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A new approach to assessing competition from trees on Nelder wheels

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Abstract

Aim of study: To develop an index to describe the competition of trees of Eucalyptus spp. clones in different densities; also, to evaluate the productivity of the clones on Nelder wheels (NWs).

Area of study: Ten *Eucalyptus* spp. clones distributed in nine NWs, located in the northern state of Tocantins, Brazil.

Material and methods: A new competition index was formulated as the ratio of geometric areas and average cross-sectional areas of sampling units from different locations on the NW referenced to a unit taken in the center of it. Besides, two distance-dependent indices were tested to evaluate their performance in different spacings. The correlation between the competition indices and the variables height, diameter, volume and cross-sectional area, average distance and mortality percentage was evaluated. To check the difference in productivity between the clones we used MANOVA and discriminant analysis.

Main results: The Alba-Péllico index provides a better understanding of the competitive relationship between trees, as well as a better explanation of the competitive process in the NWs than the other indices evaluated. The variation in the basal area between the clones in the less dense locations, substantiates the characteristics of each clone or possible interferences of the location since in this condition they are free from the influence of spacing and competition. This shows that competition is more influential than other characteristics of sites and genotypes in the behavior in diameter, basal area and volume in the densest sites.

Research highlights: The characteristics of the Alba-Péllico index indicate good interpretation to understand the competitive relationship among trees since the results vary between 0 and 1, and the closer to zero the smaller or non-existence of competition.

Additional key words: competition index; spacing; spatial structure; *Eucalyptus*; clones

Abbreviations used: *Ai* (area per plant); *dbh* (diameter at breast height, in centimetres, considered at 1.30 m aboveground); D_{ij} (distance between the reference tree and the competing tree); d_{max} (maximum *dbh* of the sampling unit); *g* (cross-sectional area); *h* (total height); M(%) (percentage of mortality); NW (Nelder wheel); *pps* (probability-proportional-to-size); *q* (mean square diameter of the sampling unit); SU (sampling unit), v (volume).

Authors' contributions: Conduction of the experiment and data collection: AMF, CCC. Statistical analysis and writing the manuscript: FAS, SPN, AB.

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Introduction

A determining factor in forest dynamics, productivity and ecological structure is competition among trees (Begon *et al.*, 2006; Pretzsch, 2009) since it involves complex processes, which promote interaction between trees that depend on the available resources, *e.g.*, light, water, nutrients, and the efficiency of their use (Kuehne *et al.*, 2019). More competitive environments reduce growth performance and influence tree survival (Pommerening & Maleki, 2014). Understanding how neighbouring trees interact in a forest community is crucial for forest management practices (Hui *et al.*, 2018).

Different conditions within the stand may respond to competition differently, for example, in clonal forest plantations the genetics of the trees impact their growth potential and competitiveness (Resende *et al.*, 2018). Each genotype has specific competitive capabilities (Pavan *et al.*, 2014; 2021) and genotypes differ in their ability to tolerate competition, with some being more able to compete than others (Pavan *et al.*, 2019). Thus, genotypes are expected to have different patterns of interactions with their neighbours as they exhibit differences in growth, disease resistance, and wood properties (Boyden *et al.*, 2008). Resende *et al.* (2018) stated that different eucalyptus clones can have varying levels of competition in plantations.

Another factor fully related to competitive interactions is the spatial arrangement and density between the trees (Das *et al.*, 2011; Aakala *et al.*, 2013). Thus, the study of competition in distinct spacing patterns has the potential to answer questions about the behaviour of neighbouring trees, resulting from the density in stands (Jiang *et al.*, 2018). A structure that makes possible the study of tree density and growth relations and the competition between trees are the Nelder Wheels (NWs) (Affleck, 1998). The design was structured by Nelder (1962) as a circular experimental arrangement that sought to frame several spacings in relatively small areas, reducing the need for experimental plantations with large areas and separate experimental plots for each spacing (Parrott *et al.*, 2012). This arrangement experience created in the agricultural field was soon very useful in studies on the effect of spacing on tree growth (Freeman, 1964; Namkoong, 1966; Panetsos, 1980; Affleck, 1998; Mabvurira & Miina, 2002; Uhl *et al.*, 2015). According to Vanclay (2006), NW reports the response of competition rates rather than rectangular plantings in a regular grid. Rectangular spacing gives only a narrower range and distances between trees, and the nearest neighbour is approximately constant. However, in forestry literature, there are few studies testing competition rates on NW, with emphasis on Vanclay (2006), Vanclay *et al.* (2013) and Uhl *et al.* (2015).

Due to the importance of describing the competition between trees quantitatively, many competition indices have been developed and presented in the literature (Moore *et al.*, 1973; Stage, 1973; Hegyi, 1974; Glover & Hool, 1979; Tomé & Burkhart, 1989; Rouvinen & Kuuluvainen, 1997; Hui *et al.*, 2018). Despite the wide application of the competition indices available in the literature, in many cases, it is difficult to make them comparable in their results, because indices do not express values on a standardized scale and most of them do not result in dimensionless values. The interpretation of the outcome of the competition depends critically on how it is measured (Pommerening & Maleki, 2014). Thus, the selection and use of competition measures have a strong influence on the description of the variables that competition affects, which in turn can condition the mistaken inferences about the forest (Weigelt & Jolliffe, 2003). The search for an easily interpreted index with such conditions is an encouraging task and quite interesting from a practical point of view.

In this research, we explored how the structure of a NW with different densities influences the competition between trees of different clones of *Eucalyptus* species in different sites. We focused on the idea that in NWs the competition of trees decreases from their centres to the periphery, with an interactive effect between the area of occupation and the cross-sectional areas of the trees, for all clones. Consequently, we propose a competition index following the hypothesis: "The index to express this competition effect may be expressed by the ratios of geometric areas and mean cross-sectional areas taken from successive sampling units in the NW and always related to a sampling unit located near the center of it (as the reference of maximal observed competition)". We expect that this proposed new index will allow an easy interpretation of competition in forests with different distances between trees, as it is expressed in a scale of values that varies within a range between 0 and 1.

The new index, which we call Alba-Péllico, was developed specifically to measure competition in Nelder's systematic experiments, in which this condition is of fundamental importance to explain the behavior of the tree growth process in the evolutionary circumstances of tree spacing. Furthermore, the productive capacity of the site, and the genetics of the trees impact the competitiveness and, consequently on the productivity of eucalyptus plantations (Resende *et al.*, 2018). Thus, we sought to answer the eucalyptus clones planted on different sites with NW, express differences in their competitive interactions and productivity.

After such considerations the following objectives were to: 1) develop an index to describe the competition of trees in different spacings; 2) compare the new index with traditional indices (Moore *et al.*, 1973; Hegye, 1974); 3) evaluate the effect of density and competition on tree mortality and the difference between clones; and 4) evaluate the production in basal area and volume per hectare for the different eucalyptus clones.

Material and methods

Study area

The data used in this study came from an experiment with ten *Eucalyptus* spp. clones, in which nine NWs were installed from 2010 to 2014, in different municipalities in the state of Tocantins, Brazil. This region has characteristics of semi-humid tropical climate, Aw in the Köppen climate classification. The site has high temperatures during the year, with a minimum of 20º C and a maximum of 32º C; a defined rainy season from October to May, and a dry season from June to September, with annual precipitation above 1800 mm.

Description of the experiment

The design used in this research has the same spacing between trees along the ray, consequently, it was not necessary to use ratio values of the geometric progression (α) of the rays. The same spacing was used between trees within the ray (~3 m) throughout the experiment, therefore the spacing area was calculated using only the constant distance between trees within the ray and the increasing distance between concentric circles and the rays increasing outwards delimited by the radius opening angle (θ). The NWs were adopted in the present experiment because the original systematic design proposes that the experimental arrangement be defined values of the initial radius r_0 (distance from the centre of the circle to the inner border), a ratio of the geometric progression of the rays (α), the angle between them (θ) and the area (Ai) per tree (Nelder, 1962). The number of concentric circles with the same spacing varied from 32 to 34 in each NW.

Eucalyptus clones have distinct characteristics and, to identify them, we created an alphanumeric coding, where a letter indicates the clone and a number the NW (Table 1). Two to four different eucalyptus clones were planted between the years 2010 and 2014 in each NW, covering 24 rays. To avoid the edge effect and no interference from other clones, we measured only 12 rays per clone. Thus, an average of 384 trees was measured in each clone. An average of 768 to 1536 trees were measured per NW, depending on the number of clones planted in each wheel.

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Data collection

Data were collected in 2016 when the NWs were 2 to 5 years old. The dendrometric variables measured were: (d) diameter at breast height in centimeters, considered at 1.30 m aboveground; and (h) total height in meters.

Competition study

Sampling method and selection of competing trees

To sample the trees at different spacings we used the Prodan sampling method (Prodan, 1968; Péllico Netto & Brenna, 1997; Silva *et al.*, 2020) to define plots and to select the reference trees and their competitors. We adapted the number of trees selected in the sampling unit (SU), in which we consider a tree as the central point of the SU, called a reference tree, and the eight trees closest to it to integrate the SU, called neighbouring trees, as they represent distinct individual areas and, consequently, they compete differently. Since Nelder circles consist of 2 to 4 clones, the number of SUs ranged from 500 to 1100 on average per circle.

Development of the competition index

Competition between trees in a stand is influenced by their greater or lesser proximity to each other (Assmann, 1970; Das *et al.*, 2011). This process results from the greater or lesser availability of nutrients, light, and water in the stand (Begon *et al.*, 2006; Weber *et al.*, 2008; Kuehne *et al.*, 2019).

A new index for assessing tree competition in a forest stand was proposed, and for its formulation, the competition was considered dependent on stand density, that is, the closer the trees are to each other, the greater the competition will happen (Maleki *et al.*, 2015). Besides, high density also has a strong influence on stand diameters (Weiskittel *et al.*, 2011), because the closer they are to each other, their diameters will also tend to homogeneity of values. As the area available for each tree increases, any putative spatial autocorrelation, as well as the competition process, decreases and, consequently, the diameters will become more variable in their diameter dimensions.

Table 1. Characteristics of the eucalyptus clones and information about their inclusion in the Nelder wheels (NW), located in the state of Tocantins, Brazil.

Clone	Characteristics	NW
A	Urograndis hybrid, high productivity clone with medium drought resistance.	1, 6, 7
B	Urograndis hybrid, high productivity clone with low drought resistance and phytosanitary problems in the lowland.	7, 8
C	Urograndis hybrid, high productivity clone with medium drought resistance.	6, 7, 8, 9
D	Urograndis hybrid, high productivity, and low drought resistance.	2
E	Urograndis hybrid, high productivity, and medium drought resistance.	2, 3, 6, 8, 9
F	Urocam hybrid, medium productivity, and high drought resistance.	1, 2
G	Urograndis hybrid, high productivity, low drought resistance and phytosanitary problems in the lowland.	3, 8, 9
H	*Eucalyptus platyphylla*, medium yield, high drought resistance and phytosanitary problems in lowland.	3, 4, 5
I	*Eucalyptus platyphylla*, medium yield, high drought resistance.	3, 4, 5
J	Urograndis hybrid, high productivity, and medium drought resistance.	6

These initial assumptions being formalized, the proposed Alba-Péllico competition index incorporates these two effects simultaneously. Thus, it results from the product of two ratios: the first one expresses the proportion of the average geometric area of the distances taken from each tree of the sample from a reference tree concerning the same average taken "with the highest competition plot (plot in denser condition); the second ratio is expressed by the average cross-sectional areas of sample units from different locations on the NW referenced to a unit taken in the center of it (Eq. 1).

$$AP = \frac{\left(\prod_{i=1}^{n-1} D_{i1}^2\right)^{\frac{1}{n-1}}}{\left(\prod_{i=1}^{n-1} D_{ij}^2\right)^{\frac{1}{n-1}}} \frac{\bar{g}_{i1}}{\bar{g}_{ij}} = \frac{\left(\prod_{i=1}^{n-1} D_{i1}^2\right)^{\frac{1}{n-1}}}{\left(\prod_{i=1}^{n-1} D_{ij}^2\right)^{\frac{1}{n-1}}} \frac{\sum_{n=1}^{n} \frac{\pi}{4} \frac{d_{ij}^2}{n}}{\sum_{n=1}^{n} \frac{\pi}{4} \frac{d_{ij}^2}{n}} = \tag{1}$$

$$= \frac{\left(\prod_{i=1}^{n-1} D_{i1}^2\right)^{\frac{1}{n-1}}}{\left(\prod_{i=1}^{n-1} D_{ij}^2\right)^{\frac{1}{n-1}}} \frac{\frac{\sum_{i=1}^{n} d_{i1}^2}{n}}{\frac{\sum_{i=1}^{n} d_{ij}^2}{n}} = \frac{\left(\prod_{i=1}^{n-1} D_{i1}^2\right)^{\frac{1}{n-1}}}{\left(\prod_{i=1}^{n-1} D_{ij}^2\right)^{\frac{1}{n-1}}} \frac{\sum_{i=1}^{n} d_{i1}^2}{\sum_{i=1}^{n} d_{ij}^2}$$

where: AP is the Alba-Péllico competition index; D_{i1} are the distances from the trees to the reference tree in the sampling unit with the highest competition among trees in the NW; g_{i1} are the cross-sectional areas of the trees in the sampling unit with the highest competition among trees in the NW; d_{i1} are the tree diameters taken in the sample unit with the highest competition among trees in the NW; D_{ij} are the distances from trees to the reference tree in all sampling units taken in the NW, for j = 1, 2, 3 …*s*, and s is the number of sampling units in each NW; g_{ij} are the cross-sectional areas of all trees taken in the remaining sampling units in the NW; d_{ij} are the diameters of all trees taken in the remaining sampling units in the NW; n is the number of trees of the sampling unit, in the present case is always 8.

Maximum competition is observed when both proportions are equal to one, *i.e.* when the geometric mean of the quadratic distances of all trees included in the SU with the highest competition among trees in the NW is divided by the same value in the SU and, also, when the average of the cross-sectional areas of all trees taken in the SU with the highest competition among trees in the NW is divided by the same value of the SU; in this case, called the reference plot. In this situation, the index results in a value of one, whereas in all other circumstances the index will be less than one. Both proportions under these conditions are smaller than one and the smaller it is, the less competition will occur.

Index values close to zero occur when tree distances from reference trees are too large, and, in this case, the first proportion approaches zero. Besides, the larger the tree diameters in the other *SUs*, the second proportion will result in a value tending to zero.

Note that diameters under extreme competition tend to be closer to the same value than diameters of competition-free growing trees.

The evaluation of the maximum competition in the center of the NW was exhaustively evaluated by the authors before proposing the Alba-Péllico index. The following points were considered during the evaluations: 1) Prodan's sampling units are taken with a fixed number of trees, whose inclusion occurs with probability proportional to their distance to a reference tree taken in the center of the SU; consequently, this is a probability-proportional-to-size (*pps*) sampling, and the statistical estimates are obtained directly per hectare, being an assessment required by foresters. 2) When mortality occurs, the sampling unit will continue to be taken with eight trees closest to its center, which results, in some circumstances, an increase of their distances from the center of the sampling unit. 3) The direct consequence of the application of this methodology is the variations on the reported results per hectare, that is, smaller number of trees, most probably greater basal area, and volume. 4) The comparative effect of the sampling units furthest from the center of the NW, related to the first unit taken close to it will continue to be obtained normally, regardless of other factors concerning site, clone, or age. 5) Applying the Prodan *pps* sampling allows us to obtain consistent estimators per hectare by taking the sampling units in any position in the NW that makes it possible to have them completely inside.

Comparison with other indices

In addition to the application of the Alba-Péllico index in this research, we also tested two distance-dependent competition indices widely used in the literature (Table 2). We conducted this analysis to answer objective 2 and compare their performance in different densities.

Data analysis

Correlation

We applied correlation analysis to characterize the relationship between the competition indices and the variables diameter, height, volume, transversal area, distance, and mortality rate. Correlation analysis is widely used to evaluate the relationship between the competition indices and the variables under study (Tomé & Burkhart, 1989; Weiskittel *et al.*, 2011; Hui *et al.*, 2018).

Data normality of the variables was assessed using the Kolmogorov-Smirnov test at 95% probability. Variables that did not meet the hypothesis of normality were transformed

Table 2. Description of the competition indices.

Competition indices	Math formula	Interpretation	Variation interval
I(1): Moore *et al.* (1973)	$\sum_{j=1}^{n} \frac{d_i^2}{d_i^2 + d_j^2} D_{ij}$	The higher the index value, the lower the competition.	—
I(2): Hegyi (1974)	$\sum_{j=1}^{n} \frac{dj}{di} \frac{1}{D_{ij}}$	The smaller the index value, the lower the competition.	—
I(3): Alba-Péllico	$\frac{\left(\prod_{i=1}^{n-1} D_{i1}^2\right)^{\frac{1}{n-1}} \sum_{i=1}^{n} d_{i1}^2}{\left(\prod_{i=1}^{n-1} D_{ij}^2\right)^{\frac{1}{n-1}} \sum_{i=1}^{n} d_{ij}^2}$	Values closer to 0, the smaller the competition.	0 to 1

di and *dj* are the diameters at 1.30 m aboveground (*dbh*) of the reference tree *i* and the competing tree *j* (cm); D_{ij} is the distance between the reference tree and the competing tree (cm).

using the *Box-Cox* system. After this procedure, some variables still did not meet the normal condition and, therefore, the Spearman correlation was applied. The significance of these variables was assessed by the t-test at 95% probability.

Graphical analysis performance of the Alba-Péllico competition index in this work, as well as for the other tested indices, was evaluated using scatterplots of the index values for growing sizes of vital areas per tree. The average behaviour of competition indices at different densities was analysed for all clones.

To analyze the stability of the correlation between the proposed index and the variables height, diameter, cross-sectional area, volume and mortality, the homogeneity test of the correlation coefficients was applied. Initially, the test was performed to test the difference of the correlation coefficients between the clones, that is, it was compared the correlation coefficients of the clones into each NW. This was effectuated to maintain the same conditions of sites and ages. Once the correlation values were converted to *z* values, the Chi-square test was used to test the null hypothesis of no differences in correlation among the clones (Eq. 2).

$$\chi_c^2 = \sum \left(\frac{z_i' - \bar{z}_w'}{1/\sqrt{n_i - 3}} \right)^2 = \sum (n_i - 3)(z_i' - \bar{z}_w')^2 \qquad (2)$$

where $\bar{z}_w' = \frac{\sum (n_i - 3) z_i'}{\sum (n_i - 3)}$ The value of χ_c^2 has χ^2 distribution with *k*-1 degrees of freedom, where *k* is the number of correlations.

Mortality

Mortality was assessed using graphs of their respective percentages for the different clones and ages within each defined spacing class. The classes were considered very dense when the spacing had less than 5.9 m², moderate dense between 6 m² and 10.9 m², slightly dense between 11 m² and 15.9 m² and not dense in spacing greater than 16 m². We decided to consider the classes because it was a better way to quantify the mortality. The percentage of tree mortality was evaluated by clones along with the rays. To quantify the percentage of mortality, the initial number of trees planted was considered, and the proportion of dead trees and the failures were evaluated.

Comparison between groups: Clones cultivated in different sites with different ages

The values of the basal area (*G*) and volume (*V*) variables were converted per hectare, as it is of interest to foresters and appropriate for the evaluation of forest production. This was possible due to the application of Prodan's sampling method presented in Prodan (1968) and Péllico Netto & Brena (1997). Thus, an analysis of MANOVA was performed for G (in m² ha^{-1}) and another for *V* (in m³ ha^{-1}), since G is a function only of the diameter variable and V is a function of the variables diameter, height, and tree form. Basal area (Eq. 3) was obtained using a proportional expansion based on the diameters of the eight trees included in the sampling unit. The volume estimates per hectare were obtained using appropriately the volume of the 8 trees included in the sampling unit (Eq. 4).

$$\hat{G} = \frac{d_1^2 + d_2^2 + \dots\dots + \frac{d_8^2}{2}}{R_8^2}(2{,}500) \qquad (3)$$

$$\hat{V} = \frac{v_1 + v_2 + \dots\dots + \frac{v_8}{2}}{\pi R_8^2}(10{,}000) \qquad (4)$$

where: $\hat{G}$ is the estimate of basal area (m² ha^{-1}), $\hat{V}$ is the estimate of volume per hectare (m³ ha^{-1}), R_8 is the ray of the eighth tree (m), *di* is the diameter of the ith trees in the sampling unit (cm), and v_i is the estimated volume of the i^{th} trees in the sampling unit (m^3).

In this sense, to compare the effects of clones within the same NW, the effect of age under the same clone at the same site and the effect between sites for the same clone at the same age, two multivariate analyses were applied: 1) analysis of multivariate variance (MANOVA) and 2) discriminant analysis. For this purpose, groups were defined, in which each corresponds to treatment (a clone of an NW, which is under the influence of a site and an age). Thus, the independent variable in MANOVA represented 26 groups. In the discriminant analysis, the dependent variable represented the groups. Therefore, through these two analyses, it was possible to assess whether there are differences between the groups (MANOVA), and if this is confirmed, an additional question was asked about which groups (treatments) were similar (discriminant analysis).

Since in each replication the values of these experimental units are autocorrelated due to the experimental structure of the NW, this dependence was considered when including the values of G and V as dependent variables in MANOVA, in each of the analyses, as well as in the discriminant analysis. The dependent variables on MANOVA. If differences were detected between the groups, indicated by MANOVA, discriminant analysis was applied to assess the following points: effects of clones within the same NW, submitted to the same site and at the same age; effect of age under a clone, submitted to the same site; effect of age under a clone, submitted to different sites; effect between sites for the same clone, submitted to the same age; general assessment of the groups, that is, when the highest values of G and V yields were obtained.

Results

Competition

The Alba-Péllico index performed better with higher correlation coefficient values with all variables tested in all clones: diameter, cross-sectional area, volume, mean distance and percentage of mortality and Hegyi and Moore *et al.* indices, at all ages (Table 1). The average behaviour of this index (Fig. 1) resulted in decreasing values with the increase of the area per tree, reaching values close to zero in areas with lower density. When analyzing the homogeneity of the correlation between the clones in the same NW, all analyses showed homogeneous correlation coefficients (p>0.05), indicating that they follow the same pattern between clones.

At all clones, the correlation between the Alba-Péllico index and the variables diameter, cross-sectional area and volume were significant, with values ranging from moderate to extraordinarily strong. The correlation of height with this new index was moderate to remarkably high (Table 3).

The Moore *et al.*´s index resulted in average values on a larger scale than the other indices tested. The interpretation of the indices in Fig. 1 is quite difficult. The scale for interpreting this index is presented on the right axis of the figure, ranging from 12 to 24. The Hegyi index exhibited the same behaviour as the Alba-Péllico index, that is, the lower the competition, the lower the value of the index (Table S1 [suppl]).

Clone competition and mortality multivariate analysis

As the results of the Alba-Péllico index were very satisfactory, it was used to evaluate clone competition. The values resulting from the Alba-Péllico index behaved in a decreasing way with the increase of the average area per tree in all studied clones, evidencing that in smaller available areas per tree the competition was higher (Fig. 2). Areas with higher tree densities contributed significantly to competition, consequently, sites with higher competition had the highest mortality rates (Fig. 3). Besides, a positive correlation ranging from moderate to extraordinarily strong was observed between the Alba-Péllico index and the percentage of mortality, showing that this was strongly influenced by density and competition.

At the age of three years, the clones presented distinct Alba-Péllico index values in the areas between 10 m² and 15 m² and remarkably close values at lower densities and a considerable increase in the percentage of mortality was observed. These results show that competition changes depend on the stage of stand development and the effects of interactions were detected between neighbouring trees in older stands, but not always observed in younger stands.

Differences in mortality rates in low dense spacings for the different clones suggest that factors beyond competition are playing a substantial role in these results. Specific

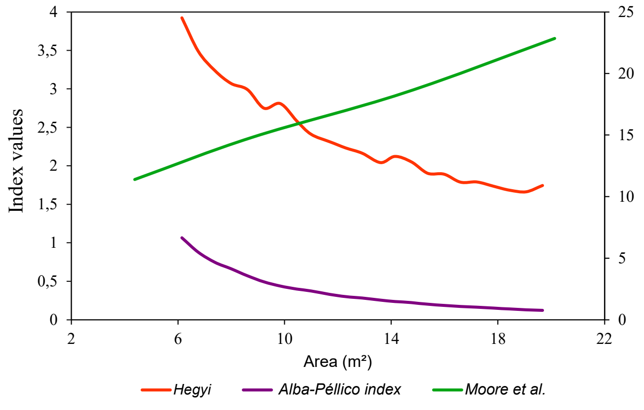

Figure 1. The average behaviour of the competition indices.

Table 3. Summary of multivariate analysis of variance for the basal area (G, in m² ha^{-1}) and volume (V, in m^3 ha^{-1}) variables

		G	V
	Pillai trace	2.538**	1.807**
Clones	Wilks Lambda	0.007**	0.79**
	Hotelling trace	17.231**	3.828**
	Roy's largest root	13.530**	1.761**

characteristics related to genetic material, such as adaptability to the site, resistance to climate events and phytosanitary characteristics also contribute to mortality.

The results of MANOVA, considering the evaluated variables, are presented in Table 3. They indicate that for all tests applied in MANOVA there were significant differences between the groups evaluated for the variables basal area and volume per hectare.

The comparison between the clones, regarding the effect within the same NW is shown in Table S2 [suppl]. The effect of age on the same clone in different locations is shown in Table S3 [suppl]. Table S4 [suppl] shows the relationship between basal area and volume and clones. Table S5 [suppl] shows the general assessment of the groups, in which greater productivity was obtained. All the evaluation was made for the results of centroid test.

With the results of the discriminant functions, we observed that 78.5% of the total variation for basal area among the clones is presented in the spacings above 16 m². For the volume, areas between 6 and 10 m² absorbed the greatest variation of the variable, 46% and areas

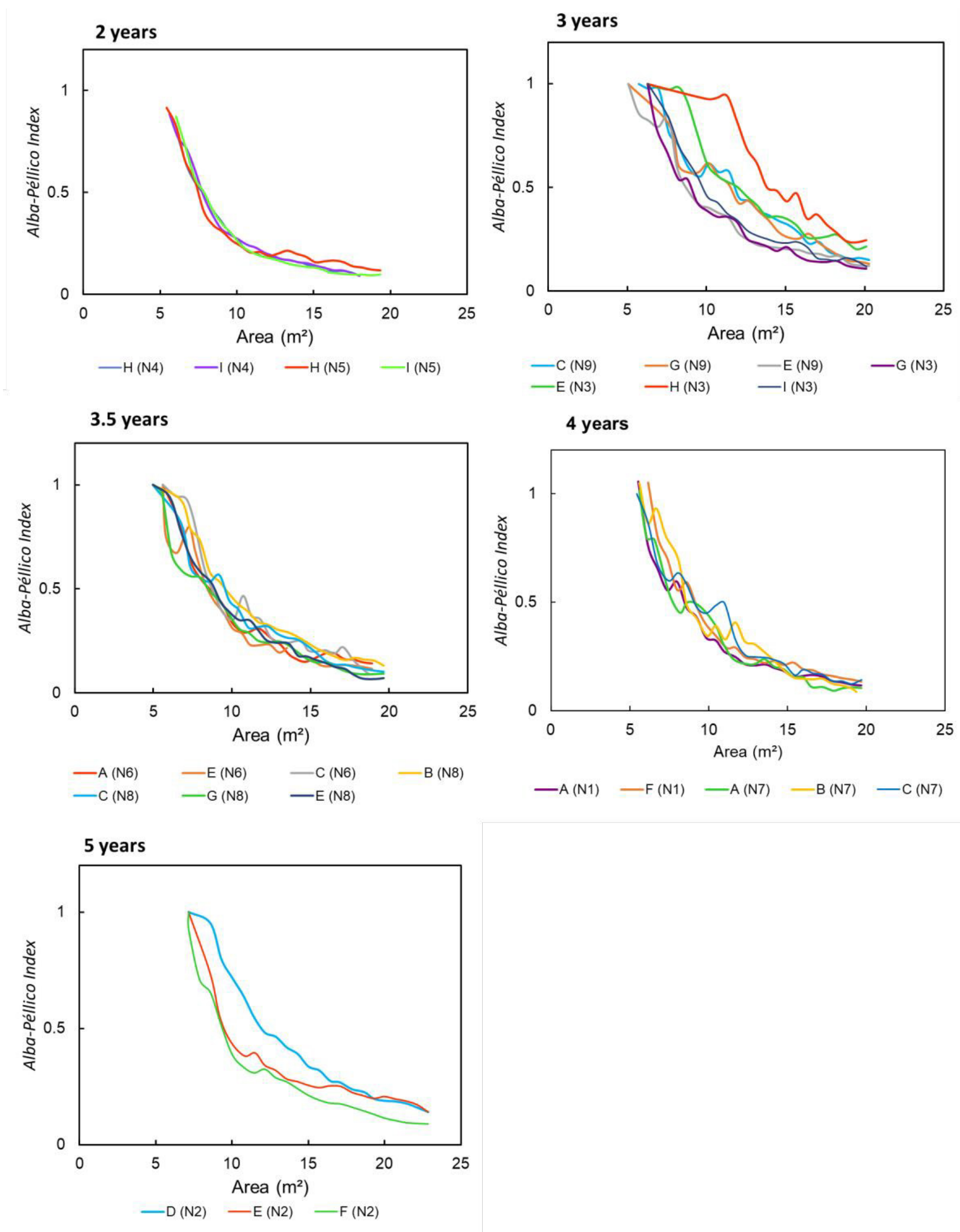

Figure 2. The behaviour of the competition index Alba-Péllico in Nelder wheels (NWs) with different eucalyptus clones (Table 1) and spaces in the state of Tocantins, Brazil.

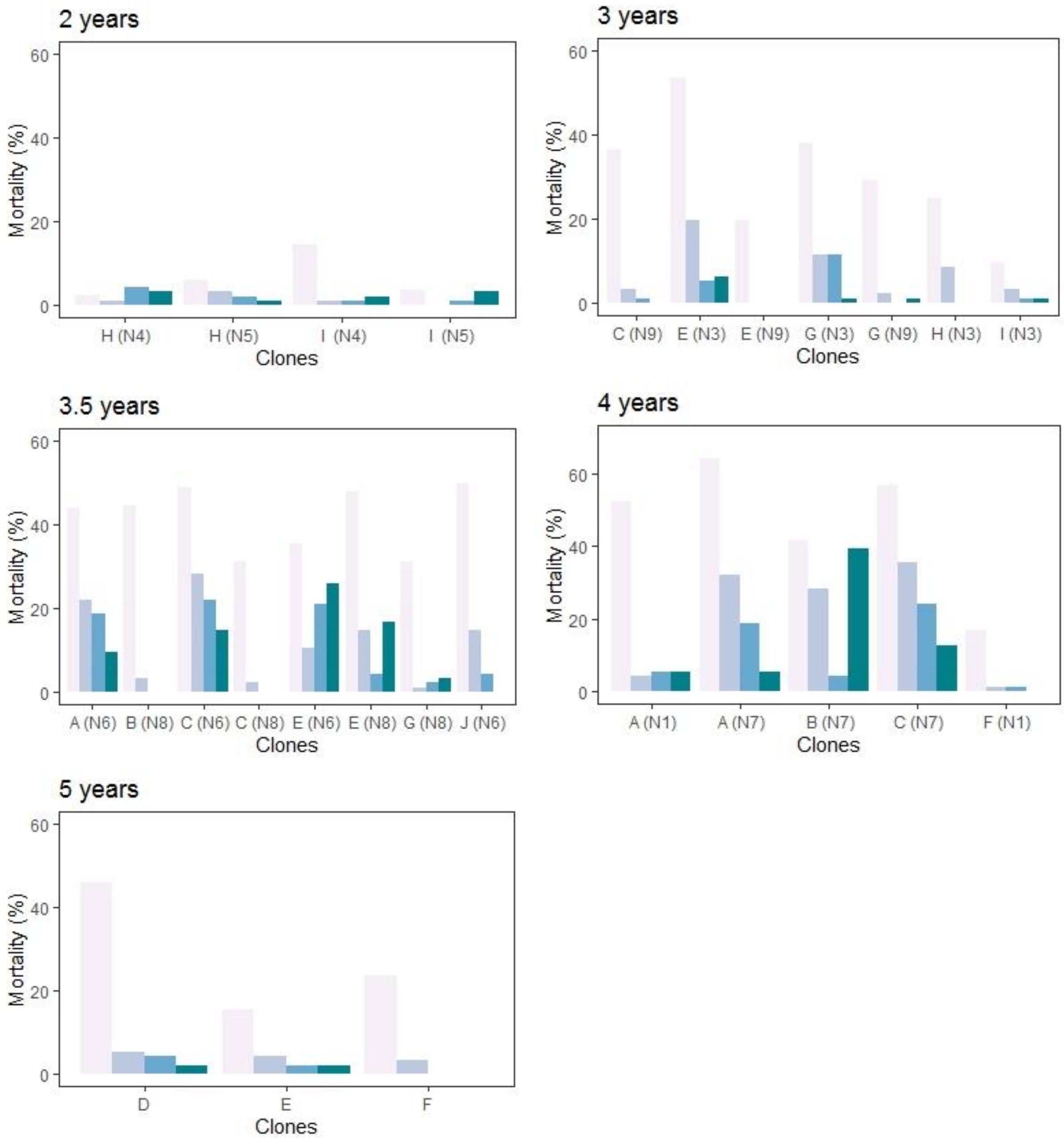

Figure 3. Percentage of mortality in ages two, three, three years and a half, four and five years, in NWs with different eucalyptus clones (Table 1) and spaces in the state of Tocantins, Brazil.

between 11 and 16 m² dissolved 28.7%. Note that the performance of the clones, for both G and V, was not defined by positions with more density, due to the high competition existing in this part of the NW.

Discussion

We have developed an index to evaluate the competition of trees in different tree densities. The Alba-Péllico index was calculated and analysed focusing on the spatial distribution structure of the trees and the relationship of growth between trees in different densities. An advantage of this index is that it considers the spatial distribution of neighbouring trees present in each sampling unit relative to a central sampling unit that represents the location with the more evidenced attribute of competition. Since all trees are equivalent competitors and the competitive intensity changes linearly with the distance and diameter of competitive neighbours (Hui *et al.*, 2018), we were able to ensure that the values of our competition index will vary in a standardized scale, *i.e* between 0 and 1, facilitating its interpretation. For the other indices tested, the competition varies in an undefined range, and this makes it difficult to compare the effect of competition in different conditions influencing the same species or for the same condition evaluated between species. Even so, it is difficult to understand the value of the index expressing the maximum competition, or even the intermediate situations. This was the main motivation for developing a competition index that varies over a specific range, as this would make it possible to overcome these problems. According to Tomé & Burkhart (1989), the proper interpretation of the relationships between neighbouring trees is essential to quantify the competition in a single mathematical expression.

The correlation analysis and graphical evaluation were enough to report the relationship of the indices with the variables and describe the behaviour of the indices in different spacing. Our results showed that the performance of the distance-dependent rates express that in denser locations there is more competition, and this decreases in locations with lower density. Corroborating these claims, Looney *et al.* (2018) mention that higher densities in the forest stand influence both tree productivity and size inequality, intensifying competition locally. Aakala *et al.* (2013) claim that the process of the spatial distribution of trees influences competition for nutrients, light, and water, which affect tree growth. Vettenranta (1999) considers knowledge of the spatial distribution of trees to be fundamental in the study of competition and suggests that there is no natural reason for the competition to decrease at a certain distance, but it is more realistic to suppose that competition decreases as the distance between a given competition tree and the reference tree increases. Daniels *et al.* (1984) reported that the best distance-dependent indices performed in slightly higher basal area growth models than the distance-independent indices for Pinus taeda L. plantations in northern Louisiana. Contreras *et al.* (2011) concluded that distance-dependent indices performed better than distance-independent indices in western Montana forests. Tenzin *et al.* (2017) observed results of a higher correlation between distance-dependent indices and growth in Bhutan forests.

The stability of the correlation between the Alba-Péllico index and the variables under study, for the variation of clones and locations, as evidenced by the test of homogeneity of the correlation coefficients. The correlation between this index and the studied variables was negative, indicating that the smaller the distance between trees and the smaller the values of diameter, height, basal area, and volume, the greater the competition, which corroborates the theory used for the development of the Alba-Péllico index, where the higher the value of the index, the lower the values of the tree variables, the greater the competition. The high correlation of this index with growth variables of different clones makes it possible to better express the performance in the competition evaluation, compared to traditional indices.

The fact that the Alba-Péllico index results in high correlations, even at early ages, was expected since the index was designed to be so. Even at an early age, the competitive effect exists in the centre-edge direction of the NW, gradually increasing with the effect of age. The Alba-Péllico index is based on a sampling unit located in the center of the NW and considers it a reference for the other units sampled, gradually moving away from the center towards its periphery. The strong influence of small spacing between diameters in the center of the NW, when the index reports the maximum value equal to one, develops inversely as the sampling is taken in positions away from this center. This reality is maintained equally in all NWs, irrespective of species, clones, or site.

Tree mortality is another crucial issue for the study of competition (Adame *et al.*, 2010), in which many studies have shown that there is a strong relation between tree mortality rate with competition and density among trees (Luo & Chen, 2011; Du *et al.*, 2017). This statement was strongly found in our study, where the results showed that for all NWs, in different experimental sites, the mortality rate was higher in the lower spacing, where the competition is greater. Besides, mortality rates at all clones presented the highest correlation values with the Alba-Péllico index introduced in this research. This characterizes it as a good index to explain mortality since indices are a direct measure, used to develop relationships between mortality and competition (Das *et al.*, 2011).

The multivariate analysis of variance and the discriminant analysis allowed us to observe the differences between the clones, spacing and locations of NWs. The variation in basal area between the clones in the less dense locations, verified with the use of discriminant analysis, substantiates the characteristics of each clone or possible interferences of the location since in this condition they are free from the influence of spacing and competition. This shows that competition is more influential than other characteristics of sites and genotypes in the behavior in diameter and basal area in the densest sites. The volume, which is obtained combining the variables diameter, height, and form factor, and these are influenced by the spacing, showed the biggest variations in the high-density positions.

The F Urocam hybrid clone (Table 1), with medium productivity and high resistance to drought, had a low percentage of mortality in both locations, NW 1 and 2, at the ages of four and five years. The characteristic of low productivity was well evidenced by the low values of basal area and volume per hectare, in comparison to the other clones in the same NW. Trees of the same clone and age when planted in NWs in different sites, the mortality rates, the basal area and volume per hectare did not follow the same pattern, for example, the E Urograndis hybrid clones, with characteristic of high productivity and medium drought resistance (clone E, Table 1). In this case, site-specific characteristics such as soil type and climatic conditions could affect the available resources, like water and essential nutrients, and can accelerate the process of competition and raise mortality rates (Jane *et al.*, 2016; Jiang *et al.*, 2018).

Thus, we affirm that productivity is highly influenced by the site and how the genotype interacts with it since the clones have different production capacities and different environmental resistance characteristics that affect mortality. As for competition, similar values were observed and the response of the clones' regarding competition is visible in denser spacing. Our results agree with Resende *et al.* (2018), who found that productivity was influenced by all variables, with site quality having the highest effect, environmental uniformity having an intermediate effect and competitive capacity having the lowest effect.

For local resources to be used more efficiently, as they directly affect productivity, it is important to understand the response of genotypes at different spacings and the competitive interaction between neighbouring trees (Resende *et al.*, 2018). With that, the Alba-Péllico index can be useful as an initial tool to evaluate the condition of the competition in different sites and different clones and to indicate appropriate silvicultural interventions. The Alba-Péllico index allows a view of the evolution between different sites; it can be an indicator of the density condition in the forest stand. The Alba-Péllico index indicates the scale of variation, therefore interpretation becomes easier for forest managers.

The flexibility of a competition index is restricted by several factors, including forest types, site conditions and the mathematical structure of the index. Following this statement, the Alba-Péllico index presents a relatively simple mathematical formulation, since it is composed only of the cross-sectional areas and distance variables, expressed by two ratios. Thus, it is a flexible and practical index to be applied in locations with different spacing, as in NWs. Future research may employ the methodology in other planted forests, provided that the spatial characteristics of the forests are considered to improve the Alba-Péllico index, with the necessary adaptations to obtain consistent results in each of the specific forest conditions.

In summary, the Alba-Péllico index applied in this research is appropriate to evaluate the competition of trees in different densities. Their characteristics indicate practical and interpretative gains to understand the competitive relationship among trees and can be used for decision making in forest management. The tendency for greater competition in the denser spacing was the same for the different *Eucalyptus* clones. However, the clones showed a difference in terms of the basal area and volume per hectare variables. In the wider spacing, free of competition, the genetic and local characteristics were better detectable for basal area. For volume, this variation was greater between moderate to light densities. The choice of the clone to be planted in the stands of the study region will depend on the objectives of planting. Clones with characteristics of medium productivity and high resistance to drought showed a low percentage of mortality, but low productivity in basal area and volume per hectare, for example, the clone F Urocam Hybrid. Clones with high productivity characteristics, however, followed this characteristic, despite showing a high percentage of mortality. Clones with characteristics of medium resistance to drought and high productivity are the most suitable for the region under study, as they presented good productivity and an average mortality percentage, for example, clone A, E and C, Urograndis hybrids.

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