trees in the sampling unit (cm); $g_i$ - transversal area of the larger trees in relation to the object tree (m²); $h_i$ - object tree height (m); h - arithmetic mean value of height of trees in the sampling unit (m).

To assess the competition indexes, the correlation matrix between these indexes with dendrometric and stand variables was firstly elaborated (Daniels et al., 1986; Martins et al., 2011; Lustosa Junior et al., 2019; Curto et al., 2020). For the determination of the coefficient to be applied in the correlation matrix, the variables to be correlated were submitted to the Kolmogorov-Smirnov normality test (5% statistical significance). At this stage, the variables were used in their original scale, the

$$\sqrt{x+1},\ \mathrm{Ln}\left(x+1\right),\ \sqrt[4]{x+0.5}$$

transformations and, subsequently, the Box-Cox transformation were tested, where x represents the variable submitted to the transformation.

The correlation analysis was performed by the Spearman coefficient (ρ). The variables used in the correlation matrix were increment in diameter at breast height (In.d) and increment in total height (In.h), diameter at breast height (d), total height (h), annual probability of mortality by diameter class (Pm), basal area per hectare (G), and the competition indexes IC.1 to IC.8. The probability of mortality was calculated by

$$Pm_i = N_m\left(N_v + N_m\right)^{-1},$$

where $Pm_i$ is the non-accumulated annual probability of mortality in the diametric class I; $N_v$ and $N_m$ are the number of living and dead trees in the sampling unit by hectare, respectively, for the same age, similarly to the one used by Miranda et al. (2017).

The number of living trees ($N_v$) was determined with the number of living trees of the sampling unit at a given age. For the $N_m$ calculation, the exact age when the death occurred was observed, what was essential for this variable not to be repeatedly counted in successive measurements, and consequently overestimated. For ages up to 5 years, mortality was disregarded. Otherwise, the number of dead trees corresponded to the average up to the present age of the sampling unit, from 5 years.

In addition to the correlation analysis, the average behaviour of competition indexes according to age was observed for different diameter and site classes (Martins et al., 2011). These diameter classes were established according to the arithmetic mean value (d) and the standard deviation ($s_d$) of the diameters, considering all ages. Three classes were established, where class 1 consisted of trees with a minimum diameter of 21.3 cm (d + 0.5$s_d$), class 2 with diameters between 15.8 and 21.2 cm (d - 0.5$s_d$ to d + 0.5$s_d$), and class 3 with diameters smaller than 15.8 cm (d - 0.5$s_d$).

## Results and Discussion

The Kolmogorov-Smirnov test indicated no data normality for all the variables and site classes, even when submitted to transformations. This result is mainly due to a large variation of the variables used, and the substantial occurrence of extreme values, except for basal area by hectare. Depending on the mathematical specification of the index (i.e., IC.6), as well as the variation of the variable used in its calculation (i.e., d), these extreme values become inevitable. Thus, the Spearman correlation coefficient was used. The correlation matrices for the dendrometric and stand variables with competition indexes by site class are shown in Table 2. There were low but significant correlation values (p-value < 0.05). In large datasets, very small correlation coefficients can be “statistically significant”, but this value must not be confused with an expressively relevant correlation (Schober et al., 2018). It is possible that the weak correlations are not due to chance factors, but because with the large sample the low correlation is statistically representative of the population.

A large part of correlations was significant with the t test (p-value ≤ 0.05), where the highest correlation values were diameter and diameter increment (Table 2). For all sites, IC.2 showed the highest correlation with age, indicating and increase in the value of competition index throughout time. This result was expected even for the formulation of IC.2 (BAL), resulting in an increase of the basal area of trees with aging.

**Table 2.** Spearman correlation matrix between dendrometric and stand variables with competition indexes assessed by site class, in a *Pinus taeda* stand in the Telêmaco Borba region, Paraná, Brazil.

| Site | Var | IC.1 | IC.2 | IC.3 | IC.4 | IC.5 | IC.6 | IC.7 | IC.8 |
|---|---|---|---|---|---|---|---|---|---|
| | I | -0.02* | 0.55* | 0.01$^{ns}$ | -0.02* | 0.00$^{ns}$ | -0.18* | -0.18* | -0.11* |
| | d | 0.59* | 0.00$^{ns}$ | 0.68* | 0.52* | 0.59* | -0.60* | 0.43* | 0.49* |
| | h | 0.19* | 0.35* | 0.21* | 0.20* | 0.21* | -0.39* | 0.03* | 0.11* |
| I | In.d | 0.40* | -0.65* | 0.39* | 0.40* | 0.40* | -0.26* | 0.48* | 0.44* |
| | In.h | 0.17* | -0.31* | 0.17* | 0.17* | 0.18* | -0.12* | 0.19* | 0.18* |
| | Pm | -0.16* | 0.13* | -0.14* | -0.13* | -0.14* | 0.11* | -0.15* | -0.14* |
| | G | -0.01* | 0.57* | 0.00$^{ns}$ | -0.04* | -0.01$^{ns}$ | -0.10* | -0.15* | -0.08* |
| | I | 0.00$^{ns}$ | 0.51* | 0.00$^{ns}$ | -0.05* | -0.01$^{ns}$ | -0.14* | -0.08* | -0.07* |
| | d | 0.65* | -0.12* | 0.71* | 0.54* | 0.64* | -0.66* | 0.58* | 0.59* |
| | h | 0.19* | 0.31* | 0.20* | 0.17* | 0.20* | -0.36* | 0.13* | 0.14* |
| II | In.d | 0.39* | -0.61* | 0.39* | 0.41* | 0.40* | -0.28* | 0.41* | 0.40* |
| | In.h | 0.15* | -0.27* | 0.15* | 0.15* | 0.16* | -0.11* | 0.15* | 0.17* |
| | Pm | -0.12* | 0.11* | -0.10* | -0.08* | -0.09* | 0.08* | -0.10* | -0.10* |
| | G | 0.00$^{ns}$ | 0.53* | 0.00$^{ns}$ | -0.06* | -0.01* | -0.06* | -0.04* | -0.03* |
| | I | 0.02* | 0.46* | 0.00$^{ns}$ | -0.04* | -0.01$^{ns}$ | -0.10* | -0.05* | -0.02$^{ns}$ |
| | d | 0.69* | -0.21* | 0.70* | 0.56* | 0.67* | -0.69* | 0.65* | 0.67* |
| | h | 0.27* | 0.27* | 0.25* | 0.22* | 0.25* | -0.31* | 0.22* | 0.24* |
| III | In.d | 0.39* | -0.58* | 0.40* | 0.40* | 0.41* | -0.34* | 0.41* | 0.39* |
| | In.h | 0.12* | -0.18* | 0.13* | 0.14* | 0.14* | -0.11* | 0.10* | 0.10* |
| | Pm | -0.12* | 0.11* | -0.10* | -0.09* | -0.10* | 0.09* | -0.10* | -0.08* |
| | G | 0.03* | 0.51* | 0.00$^{ns}$ | -0.05* | -0.01$^{ns}$ | 0.04* | -0.01$^{ns}$ | 0.01$^{ns}$ |

Where: Site: I (30.5 m), II (25.5 m), and III (20.5 m); Var - Variable; I - stand age (years); d - diameter at breast height (cm); In.d - increment in diameter at breast height (cm); h - total height (m); In.h - increment in total height (m); Pm - probability of mortality by diameter class (%); G - basal area by sampling unit ($m^2$ $ha^{-1}$. sampling unit); IC.1 to IC.8 - competition indexes from 1 to 8, respectively; * and $^{ns}$ - significant and non-significant correlation, respectively, 5% significance.

The competition index most correlated with diameter at breast height was IC.3, for sites I, II, and III (Table 2). For site II, the direct relation between diameter increments and increase in the competition index value was more evident, indicated by the higher correlation. For sites I and III, correlations were subtly lower. IC.3 indicates that the higher the diameter, the lower the competition against the object tree. According to the formulations, IC.1 and IC.3 competition indices provide similar values. However, the highest correlations for IC.3 may be associated with the variability of tree diameters, especially when there are discrepant values in the sampling units, as the average is steadier, differently the quadratic diameter, which is more sensitive.

For the variable total height, correlation values were below 0.40, lower than those found for diameter, IC.2 being the only exception (Table 2). In all site classes, the competition index most correlated with total height was IC.6. IC.6 was more negatively correlated with height, probably due to the strong hypsometric relationship, in which shorter trees have smaller diameters and, consequently, greater competition. By formulating this index, the number of competitors also influences the competition, which is directly associated with the sample unit size.

The competition index IC.2 was the most correlated with increment in height, increment in diameter and basal area, for all site classes (Table 2). The correlation values for increment in diameter were higher than those of increment in height, in all analysed situations. For basal area, expected result according to the index formulation, which is obtained as a function of the transversal area of the competitor trees. This index was negatively correlated with the increase in height and diameter, in which smaller trees (suppressed trees, in certain situations) show reduced growth and have greater competition.

When comparing correlation values of increment in diameter and height with those obtained for diameter and height, the former was lower for nearly all assessed indexes (Table 2). It can indicate that the use of production models has advantages over increment models to estimate diameter and height in different ages for commercial plantings of *Pinus taeda*. All in all, among the analysed variables, the probability of mortality generated the lowest correlations. This result is directly associated to the fact that mortality is a random event in forest stands (Fiorentin et al., 2019). Moreover, a non-regular high mortality percentage caused by capuchin monkeys (*Sapajus nigritus*, Goldfuss, 1809) was observed in this study area, what reduced relevantly the regular mortality. The irregular mortality caused by the capuchin monkey was 18, 17, and 13% for sites II, III, and I, respectively. In some sample units, this percentage was higher, approximately 30%. For this variable, in all site classes, index IC.7 showed the highest correlation, indicating that the probability of mortality was higher for trees with smaller diameters (Table 2).

Other studies in the literature used the correlation matrix to select competition indexes. For example, Tomé & Burkhart (1989) for individual trees of *Eucalyptus globulus*, in Portugal;

Martins et al. (2011) for clonal plantings of eucalyptus, in the Monte Dourado region, Pará, Brazil. The Spearman correlation coefficient was also used by Maleki et al. (2015), who used the Spearman correlation matrix to select distance-dependent and independent competition indexes more correlated to the diameter increment for silver birch (*Betula pendula* Roth) in Estonia.

Figure 1 shows the behaviour of competition indexes IC.1 to IC.4 according to age and diameter class by class of site index. According to their formulations, the higher the index value, indexes IC.1, IC.3 and IC.4 assume the increase of competition. On the other hand, IC.2 indicates higher competition the lower the index value.

In general, for the same competition index, the trend was similar in the different site classes (Figure 1). For index IC.1, in the three diameter and site classes, there was an increase in competition with tree aging, essentially due to the increase in diameter. In the early ages, the competition was low due to the small sizes of trees, and the stand was more homogeneous, with low diameter variation, resulting in higher proximity of the arithmetic mean diameter with the quadratic diameter. Still in these ages, the mean quadratic diameter was lower than the diameter median, generating a higher number of trees with higher diameters than the quadratic diameter, increasing the value of IC.1.

The stands became more heterogeneous with age, with well-defined dominant and suppressed trees, where the latter started to invest more effectively in height growth than diameter growth. This has contributed to the increase in diameter variance, distancing the mean arithmetic value from the quadratic diameter, which became higher than the median and reduced the number of trees with higher diameter than the quadratic diameter, resulting in a reduction in the value of IC.1 (Figure 1). The percentage difference between the mean arithmetic value and the quadratic diameter in forests is higher the higher the standard deviation of diameters, for populations with similar mean diameters, a characteristic of commercial plantings.

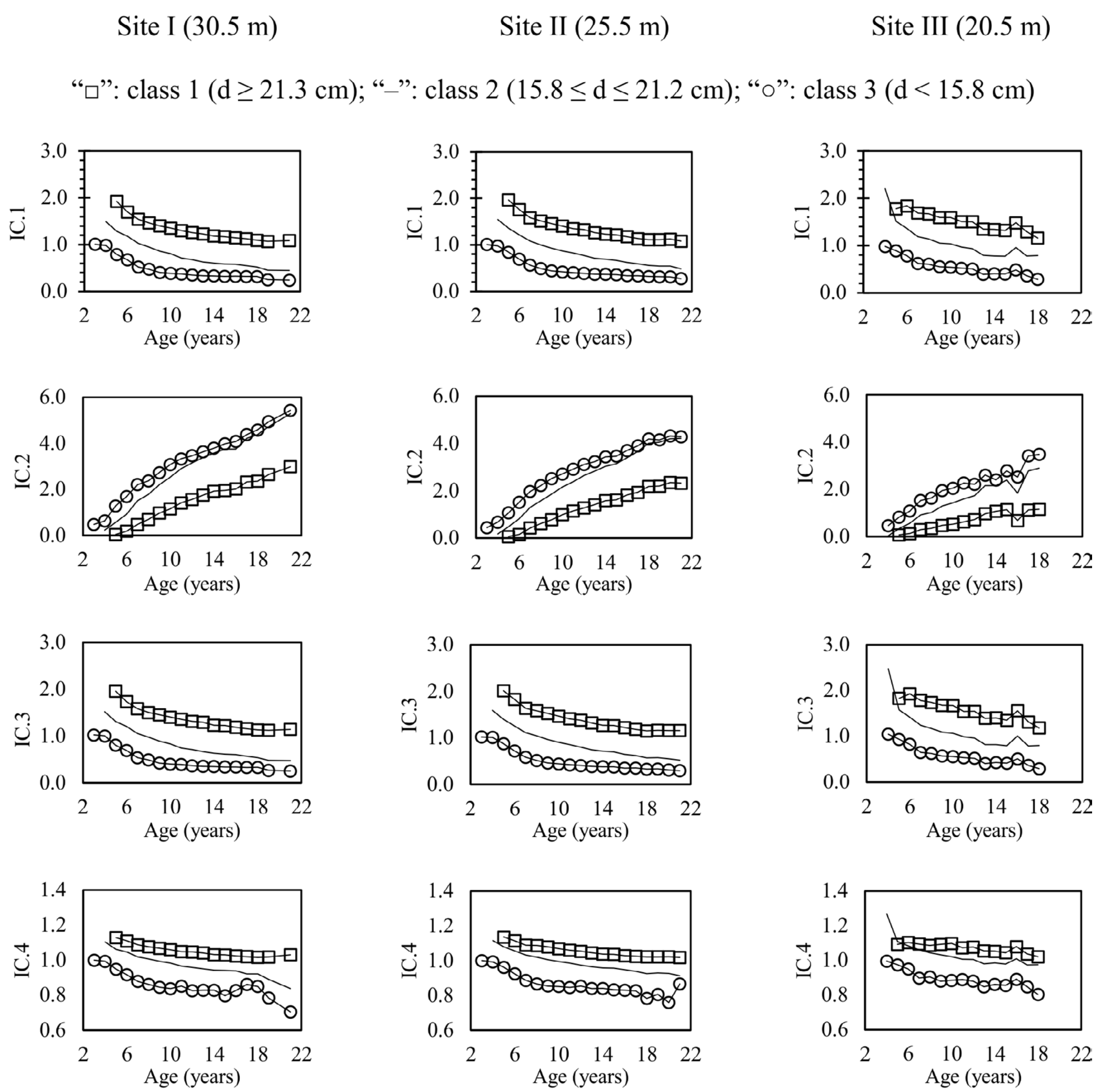


**Figure 1.** Average behaviour of competition indexes IC.1, IC.2, IC.3, and IC.4 according to age and site, in the diameter classes 1 (d ≥ 21.3 cm), 2 (15.8 ≤ d ≤ 21.2 cm), and 3 (d < 15.8 cm), in a *Pinus taeda* stand located in the Telêmaco Borba region, Paraná, Brazil.

The results for competition index IC.2 were similar for the diameter classes 2 and 3, for the same site (Figure 1). The increase of competition with tree aging is evident, given strictly in relation to this index and the basal area. Furthermore, lower index values occurred in site class III due to the smaller increment in basal area. The lower index values were for dominant trees (diameter class 1), given the reduced number of trees with larger basal areas in relation to these dominant trees.

Index IC.3 showed the same behaviour as IC.1, however, with slightly lower values resulting from the similarity of the mathematical formulations of these indexes, differentiated only by the quadratic and mean diameter (Figure 1). This index was broadly recommended to determine the competition of homogeneous stands with the same age, size, and potential growth (Dimov et al., 2008) due to the advantage of being distance-independent and explain a considerable part of the growth variation. Index IC.4 also indicated an increase in competition with aging. However, it oscillated less in relation to the other indexes, mainly for trees with larger diameter and in site I.

The behaviour of competition indexes IC.5 to IC.8 according to age and diameter class by site index class is shown in Figure 2. The interpretation of indexes IC.5, IC.7, and IC.8 are similar, indicating an increase of competition as the index value increases. On the other hand, index IC.6 shows increase of competition the lower the index value.

Index IC.5 indicated an increase in competition with tree aging (Figure 2). This index was obtained by the diameter and height of the object tree and the respective mean values by sampling unit, representing the result of indexes IC.3 and IC.4. Index IC.6 showed that dominant trees suffered a minor effect from competition, regardless of site class and age. Also, it showed that smaller trees are the most affected, what is more pronounced in advanced ages. Indexes IC.7 and IC.8 showed similar trends (Figure 2). However, IC.7 showed slightly lower values, by considering the maximum diameter, in contrast to IC.8 that used the quadratic diameter of dominant trees. The

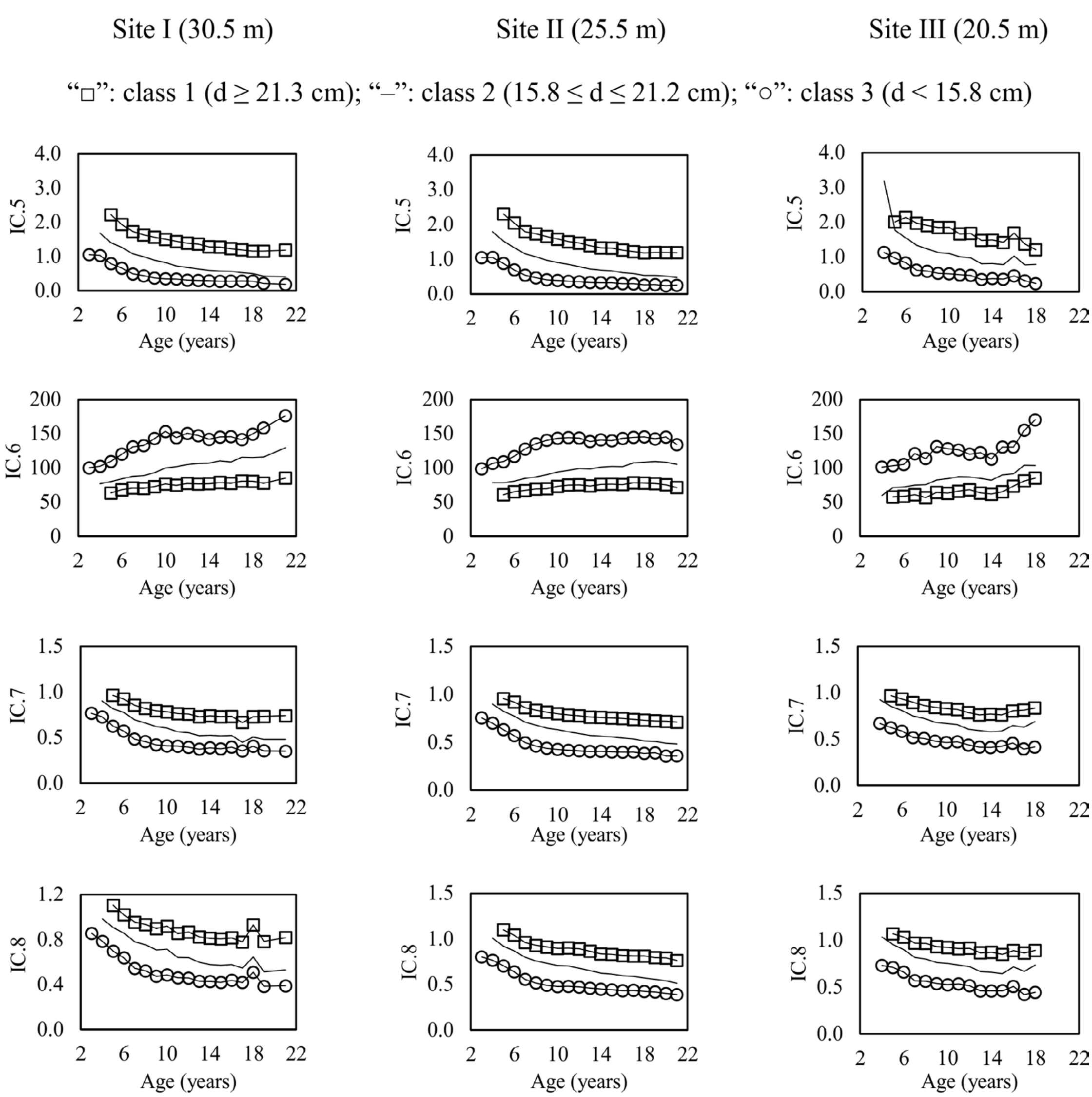


**Figure 2.** Average behaviour of competition indexes IC.5, IC.6, IC.7, and IC.8 according to age and site, in the diameter classes 1 (d ≥ 21.3 cm), 2 (15.8 ≤ d ≤ 21.2 cm), and 3 (d < 15.8 cm), in a *Pinus taeda* stand located in the Telêmaco Borba region, Paraná, Brazil.

behaviour was similar for the different classes of site index and diameter.

Martins et al. (2011) analysed the average behaviour of five distance-independent competition indexes for clonal eucalyptus plantings from the Monte Dourado region, in Pará, Brazil. The trend for IC.1 was similar to the one found in this study, except for the class of dominant trees, which showed an opposite trend with tree aging, a result also observed for indexes IC.3, IC.4, and IC.5. For index IC.2, the results found were similar to the ones found in this study.

According to the assessment criteria, there was not a single index that correlated the most with all variables. However, there were those that stood out in one or another variable, such as indexes IC.3, IC.6, and IC.1, for diameter, total height, and probability of mortality, respectively. The selection of a single index will however depend on its use. To this end, specific assessments are needed according to the purpose of the competition index. The results indicate the non-rejection of our hypothesis since the distance-independent competition indexes have satisfactorily shown the average behaviour of tree competition in relation to age and classes of site index.

## Conclusions

For the diameter at breast height, total height and probability of mortality, the indexes of Glover and Hool (IC.3), Lorimer (IC.6), and Stage (IC.1) were the most correlated, respectively, regardless of class and site.

The correlation values for the production in diameter and total height were higher than their respective increments, for nearly all competition indexes, indicating the use of production models to estimate the variables diameter and total height at different ages.

The distance-independent competition indexes have satisfactorily shown the average behaviour of tree competition in relation to age and site classes.

The selection of a single index will depend on its use, with specific assessments being necessary according to the purpose of the competition index.

## Compliance with Ethical Standards

**Author contributions:** Conceptualization: ROVM, AFF, AAE; Data curation: ROVM, AFF; Formal analysis: ROVM; Funding acquisition: AFF; Investigation: ROVM, AFF, RAC, AAE, HCD; Methodology: ROVM, AFF, RAC, LDF; Project administration: ROVM, AFF; Resources: ROVM; Software: LDF, HCD; Supervision: AFF; Validation: ROVM, RAC, AAE, LDF, HCD; Visualization: ROVM, RAC, AAE; Writing - original draft: ROVM, AFF, RAC. Writing - review & editing: AAE, LDF, HCD.

**Conflict of interest:** The authors declare that there is no conflict of interest (professional or financial).

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