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ARTICLE

A novel approach to selecting a competition index: the effect of competition on individual-tree diameter growth of Calabrian pine

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Abstract: In this study, we evaluated the performance of 18 competition indices composed of nine distance-dependent and nine distance-independent indices in explaining the variation in individual-tree diameter growth of Calabrian pine (*Pinus brutia* Ten.) in the central Mediterranean region of Turkey. The data were obtained from 432 sample plots with varying stand age, site index, and stand density. To evaluate the performance of each competition index, the mean square error reduction approach was used relative to the noncompetition. Also, this study compared fixed and mixed effects models to analyze diameter growth. Statistical analyses showed that the best distance-independent competition indices performed as well as the best distance-dependent competition indices. The distance-independent competition index of Schröder and Gadow (1999; Can. J. For. Res. **29**(2): 280–283, doi:10.1139/x98-199) performed best and is recommended for use in future growth and yield models to be used in the central Mediterranean region of Turkey. Also, the best selection of competitive neighbors was achieved using the area of influence overlap method, whereas the fixed-radius and angle count sampling methods had no significant improvement in quantifying the competition effects. On the other hand, all mixed effects models provided much better fits than their fixed model counterparts.

Key words: diameter growth, competition indices, selection of competitor, fixed and mixed models, Calabrian pine.

Résumé : Dans cette étude, nous évaluons la performance de 18 indices de compétition, comprenant neuf indices dépendants des distances et neuf indices indépendants des distances, pour expliquer la variation de la croissance en diamètre d'individus de pin de Calabre (*Pinus brutia* Ten.) dans la région méditerranéenne centrale de la Turquie. Les données ont été obtenues de 432 placettes échantillons couvrant une gamme d'âge du peuplement, d'indice de qualité de station et de densité du peuplement. Pour évaluer la performance de chaque indice de compétition, nous avons utilisé l'approche de la réduction de l'erreur quadratique moyenne par rapport à l'absence de compétition. De plus, cette étude compare des modèles à effets fixes et mixtes pour analyser la croissance en diamètre. Les analyses statistiques montrent que les meilleurs indices de compétition indépendants des distances sont aussi performants que les meilleurs indices dépendants des distances. L'indice de compétition indépendant des distances de Schröder et Gadow (1999; Can. J. For. Res. **29**(2): 280–283, doi:10.1139/x98-199) est le plus performant et son utilisation est recommandée pour les futurs modèles de croissance et de production qui seront utilisés dans la région méditerranéenne centrale de la Turquie. De plus, la meilleure sélection des arbres voisins concurrents a été réalisée à l'aide la méthode de chevauchement de l'aire d'influence alors que les méthodes à rayon fixe et par balayage sous angle constant n'ont pas significativement amélioré la quantification des effets de compétition. Par ailleurs, tous les modèles à effets mixtes ont produit de bien meilleurs ajustements que les modèles à effets fixes équivalents. [Traduit par la Rédaction]

Mots-clés : croissance en diamètre, indices de compétition, sélection du compétiteur, modèles à effets fixes et mixtes, pin de Calabre.

Introduction

Competition indices are the numerical expression of the degree of use of the growth potential limited by the genotype of a tree species (Pretzcsh 2009). The success of a competition index varies depending on tree species, available data, and, in particular, the structure of the selected model (Tomé and Burkhart 1989; Biging and Dobbertin 1995). Competition indices are divided into two groups: distance-independent (Wykoff et al. 1982; Lorimer 1983; Schröder and Gadow 1999) and distance-dependent (Bella 1971; Hegyi 1974; Alemdağ 1978; Martin and Ek 1984; Burkhart and Tomé 2012). Distance-independent competition indices do not require the knowledge of tree coordinates and the distance between trees because they are functions of the general parameters at the stand level or the initial dimensions of the subject tree. Distance-dependent competition indices are calculated as functions of the initial dimensions of the subject tree and the distance and dimensions of the neighboring competitor trees.

Distance-independent competition indices can be considered more advantageous compared with distance-dependent competition indices as they require less data and are easier to calculate (Corral Rivas et al. 2005). Conceptually, distance-dependent competition indices are expected to perform better than the distance-independent competition indices, and several studies have supported this expectation (Martin and Ek 1984; Wimberly and Bare 1996; Contreras et al. 2011; Maleki et al. 2015; Tenzin et al. 2017); however, some researchers have reported that there was no significant difference between the model successes of the two

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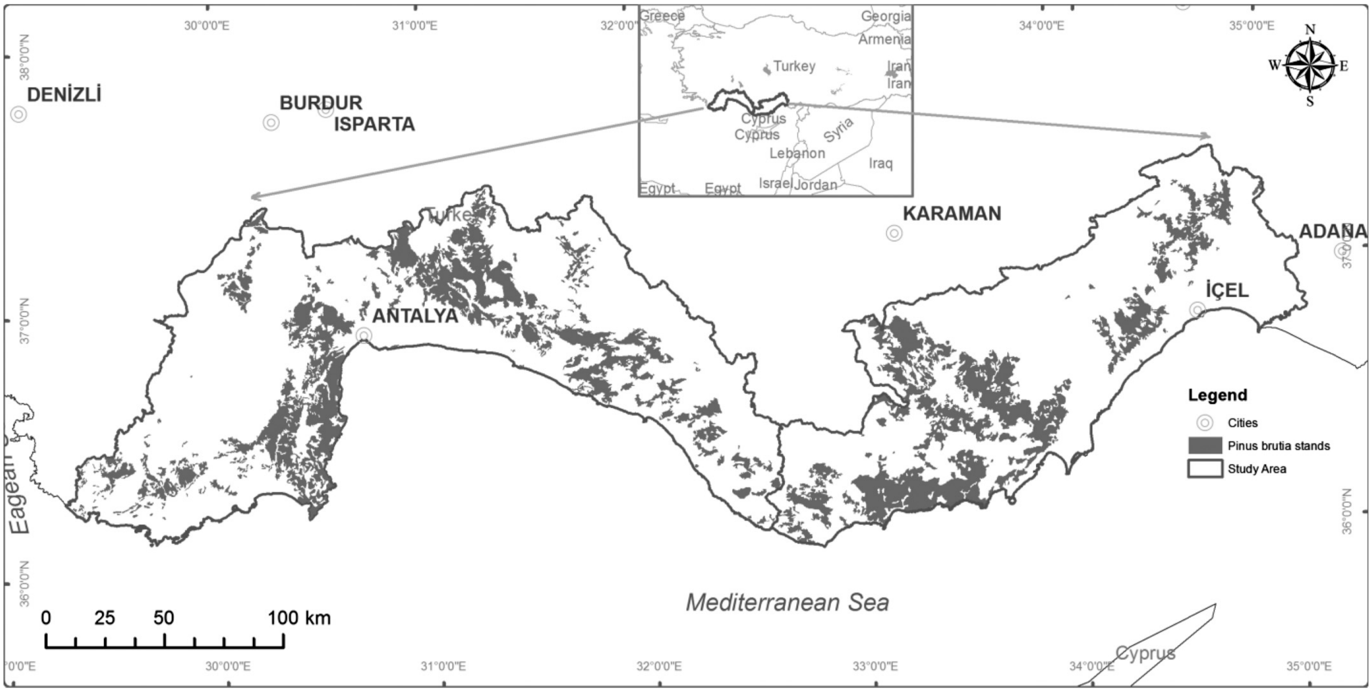
Fig. 1. The study area from which 432 sampling points were taken within the Calabrian pine stands.



types of indices (Lorimer 1983; DeBell et al. 1997; Özkaynak 2003; Corral Rivas et al. 2005; Ledermann 2010; Sharma et al. 2016). The inability to accurately determine the competitor trees or the insufficiency of the selected model is proposed as the reason for the lack of significant difference (Prévosto et al. 2000). In fact, some researchers have determined that the distance-independent competition indices yield a little more successful results (Biging and Dobbertin 1995; Schröder et al. 2007; Kaya 2013; Śmigielski et al. 2017; Bérubé-Deschênes et al. 2017). On the other hand, distance-dependent competition indices are more appropriate for natural stands, whereas distance-independent competition indices are used for afforestation sites (Prévosto et al. 2000).

Competition indices are generally used as an explanatory variable in individual-tree yield models as competition among trees contributes significantly to the determination of growth relationships. The contribution of the competition index in these models is to put forward the competition status of the subject tree in relation to the neighboring competitor trees (Radtke et al. 2003). Competition among trees depends on tree species, size of the tree (diameter, height, crown width, etc.), size and location of the neighboring trees, and therefore stand conditions. Numerous numerical or theoretical competition indices, the first of which was defined by Staebler in 1951 and produced useful results in individual-tree yield studies, have been developed (Staebler 1951; Newnham 1966; Gerrard 1969; Bella 1971; Hegyi 1974; Sun 1977; Alemdağ 1978; Arney 1973; Wykoff et al. 1982; Lorimer 1983; Martin and Ek 1984; Hamilton 1986; Tomé and Burkhart 1989; Corona and Ferrara 1989; Nagel 1999; Schröder and Gadow 1999). It becomes rather challenging to determine the optimal competition index because the success of the competition index, which is a numerical expression of the competition among trees, will change as a result of stand conditions. Therefore, it has not been possible to formulate the optimal competition index for all tree species in various yield studies conducted so far (Pretzcsh 2009).

Calabrian pine (*Pinus brutia* Ten.) is one of the primary forest tree species of Turkey based on its range, growth and yield properties, and the economical revenue that it generates. The reason for selecting Calabrian pine as the tree species in this study is based on the fact that it covers wide sections of our country's forested areas (approximately 5.61 million ha and 27% of the total forest area) and is a characteristic natural tree species (General Directorate of Forestry 2015). Therefore, it is possible to use the results of the study in practice.

In this study, our objectives were to (*i*) determine the contribution of competition indices to estimating diameter growth, (*ii*) compare the performance of distance-dependent and distance-independent competition indices, (*iii*) compare the successes of some competitor selection methods used, (*iv*) compare fits and predictions with fixed and mixed effects models, and (*v*) estimate the diameter increment with the model used to determine the most successful competition index. Data collected from natural and even-aged Calabrian pine stands located in the central Mediterranean region of Turkey (Antalya and Mersin provinces) were used to realize these objectives.

Material and methods

Study area and data

The study area covers the even-aged, pure natural Calabrian pine stands of the central Mediterranean region (Antalya and Mersin provinces, 36°00′N–37°30′N, 29°20′E–35°00′E) of Turkey (Euforgen 2009; Kahriman et al. 2016) (Fig. 1). Temperatures range from 10 °C to 25 °C, with the lowest temperatures ranging from 4 °C to −11 °C and the maximum temperature reaching 45 °C in the distribution zones of the Calabrian pine stands used in the study. Total annual rainfall varies from 400 to 2000 mm (with uneven distribution of rainfall over a year), and relative humidity ranges from 60% to 70%. The climatic regime is a typical Mediterranean climate, characterized by a mild and rainy winter and a hot and dry summer. The elevation of the study area varied from 79 to 1473 m ($\overline{X}$ = 579.0 m), and the slope ranged between 2% and 120% ($\overline{X}$ = 38.9%).

The data were obtained from 432 circular sample plots with a range of stand ages, site index, and percent density. The sizes of the sample plots in the study varied between 400 m^2 and 2000 m^2 depending on stand structure. Azimuth angle, distance from plot center (for *X* and *Y* coordinates (m)), diameter at breast height (cm), total height (m), average crown width at the base of the live crown (m), and crown base height (m) of each tree (totaling 15 845) in 432 sample plots were measured. Additionally, the last 5-year radial growth (mm) and double bark thickness (mm) of 6417 trees and age (year) of 4092 trees were measured. The trees measured for radial growth over the last 5 years at each site were randomly selected from each of the following crown classes: dominant, co-dominant, intermediate, and suppressed trees. Then, for every tree, crown length (CL) was calculated in the sample plots. The CL was obtained by subtracting the crown base height from the top height.

Diameter at breast height (DBH) 5 years ago (diameter at the beginning of the period) was calculated by taking the difference between DBH without bark at the end of the period and the 5-year diameter growth value without bark and multiplying the difference by the bark factor value calculated from the DBH without bark. Thus, diameter growth for the next 5 years was predicted as a function of the diameter value at the beginning of the period. Also, stand density was calculated based on the beginning of the growth period.

Variables including quadratic mean diameter ($\bar{d}_q$), mean height ($\bar{h}_q$), stem number per hectare (N), basal area (BA), stand age (t), site index (SI), and stand density (relative stand density, SD) were also calculated for each plot to establish diameter growth models. The site index of the Calabrian pine stands investigated in this study was developed by Kahriman et al. (2016) using the Hossfeld model. Relative density index, which was developed by Curtis et al. (1982), was used to estimate SD according to the following formula:

$$(1) \qquad SD = BA/\sqrt{\bar{d}_q}$$

where BA (m²·ha⁻¹) and $\bar{d}_q$ (cm) are as defined above.

Descriptive statistics including mean, minimum, maximum, and standard deviation of tree components such as 5-year diameter growth (i_{d5}), diameter at breast height (DBH) 5 years ago, double bark thickness (DBT), total height (h), crown width (CW), and crown length (CL), of plot characteristics such as stand age (t), site index (SI), stand density (SD), stand basal area (BA), quadratic mean diameter ($\bar{d}_q$), mean height ($\bar{h}_q$), and relative spacing index (RS), and of 18 competition indices are listed in Table 1.

Table 1. The descriptive statistics of tree components, plot characteristics, and competition indices.

Variables	Minimum	Mean	Maximum
i_{d5} (mm)	0.40	3.01	15.60
DBH (cm)	4.00	28.01	97.40
DBT (mm)	10.42	56.14	140.00
h (m)	3.00	15.74	34.00
CL (m)	1.00	7.31	22.80
CW (m)	1.00	5.97	15.90
$\bar{d}_q$ (cm)	7.18	28.36	61.78
$\bar{h}_q$ (m)	4.80	15.85	31.20
BA (m²·ha⁻¹)	3.76	29.15	69.90
N (no.·ha⁻¹)	80.00	542.07	2 300.00
T (year)	13.17	55.48	134.83
SI (m)	8.47	21.46	33.84
SD	0.96	5.37	12.36
RS	0.13	0.28	1.00
CI_1	0.00	17.47	69.87
CI_2	53.54	538.35	3 768.55
CI_3	0.16	0.99	2.38
CI_4	0.12	0.66	1.00
CI_5	0.03	1.04	5.66
CI_6	0.01	0.47	1.00
CI_7	38.58	658.34	12 119.64
CI_8	0.92	3.80	7.97
CI_9	88.36	7 960.37	58 343.45
CI_{10}	0.01	23.11	448.34
CI_{11}	0.11	1.94	61.92
CI_{12}	0.00	0.18	7.02
CI_{13}	0.00	0.17	11.34
CI_{14}	100.00	522.30	3 106.54
CI_{15}	0.08	9.03	324.95
CI_{16}	0.01	2.18	161.43
CI_{17}	0.16	8.28	132.73
CI_{18}	0.24	4.92	63.13

Competition indices and their evaluation

A total of 18 competition indices (nine distance-independent and nine distance-dependent types) to be used in this study were selected based on a literature search (Table 2).

The relative spacing index (RS) of a given plot was calculated using the following formula:

$$(2) \qquad RS = \frac{\sqrt{10000/N}}{H_{Dom}}$$

where 10 000 represents the plot area (m²), N is the number of trees in the plot, and H_{Dom} is the stand dominant height (m) (mean height of the 100 thickest trees per hectare).

It may not be possible to determine the relationship of a tree with its neighbors directly if its location within the stand is not identified. In this case, the only way to calculate the competition indices among trees is to compare the size of the subject tree with the sizes of all other trees within the stand. There are different approaches used to calculate the distance-independent competition indices (Tomé and Burkhart 1989; Pretzcsh 2009). The approaches used in the nine distance-independent competition indices tested in this study (Table 2) can be summarized as follows: (*i*) the sum of the basal areas of the trees with greater diameters than the subject tree is considered the competition index (CI_1 (BAL); Wykoff et al. 1982); (*ii*) the ratio of the sum of the breast height diameters of neighboring trees in the plot to the breast height diameter of the subject tree (CI_2; Lorimer 1983); (*iii*) and (*iv*) the ratio of the diameter of the subject tree to the quadratic mean diameter (CI_3; Hamilton 1986) and to the diameter of the tree with the greatest diameter (CI_4; Tomé and Burkhart 1989); (*v*) and (*vi*) the ratio of the basal area of the subject tree to the mean basal area of the stand (CI_5; Tomé and Burkhart 1989) and to the basal area of the tree with the largest diameter in the stand (CI_6; Tomé and Burkhart 1989); (*vii*) the ratio of the sum of the basal areas of the neighboring trees in the plot to the basal area of the subject tree (CI_7; Corona and Ferrara 1989); (*viii*) the ratio of competition index number 7 to the relative spacing index (RS) (CI_8 (BALMOD); Schröder and Gadow 1999); and (*ix*) the sum of the crown projection areas of all trees in the stand at 66% height of the live crown length of the subject tree (CI_9; Latham et al. 1998; Nagel 1999). The decrease in the values of distance-independent competition indices CI_1, CI_7, CI_8, and CI_9 indicates that the subject tree has a competitive advantage or it has approached free growth. The increase in the values of the remaining five distance-independent competition indices (CI_2–CI_6) indicates that the subject tree has approached free growth. In this case, the subject tree can reach the maximum yield enabled by its genotype potential and the growth medium.

In this study, two approaches to quantify the level of competition in distance-dependent competition indices were assessed: influence-zone overlap indices or crown-area overlap indices and size-ratio indices or distance-weighted size ratio. The five competition indices in Table 2 (CI_{10}–CI_{14}) (Staebler 1951; Newnham 1966; Gerrard 1969; Bella 1971; Arney 1973) are termed as influence-zone overlap indices. In this first group of indices, the growth zone of a tree is assumed to be circular and is named the "influence zone". In this method, it is assumed that the horizontal circle surrounding the subject tree represents the active competition zone and

Table 2. The list of competition indices tested to be used in the tree diameter growth model.

Source	Competition index
Distance-independent competition indices	
Wykoff et al. (1982)	$\mathrm{CI}_1 = \mathrm{BAL}_i = \left(\sum_{d_i<d_j}^{n} g_i\right) \Big/ S$
Lorimer (1983)	$\mathrm{CI}_2 = \left[\left(\sum_{j\neq i}^{n} d_j\right) \Big/ d_i\right] \Big/ S$
Hamilton (1986)	$\mathrm{CI}_3 = \dfrac{d_i}{d_g}$
Tomé and Burkhart (1989)	$\mathrm{CI}_4 = \dfrac{d_i}{d_{\max}}$
Tomé and Burkhart (1989)	$\mathrm{CI}_5 = \dfrac{g_i}{\bar{g}}$
Tomé and Burkhart (1989)	$\mathrm{CI}_6 = \dfrac{g_i}{g_{\max}}$
Corona and Ferrara (1989)	$\mathrm{CI}_7 = \left[\left(\sum_{j\neq i}^{n} g_j\right) \Big/ g_i\right] \Big/ S$
Schröder and Gadow (1999)	$\mathrm{CI}_8 = \left[\left(\sum_{d_i<d_j}^{n} g_j\right) \Big/ G\right] \Big/ \mathrm{RS}$
Nagel (1999)	$\mathrm{CI}_9 = \left(\sum_{1}^{n} \mathrm{hca}_{j(\mathrm{HWCW}_i)}\right) \Big/ S$
Distance-dependent competition indices	
Staebler (1951)	$\mathrm{CI}_{10} = \sum_{j=1}^{n}\left(\dfrac{\mathrm{OL}_{ij} \times \mathrm{CR}_i}{2}\right)$
Newnham (1966)	$\mathrm{CI}_{11} = \dfrac{1}{2\pi}\sum_{j=1}^{n}\theta_{ij}$
Gerrard (1969)	$\mathrm{CI}_{12} = \dfrac{1}{Z_i}\sum_{j=1}^{n} O_{ij}$
Bella (1971)	$\mathrm{CI}_{13} = \sum_{j=1}^{n}\left(\dfrac{O_{ij}}{Z_i}\right)\left(\dfrac{d_j}{d_i}\right)^{\mathrm{EX}}$
Arney (1973)	$\mathrm{CI}_{14} = \left\{\left[\sum_{j=1}^{n}(O_{ij} + Z_j)\right] \Big/ Z_i\right\} \times 100$
Hegyi (1974)	$\mathrm{CI}_{15} = \sum_{j=1}^{n}\left(\dfrac{d_j}{d_i} \times \dfrac{1}{L_{ij}}\right)$
Sun (1977)	$\mathrm{CI}_{16} = \sum_{j=1}^{n}\left(\dfrac{\mathrm{ca}_i}{\mathrm{ca}_j} \times \dfrac{d_j}{d_i} \times \dfrac{1}{L_{ij}}\right)$
Alemdağ (1978)	$\mathrm{CI}_{17} = \sum_{j=1}^{n}\left\{\pi\left(\dfrac{L_{ij} \times d_i}{d_i + d_j}\right)^2\left[\dfrac{d_j/L_{ij}}{\sum(d_j/L_{ij})}\right]\right\}$
Martin and Ek (1984)	$\mathrm{CI}_{18} = \sum_{j=1}^{n}\left(\dfrac{d_j}{d_i}\right) \times \mathrm{e}^{(16\times L_{ij})/(d_i+d_j)}$

Note: CI_1, CI_2, …, CI_{18}, competition indices; *i*, subject tree; *j*, competitor tree; d_i, subject tree diameter at breast height (cm); d_j, competitor tree diameter at breast height (cm); g_i, basal area of subject tree (m²·ha⁻¹); BAL_i, basal area of trees larger than the subject tree (m²·ha⁻¹); *S*, plot area (ha); d_g, quadratic mean diameter (cm); $d_{\max}$, maximum diameter at breast height in the sample plot; $\bar{g}$, mean basal area of sample plot (m²·ha⁻¹); $g_{\max}$, basal area of the thickest diameter in the sample plot (m²·ha⁻¹); g_j, basal area of competitor tree (m²·ha⁻¹); *G*, basal area of the trees within the plot (m²·ha⁻¹); RS, relative spacing index of plot; hca_j, tree horizontal crown area (m²); HWCW_i, height of greatest crown width in 66% of subject tree height (m); OL_{ij}, distance of crown projection overlap between subject tree *i* and competitor tree *j* (m); CR_i, crown radius of subject tree *i* (m); L_{ij}, distance of subject tree *i* to competitor *j* (m); ca_i, crown area of subject tree *i* (m²); ca_j, crown area of competitor tree *j* (m²); θ_{ij}, the interior angle subtended for tree *i*'s circle by competitor *j*'s overlap zone (in radians); O_{ij}, crown overlap between the neighbour tree *j* and the subject tree *i* (m²); Z_i, the area of influence zone of subject tree (m²); EX, exponential factor (in this study EX = 1); Z_j, the area of influence zone of competitor tree *j* (m²).

that competition takes place in the areas where the subject tree and the neighboring trees intersect or overlap. The center of the influence zone is taken as the axis of the subject tree, and the diameter of the influence zone is taken as the crown width of the subject tree or the crown width of the tree growing in a competition-free fashion, which has the same DBH as the subject tree (Corral Rivas et al. 2005). The last four indices in Table 2 (CI_{15} (Hegyi 1974); CI_{16} (Sun 1977); CI_{17} (Alemdağ 1978); CI_{18} (Martin and Ek 1984)) are called size-ratio indices. In this second group of indices, the competition index is calculated as the sum of distance-weight ratios of the competitor trees. Size-ratio indices are calculated as the sum of the ratios of the dimensions (e.g., DBH, tree height, and basal area) of the subject tree to the dimensions of the competitor trees and are commonly weighted by the distance of the subject tree to its competitors. These indices are based on the hypothesis that the competitive influence of a neighboring tree increases with increasing dimensions and decreasing distance. Competitor trees are assumed to be the ones falling in the circle with a fixed radius or the certain number of trees (e.g., 4 and 8) that are closest to the subject tree.

The most challenging issue in the formulation of distance-dependent competition indices is the determination of the neighboring border because a small tree nearby and a large tree further away can have the same degree of influence on the growth of the subject tree. Distance-dependent competition indices directly or indirectly consider the size of the neighbors and the distance between them and the subject tree. The most common approaches used to select the neighboring competitor trees in terms of determining the neighboring border (competitor selection methods) can be listed as the fixed-radius method, crown overlap method, angle count sampling method, and vertical search cone method (Pretzcsh 2009; Burkhart and Tomé 2012).

In this study, the competitor neighbor trees were selected by four different approaches. The first approach (M1) used the crown overlap method (the crown overlap influence-zone method), the next two (M2–M3) used the fixed-radius method, and the last one (M4) used the angle count sampling method. M1 takes the area of influence overlap approach first proposed by Staebler (1951) as the basis. The potential area of influence of a tree is generally defined as the circle with a fixed radius (the crown radius of the subject tree) around the subject tree. Competition is said to take place when the crown areas of the subject and competitor trees overlap (Corral Rivas et al. 2005). M2 considers the influence-zone radius to be 40% of the mean height of each plot ($\mathrm{CZR}_{0.4h}$) (Sims et al. 2009). In M3, the zone of influence is calculated using the equation below proposed by Lee and Gadow (1997). The influence-zone radius is determined based on the number of trees in each plot. If the diameters of the trees within the influence zone are 30% ($d_j \geq 0.3d_i$, where d_j and d_i are the diameters of the competitor and subject trees, respectively) or thicker than the diameter of the subject tree, they are considered the active competitor trees (Maleki et al. 2015).

$$\text{(3)} \qquad \text{CZR}_k = k \times \sqrt{1000/N}$$

where CZR_k represents the dynamic radius (the radius of the influence zone), N is the number of trees per hectare, and k is a constant ($k = 2$ in this study).

If M4, the angle count sampling (Bitterlich) method, is used to identify the competitor trees, then the distances and the diameters of the competitors are taken into account. A tree was considered a competitor if its distance to the subject tree (dist_{ij}) was

$$\text{(4)} \qquad \text{dist}_{ij} \leq d_i \times \frac{50}{\sqrt{\text{BAF}}}$$

where d_i is the diameter of subject tree i, BAF is basal area factor, dist_{ij} is the distance between subject tree i and neighbor tree j, and $50/\sqrt{\text{BAF}}$ is a factor for the control of boundary trees. The boundary distances, up to which a tree is regarded as a competitor, for the most frequently used angle count factors BAF = 1, 2, and 4 are $d_i \times 50.00$, $d_i \times 35.36$, and $d_i \times 25.00$, respectively. In this study, the BAF factor was taken as 4 ($d_i \times 25.00$) (Lorimer 1983; Tomé and Burkhart 1989; Pretzcsh 2009).

In this study, when the four different competitor selection methods and 18 different competition indices were considered together, 30 combinations were assessed to manifest the change in diameter growth. Nine of these combinations were distance-independent competition indices (CI_1–CI_9), five were distance-dependent indices calculated only by the influence-zone overlap approach (CI_{10}–CI_{14}), and 16 were the combinations of the last four competition indices (CI_{15}–CI_{18}) with four different competitor selection methods.

Individual-tree diameter growth models

Individual-tree diameter growth depends on a number of factors such as genetic characteristics, DBH, height, age, crown size (e.g., crown width, crown length), competition indices, site index, stand density, stand age, and stem number per hectare (Sterba et al. 2002).

Two different diameter growth models were applied in this study: a reduced model and a complete model. The reduced model (eq. 5) is developed as a control to determine the change in diameter growth of individual trees without taking into account competition. This model is based on the hypothesis that individual-tree diameter growth (i_{d5}) is a function of the diameter at breast height at the beginning of the growth period, stand age, site index, stand density, and stand basal area. The complete model (eq. 6) is similar to the reduced model but considers the contribution of the competition index as a new variable. In other words, eq. 6 reveals the amount of contribution of the competition index to the diameter growth model in eq. 5.

$$\text{(5)} \qquad i_{\text{d5}} = b_0 + \frac{b_1}{(\text{DBH}^2)} + b_2(\text{SI}) + b_3(\ln t) + b_4\left(\frac{t \cdot \text{SD}}{\text{SI}}\right) + b_5(\ln \text{BA})$$

$$\text{(6)} \qquad i_{\text{d5}} = b_0 + \frac{b_1}{(\text{DBH}^2)} + b_2(\text{SI}) + b_3(\ln t) + b_4\left(\frac{t \cdot \text{SD}}{\text{SI}}\right) + b_5(\ln \text{BA}) + b_6(\text{CI})$$

where i_{d5} is the 5-year diameter growth, DBH is the diameter at breast height 5 years ago, t is the stand age, SI is the site index, SD is stand density, BA is stand basal area, and CI is the competition index.

This study developed fixed and mixed effects models to analyze diameter growth. First, we constructed a nonlinear multiple regression model between i_{d5} (cm) and some predictor variables that influence diameter growth. The estimation of the parameters of these diameter growth models was done with the PROC MODEL procedure available in SAS/STAT® 9.3 software (SAS Institute Inc. 2013). The goodness of fit of the regression models was determined using the adjusted coefficient of determination (R^2_{adj}), root mean square error (RMSE), Akaike's information criterion (AIC), and Schwarz's Bayesian information criterion (BIC). It is desired that R^2_{adj} be close to 1 and RMSE, AIC, and BIC values be low.

$$\text{(7)} \qquad R^2_{\text{adj}} = 1 - \frac{(n-1)\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{(n-p)\sum_{i=1}^{n}(y_i - \bar{y}_i)^2}$$

$$\text{(8)} \qquad \text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n-p}}$$

$$\text{(9)} \qquad \text{AIC} = -2\ln(L) + 2k$$

$$\text{(10)} \qquad \text{BIC} = -2\ln(L) + k \cdot \ln(n)$$

where n is the number of observations; p is the number of parameters; y_i, $\hat{y}_i$, and $\bar{y}$ are observed, predicted, and mean values of the dependent variable, respectively; L is the maximum of the likelihood; and k is number of parameters in the model including the error term.

If models are fitted to datasets that contain spatial and temporal autocorrelation using the ordinary least squares technique, biased standard errors of parameter estimates are produced (Littell et al. 2006). In this study, radial growth data of the last 5 years were obtained from a total of 432 temporary sample plots. In such data structures, the problem of "autocorrelation", also known as "serial correlation," may be observed, which means that different items of data are dependent on each other (Leites and Robinson 2004). To account for such serial correlations, the mixed effects approach has been widely recommended in diameter growth modelling, as this enables modeling of the variance–covariance matrix structure (Calama and Montero 2005; Littell et al. 2006; Weiskittel et al. 2007). The equation structure of the nonlinear mixed effects model (Pinheiro and Bates 2000) is

$$\text{(11)} \qquad \mathbf{Y}_i = f(\Phi_i, \mathbf{X}_i) + \varepsilon_i$$

Here, $\mathbf{Y_i}$ is the response vector for diameter increment measurements; $\mathbf{X_i}$ is the predictor vector for diameter increment measurements on sample plot i; Φ_i represents the parameter values of the nonlinear model ($\Phi_i = \mathbf{A}_i b + \mathbf{B}_i u_i$), where b represents fixed effects parameters with design matrix $\mathbf{A}_i$, $\mathbf{B}_i$ is the random effects design matrix for sample plot i, and u_i represents the sample plot level random effects (u_{i1}, u_{i2}) for sample plot i, which is assumed to have multivariate normal distribution with zero mean and variance–covariance matrix $\mathbf{D}$ ($u_i \sim \text{N}(0, \mathbf{D})$); and ε_i represents the model errors ($\varepsilon_i \sim \text{N}(0, \mathbf{R})$), which is normally distributed with zero mean and within sample plot variance–covariance matrix $\mathbf{R}_i$, which is obtained by the equation $\mathbf{R} = \sigma^2\mathbf{G}_i^{0.5}\mathbf{\Gamma}_i\mathbf{G}_i^{0.5}$, in which σ^2 is the residual variance common to all sample plots, $\mathbf{G}_i$ is the diagonal matrix that explains the variance of within sample plot heteroscedasticity, and $\mathbf{\Gamma}_i$ is the matrix that accounts for the within sample plot autocorrelation structure of the errors.

The mixed-effects model was estimated with maximum likelihood in SAS macro NLINMIX (SAS Institute Inc. 2013). The estimated mixed models were evaluated using RMSE, AIC, and BIC.

A partial F test was used to test whether there was a significant contribution of competition indices to the complete model. In other words, the statistical significance of the inclusion of the competition index in the reduced model (eq. 5) as shown in eq. 6 was tested using the following formula:

$$(12) \qquad F^* = \frac{(SSE_R - SSE_F)/(df_R - df_F)}{(SSE_F)/(df_F)}$$

where F^* represents an F distribution, SSE_R and SSE_F represent the error sum of squares of the reduced and full models, respectively, and df_R and df_F represent the error degrees of freedom of the reduced and full models, respectively.

In addition, the performance of each competition index and its contribution to the growth model were assessed by the mean square error reduction (MSER). Namely, MSER was calculated according to the formula below to assess the performance of a model with a competition index in comparison with a model without a competition index:

$$(13) \qquad MSER = \left(1 - \frac{MSE_6}{MSE_5}\right)100$$

where MSE_5 and MSE_6 are the mean square errors of reduced (model 5) and complete (model 6) models, respectively.

Results and discussion

The success of the competition indices was determined by both fixed and random effects diameter growth models. For fixed models, incorporating one random (b_1) parameter produced the best fits. Including more than one random parameter either produced failed model convergence or nonsignificant parameters at a significance level of 0.05 for some variance and covariance parameters and fixed parameters.

In this study, four competition indices calculated only based on size-ratio approach (CI_{15}–CI_{18}) were assessed according to four different competitor selection methods. The other 14 competition indices (CI_1–CI_{14}) were calculated only based on the area of influence overlap method of competitor selection methods.

It was determined that an increase in the adjusted coefficient of determination (R^2_{adj}) was seen in 21 of 30 different combinations when competition index was added as a variable to the diameter growth model (Tables 3 and 4). The performance criteria of the models belonging to the 21 combinations that contributed to diameter growth change are given in Table 3 for fixed models and in Table 4 for mixed effects model.

As can be seen in Table 3, MSE values were higher when distance-independent competition indices CI_1 (BAL) and CI_8 (BALMOD) were included in the diameter growth models as a variable compared with the other distance-independent competition indices. In other words, there was a significant contribution of the distance-independent competition indices CI_1 (BAL) and CI_8 (BALMOD) to the diameter growth models according to the partial F test results (Tables 3 and 4). There was no significant contribution of the one distance-independent competition index (CI_7M_1) on the diameter growth model.

There was no significant contribution of the one influence-zone overlap competition index ($CI_{10}M_1$) on the fixed diameter growth model and two influence-zone overlap competition indices ($CI_{10}M_1$ and $CI_{13}M_1$) on the mixed model when compared with the models that did not include competition indices based on the partial F test results (Tables 3 and 4, respectively). MSE values of the models decreased significantly when two of the competition

Table 3. Contribution of competition indices to diameter growth models for fixed models by competitor method.

Competition index	R^2	RMSE (mm)	AIC	BIC	MSER (%)	Partial F test
No CI	0.682	0.880	2809.2	2815.3		
Influence zone overlap (M_1)						
CI_1	0.703	0.851	2727.1	2734.4	6.581	204.67**
CI_2	0.695	0.861	2781.9	2789.2	4.387	68.63**
CI_3	0.700	0.856	2769.3	2776.6	5.548	98.98**
CI_4	0.700	0.856	2743.0	2750.4	5.419	164.04**
CI_5	0.700	0.856	2769.1	2776.5	5.548	99.38**
CI_6	0.700	0.856	2742.1	2749.4	5.548	166.47**
CI_8	0.705	0.844	2709.3	2716.6	8.129	251.11**
CI_9	0.690	0.869	2793.2	2800.5	2.452	41.87**
$CI_{10}M_1$	0.683	0.880	2810.0	2817.3	0.129	2.83ns
$CI_{11}M_1$	0.690	0.871	2794.9	2802.2	2.194	37.82**
$CI_{13}M_1$	0.683	0.879	2805.7	2813.0	0.258	12.78**
$CI_{15}M_1$	0.689	0.872	2796.4	2803.8	1.935	34.23**
$CI_{18}M_1$	0.702	0.847	2715.2	2722.5	7.355	235.60**
$CZR_{0.4h}$ (M_2)						
$CI_{15}M_2$	0.684	0.879	2808.5	2815.8	0.258	6.31*
$CI_{17}M_2$	0.687	0.874	2790.8	2798.1	1.419	47.58**
$CI_{18}M_2$	0.683	0.880	2810.0	2817.3	0.129	2.82ns
CZR_k (M_3)						
$CI_{15}M_3$	0.684	0.878	2806.6	2813.9	0.516	10.60**
$CI_{18}M_3$	0.690	0.871	2794.2	2801.5	2.194	39.60**
BAF_4 (M_4)						
$CI_{15}M_4$	0.683	0.880	2809.5	2816.8	0.129	4.04*
$CI_{16}M_4$	0.683	0.880	2809.8	2817.1	0.129	3.20ns
$CI_{18}M_4$	0.687	0.874	2790.4	2797.7	1.419	48.43**

Note: *, significant at 0.05 level; **, significant at 0.01 level; ns, nonsignificant.

Table 4. Contribution of competition indices to diameter growth models for mixed models by competitor method.

Competition index	RMSE (mm)	AIC	BIC	MSER (%)	Partial F test
No CI	0.656	2389.1	2397.7		
Influence zone overlap (M_1)					
CI_1	0.626	2323.5	2333.3	8.952	162.44**
CI_2	0.652	2382.0	2391.7	1.262	21.11**
CI_3	0.654	2384.8	2394.5	0.878	14.63**
CI_4	0.629	2330.0	2339.7	8.133	146.25**
CI_5	0.656	2390.1	2399.9	0.143	2.36ns
CI_6	0.639	2352.4	2362.1	5.236	91.28**
CI_8	0.626	2323.2	2333.0	8.993	163.25**
CI_9	0.652	2380.9	2390.7	1.407	23.57**
$CI_{10}M_1$	0.656	2391.0	2400.8	0.014	0.23ns
$CI_{11}M_1$	0.653	2383.7	2393.5	1.021	17.04**
$CI_{13}M_1$	0.656	2391.0	2400.8	0.016	0.27ns
$CI_{15}M_1$	0.653	2384.1	2393.9	0.970	16.18**
$CI_{18}M_1$	0.628	2326.9	2336.7	8.525	153.97**
$CZR_{0.4h}$ (M_2)					
$CI_{15}M_2$	0.656	2391.0	2400.8	0.014	0.23ns
$CI_{17}M_2$	0.643	2361.5	2371.2	4.032	69.41**
$CI_{18}M_2$	0.639	2353.1	2362.9	5.134	89.41**
CZR_k (M_3)					
$CI_{15}M_3$	0.654	2385.9	2395.6	0.728	12.12**
$CI_{18}M_3$	0.654	2385.3	2395.1	0.803	13.37**
BAF_4 (M_4)					
$CI_{15}M_4$	0.656	2391.0	2400.8	0.015	0.25ns
$CI_{16}M_4$	0.656	2390.1	2399.8	0.146	2.42ns
$CI_{18}M_4$	0.645	2364.1	2374.5	3.598	61.67**

Note: *, significant at 0.05 level; **, significant at 0.01 level; ns, nonsignificant.

indices ($CI_{10}M_1$ for fixed model; $CI_{10}M_1$, $CI_{13}M_1$ for mixed model) were included as variables in the diameter growth models (Tables 3 and 4).

Four size-ratio competition indices (CI_{15}–CI_{18}) were assessed according to four different competitor selection methods as part of the study. When these competition indices were calculated according to the crown overlap approach, MSE values of the diameter growth model with $CI_{18}M_1$ index were lower than the model with $CI_{15}M_1$ index for both fixed and mixed models. Likewise, when these indices were calculated according to the fixed-radius approach, which considers the 40% mean height of the plot, MSE values of the fixed diameter growth models with $CI_{17}M_2$ index were lower than the model with $CI_{15}M_2$ index, while $CI_{18}M_2$ competition index made no significant contribution. On the other hand, $CI_{17}M_2$ and $CI_{18}M_2$ competition indices made a significant contribution to the mixed diameter growth model, whereas there was no significant contribution of the $CI_{15}M_2$ competition index. When these indices were calculated according to the fixed radius approach that considers the number of trees, $CI_{15}M_3$ and $CI_{18}M_3$ competition indices made a significant contribution to both fixed and mixed diameter growth models. $CI_{18}M_4$ competition index made a significant contribution to both fixed and mixed diameter growth models, whereas there was no significant contribution of the $CI_{15}M_4$ and $CI_{16}M_4$ competition indices when these indices were calculated according to the angle count sampling approach.

Additionally, the performances of the four competitor selection methods were compared. The best selection of competitive neighbors was achieved using the area of influence overlap method, whereas the fixed-radius and angle count sampling methods had no significant improvement in quantifying the competition effects (Tables 3 and 4). On the other hand, the best performances were obtained with $CI_{18}M_1$ competition index for both fixed and mixed models using the first approach (M1), $CI_{17}M_2$ competition index for fixed model and $CI_{17}M_2$ and $CI_{18}M_2$ competition indices for fixed model using the second approach (M2), $CI_{18}M_3$ competition index for both fixed and mixed models using the third approach (M3), and $CI_{18}M_4$ competition index for both fixed and mixed models using the fourth approach (M4). The best performing competition index within each competitor selection method varies based on considering the contribution in the diameter growth model or lowering the MSE value of the model.

Overall, the best performing diameter growth models contained the size-ratio competition index $CI_{18}M_1$ developed by Martin and Ek (1984) for both fixed and mixed models (Tables 3 and 4). Crown overlap influence-zone approach was used to determine the competitor trees to calculate the best performing competition indices. The RMSE values of the diameter growth models with the $CI_{18}M_1$ index were 0.847 and 0.628 mm, MSER (%) values were 7.355% and 8.525%, AIC values were 2715.2 and 2326.9, and BIC values were 2722.5 and 2336.7 for fixed and mixed models, respectively (Tables 3 and 4). In other ways, the $CI_{18}M_1$ competition index developed by Martin and Ek (1984) was the best performing index according to partial F test results (F = 235.60 and 153.97 for fixed and mixed models, respectively, significant at the p = 0.01 level) in this study. The influence-zone approach was used to determine the competitor trees to calculate this index. In this approach, the potential influence zone of a tree is regarded as a circle with a fixed radius (crown radius of the subject tree) around the subject tree.

Distance-independent indices (CI_1 (BAL) and CI_8 (BALMOD)) performed a little better than distance-dependent competition indices ($CI_{18}M_1$) when the best performing indices were considered or rather distance-independent and distance-dependent competition indices contributed to the fixed and mixed diameter growth models at similar degrees in this study. Several researchers reported that there were no significant differences between the performances of the two types of models (Lorimer 1983; DeBell et al. 1997; Corral Rivas et al. 2005; Ledermann 2010; Sharma et al. 2016). Nevertheless, CI_1 (BAL) and CI_8 (BALMOD) competition indices can be derived easily using the already available or easy to acquire variables for each plot (basal area, tree density, and dominant height). The goal in competition index studies is to be able to determine the competition among trees without taking too many measurements and the easy inclusion of the indices in diameter or basal area growth models (Tomé and Burkhart 1989; Biging and Dobbertin 1995; Schröder and Gadow 1999; Álvarez Taboada et al. 2003; Corral Rivas et al. 2005; Pretzcsh 2009; Maleki et al. 2015). Therefore, despite the lack of a significant difference between the contributions of distance-dependent and distance-independent competition indices to the annual diameter growth models, distance-independent competition indices were preferred in the diameter growth models in this study.

Table 5. Regression model developed to predict diameter growth.

Parameters	Fixed model		Mixed effect model	
	Estimates	SE	Estimates	SE
b_0	3.869887	0.0975	3.947600	0.1133
b_1	0.008522	0.0012	0.003017	0.0013
b_2	−0.786250	0.0332	−0.779500	0.0430
b_3	−0.012867	0.0018	−0.007610	0.0020
b_4	0.078775	0.0279	0.081300	0.0377
b_5	−0.050941	0.0105	−0.064250	0.0149
σ_u^2	—	—	0.000081	7.36×10^{-6}
σ^2	—	—	0.498900	0.0195
R^2	0.705		—	
RMSE	0.844		0.626	
AIC	2709.3		2323.2	
BIC	2716.6		2333.0	

Note: SE, standard error; b_1–b_5 fixed parameters; σ_u^2, variance for random parameter; σ^2, residual variance. All parameters were significant at a significance level of 0.05.

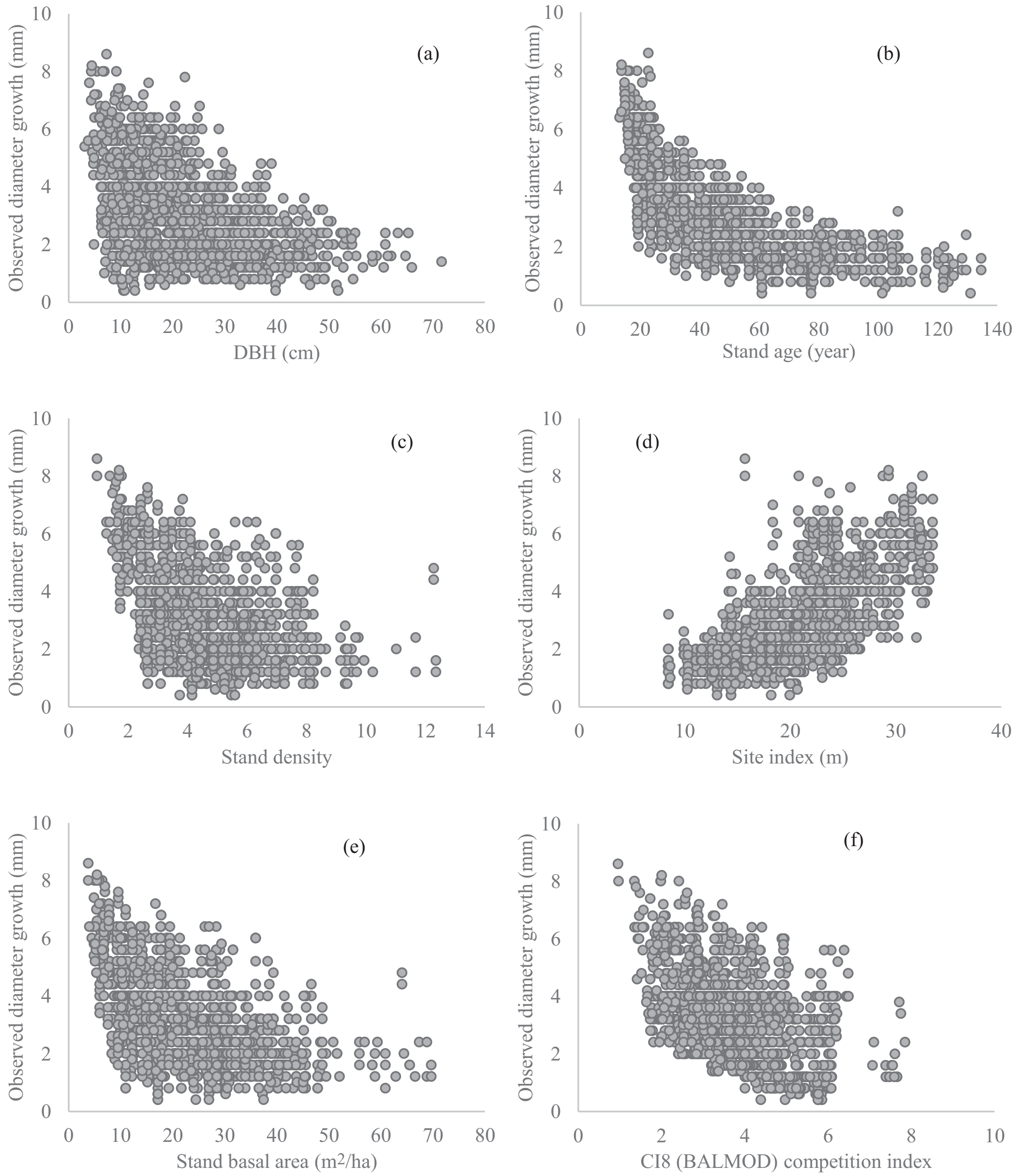
The adjusted R^2 values of the best performing fixed diameter growth models using distance-independent competition indices were 0.703 for CI_1 (BAL) and 0.705 for CI_8 (BALMOD). RMSE, AIC, BIC, and MSER values of the fixed and mixed models with the CI_8 (BALMOD) competition index were 0.844 and 0.626 mm, 2709.3 and 2323.2, 2716.6 and 2333.0, and 8.129% and 8.993%, respectively, whereas RMSE, AIC, BIC, and MSER values of the fixed and mixed models with the CI_1 (BAL) competition index were 0.851 and 0.626 mm, 2727.1 and 2323.5, 2734.4 and 2333.3, and 6.581% and 8.952%, respectively.

CI_8 (BALMOD) competition index was selected as the best performing index in this study based on the partial F test results, where the F value of the fixed and mixed diameter growth models with the CI_8 (BALMOD) were 251.1 and 163.25, respectively. Similar results have been obtained in some previous studies (Biging and Dobbertin 1995; Schröder and Gadow 1999; Álvarez Taboada et al. 2003; Corral Rivas et al. 2005; de-Miguel et al. 2010, 2012; Shater et al. 2011; Maleki et al. 2015).

In this study, fixed and mixed effects models were also compared to analyze diameter growth. The reduction rates in AIC and BIC were 14.8% (13.7%–16.3%) and 14.6% (13.6%–16.1%), respectively. Mixed effects models were more accurate and precise than those fitted without random effects as root mean square error (RMSE) was reduced by 25.4% (23.3%–27.3%) for diameter growth prediction. These results indicated that all mixed effects models provided much better fits than their fixed effects model counterparts.

The statistics and the estimated parameters of the diameter growth models generated are shown in Table 4. Fixed and mixed nonlinear regression was applied to estimate the parameters of eqs. 5 and 6. In the regression model, model coefficients were significant at a probability level of 95% (p < 0.05). The R^2_{adj}, RMSE,

Fig. 2. The relationship between tree diameter growth and main predictors: (*a*) diameter at breast height (DBH); (*b*) stand age; (*c*) stand density; (*d*) site index; (*e*) stand basal area; and (*f*) CI8 competition index.



AIC, and BIC of the fixed diameter growth model were 0.705, 0.844 mm, 2709.3, and 2716.6, respectively, while RMSE, AIC, and BIC of the mixed diameter growth model were 0.626 mm, 2323.2, and 2333.0, respectively (Table 5).

The scatterplot illustrating the relationship between the single-tree diameter growth and the main predictors such as DBH, stand age, stand density, site index, stand basal area, and competition index are given in Fig. 2. Diameter growth increased with site index and decreased with DBH, stand age, stand density, stand basal area, and CI_8 competition index (Fig. 2). The correlation coefficient between the diameter growth and CI_8 (BALMOD) competition index is −0.564. The predicted diameter growth according to the individual-tree diameter growth model containing CI_8 (BALMOD) competition index as a variable versus observed diameter growth is shown in Fig. 3*a* for the fixed model and Fig. 3*b* for the mixed model.

Residuals were plotted against the predicted diameter growth to check for the homogeneity of variance (Fig. 4*a* for the fixed model and Fig. 4*b* for the mixed model). It can be seen that the residuals were scattered randomly, and thus, we found clear indication that the variances of the residuals were constant across fitted values. The model with random effect parameters has a more homogenous error variance structure than that of the nonlinear model. Also, the error-related autocorrelation problem is remedied once the random effect parameter (b_1 random parameter) is added to the model. The error (RMSE) of the models decreased from 0.844 to 0.626 mm in the transformation of the nonlinear model to the mixed effects model.

Fig. 3. Predicted diameter growth against observed diameter growth for (*a*) fixed and (*b*) mixed individual-tree models.

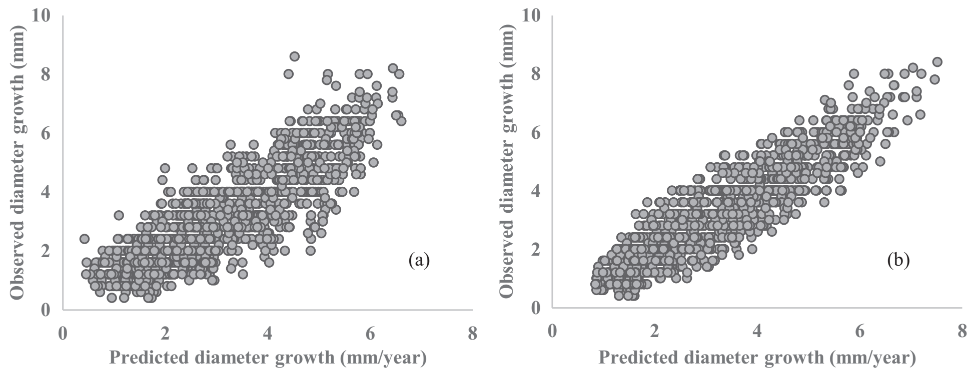
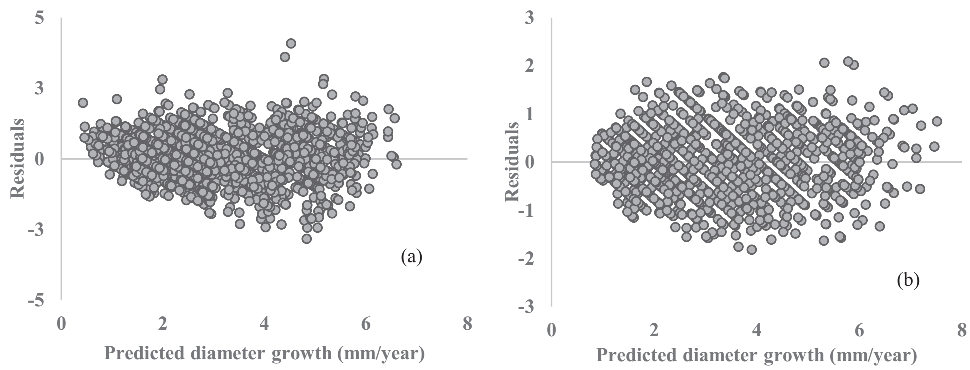


Fig. 4. Residuals against predicted diameter growth for (*a*) fixed and (*b*) mixed individual-tree models.



Conclusions

R^2_{adj} values of the fixed diameter growth models including the competition indices as variables (model 6) range from 0.683 to 0.705, as seen in Table 3. When the contributions of distance-dependent and distance-independent competition indices to the annual diameter growth models are evaluated, it can be seen that both types performed equally well. R^2_{adj} values of the fixed diameter growth models with the distance-independent competition indices were 0.690–0.705 and 0.683–0.702 in the distance-dependent competition indices. RMSE, AIC, and BIC of the fixed diameter growth model ranged from 0.847 to 0.880 mm, 2709.3 to 2810.0, and 2716.6 to 2817.3, respectively, while those of the mixed diameter growth model ranged from 0.626 to 0.656 mm, 2323.2 to 2391.0, and 2333.0 to 2400.8, respectively.

In this study, MSER criterion was used to assess whether the performance of the model increased or the errors decreased when a competition index was added to a diameter growth model without a competition index. The significance of the MSER statistic was tested by the partial *F* test. The best performing distance-independent competition indices (CI_1 (BAL) and CI_8 (BALMOD)) were found to be as successful for both fixed and mixed models as the best performing distance-dependent competition indices ($CI_{18}M_1$; Martin and Ek 1984) based on the analysis results. R^2_{adj} values increased 2.93% to 3.37% when these three competition indices were included in the fixed model. MSER values of the models with the three best performing competition indices decreased 6.581% to 8.129% for the fixed model and 8.525% to 8.993% for the mixed model compared with the models without any competition index. The difference between the MSER values of these both fixed and mixed models was significant ($p < 0.01$).

CI_1 (BAL) and CI_8 (BALMOD) competition indices can be derived easily using the already available or easy to acquire variables for a given species in each plot (basal area, tree density, and dominant height). On the other hand, the performance of the CI_8 (BALMOD) index was more significant and successful compared with the CI_1 (BAL) index. Because one of the objectives of this study is to identify a competition index that makes a significant contribution to the individual-tree diameter growth model and does not require taking too many measurements in the field, the CI_8 (BALMOD) competition index is recommended to be included as a variable in the growth models for the Calabrian pine stands in the central Mediterranean region of Turkey.

The most significant advantage of the mixed effects modeling technique over conventional regression models is that it allows the elimination of the problem of autocorrelation among the data and the homogenization of the distribution of error variance (Pinheiro and Bates 2000; Calama and Montero 2005; Littell et al. 2006; Weiskittel et al. 2007). In this study, the effect of autocorrelation was successfully reduced using random effect, and the distribution of error variance was transformed into a homogenous structure. After the addition of the random effect parameters to the model, the error-related autocorrelation problem was reduced, and the model with random effect parameters had a more homogenous error variance structure (Fig. 4*b*).

As can be seen in the literature, despite the use of many tree and stand parameters to predict tree diameter or basal area growth, generally moderate R^2 values were obtained (Tomé and Burkhart 1989; Wimberly and Bare 1996; Schröder and Gadow 1999; Corral Rivas et al. 2005; Schröder et al. 2007; Contreras et al. 2011; Kahriman and Yavuz 2012; Wang et al. 2012; Maleki et al. 2015; Sharma et al. 2016; Śmigielski et al. 2017; Bérubé-Deschênes et al. 2017; Tenzin et al. 2017). Approximately 70% of the variance in tree diameter growth could be explained by variables, including DBH, stand age, site index, stand density, basal area, and competition indices.

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