



# Considering neighborhood effects improves individual dbh growth models for natural mixed-species forests in Mexico

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## Abstract

• **Key message** More accurate diameter at breast height (dbh)-growth models are needed for developing management tools for mixed-species forests in Mexico. Individual distance-dependent dbh growth models that quantify local neighborhood effects have been developed for four species groups in such forests. The performance of the models is improved by distinguishing between inter- and intraspecific group competitions.

• **Context** The management of mixed-species forests in the northwest of Durango, Mexico, is mainly based on the selection method. Understanding the interspecific and intraspecific competition is critical to developing management tools for such mixed-species forests.

• **Aims** An individual-based distance-dependent modeling approach was used to model the growth of dbh and to evaluate neighborhood effects for four species groups in Mexican mixed-species stands.

• **Methods** Twenty-two species were classified into four groups: *Pinus* (seven species), other conifers (three species), other broadleaves (four species), and *Quercus* (eight species). Four methods were used to select neighboring trees and 12 competition indices (CIs) were calculated. Comparisons of the neighboring trees selection methods and CIs and tests of assumptions about neighborhood effects were conducted.

• **Results** Intra-species-group competition significantly reduced diameter growth for all species groups, except for the *Quercus* group. The *Pinus*, other conifers, and *Quercus* groups had significant and negative neighborhood effects on the other broadleaves species group, and not vice versa. The *Quercus* group also had negative neighborhood effect on the *Pinus* and other conifers species groups, and not vice versa. The *Pinus* and other conifers species groups had negative neighborhood effects on each other. All fitted age-independent dbh growth models showed a good of fit to the data (adjusted coefficient of determination larger than 0.977).

• **Conclusion** The growth models can be used to predict dbh growth for species groups and competition in mixed-species stand from Durango, Mexico.

**Keywords** Competition effect · Crown-overlapping · Distance-dependent indices · Subject tree · Neighbor tree

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## 1 Introduction

Forest growth and yield modeling is used to analyze and estimate different relationships in forest stand development such as species composition, site characteristics, species competition, and silvicultural management (Perin et al. 2016). Growth models, together with stand regeneration, harvesting, and mortality models, are important tools in long-term forest management systems (Andreassen and Tomter 2003). Modeling mono-specific stands has a long history, but modeling mixed-species forests has received much more attention in the last decades (Porté and Bartelink 2002), due to a worldwide trend in managing such forests to improve the biodiversity and environmental services and to assure long-term sustainable forest resources (Deal et al. 2017; del Río et al. 2016). The structure, dynamics, and productivity of mixed-species stands depend on both interspecific and intraspecific interactions. The outcome of the species interactions depends on the ecological traits of the species and the environmental conditions (del Río et al. 2016). The accurate assessment of growing stock in combination with mixed-species forest growth models is essential for sustainable forest management (Tenzin et al. 2017). Understanding the ecological process of mixed-species stands helps develop biometric tools to support forest management decision-making (Zhao et al. 2006).

Many factors such as tree size, neighborhood competition, and environmental variables should be included in growth models to explain patterns of tree or species group growth (Zhang et al. 2017). Competition among species or species groups plays a major role in stand dynamics, survival, growth, and species replacement. Individual tree growth models commonly include a competition index (CI) designed to quantify the degree of competitive stress on individual trees in a stand (Lorimer 1983). The local neighbors represent neighboring trees that have effect on the growth of a subject tree (Burkhardt and Tomé 2012). The CIs used as predictor variables in individual tree growth models indicate the competitive status of a subject tree with respect to neighboring competitors (Radtke et al. 2003), such as a positive or negative effect (Daniels 1976). A CI for a subject tree is estimated as the total competition from adjacent trees thought to be affecting the growth of that subject tree (Biging and Dobbertin 1992).

The CIs are broadly classified into two categories: distance-independent and distance-dependent measures (Munro 1974). Distance-independent indices describe the competitive status of a tree or class of trees relative to all trees in the stand, so they do not require individual tree coordinates or the distance between the subject tree and its neighbors. Distance-dependent indices attempt to describe competitive status based on the immediate conditions surrounding a tree, so they require tree spatial information and distances between the subject tree and its neighbors (Burkhardt and Tomé 2012).

The distance-dependent CIs are also known as local neighborhood indices that involve the relative attributes of the subject tree and its competitors such as relative size and their spatial separation such as distance (Stage and Ledermann 2008). Distance-dependent CIs are used in spatially explicit individual-based models, and this modeling approach is suitable to describe the competition among individual trees and species groups (Porté and Bartelink 2002; Zhao et al. 2006). Many distance-dependent and distance-independent CIs that distinguish the species or species groups have been used in individual tree growth models for predicting dbh (Bella 1971; Daniels 1976; Mabvurira and Miina 2002; Tomé and Burkhardt 1989) or basal area (Biging and Dobbertin 1992; Zhao et al. 2006), increment and growth, as well as, for annual height growth or increment (Daniels 1976; Martin and Ek 1984). In general, including competition effects in individual tree growth models improves the model performance.

Durango is the most important state in Mexico for timber production, 28.5% of total timber volume harvested in Mexico in 2015. The forests are distributed along a mountain range known as the Sierra Madre Occidental, a volcanic plateau extending from the south of the Tropic of Cancer through the western Durango and north-westerly terminating in the southern of AZ, USA (Aguirre et al. 2003). In this study, four species groups (*Pinus*, other conifers, other broadleaves, and *Quercus*) were formed following forest management planning and cluster analysis from 22 species growing in mixed-species stands. The main goals were to develop individual-based age-independent dbh growth models with neighboring effects for each species group and to explore the differences in competitive status among the species groups.

## 2 Material and methods

### 2.1 Data

The data came from 44 stem-mapped re-measurement plots in mixed-species stands in the northwest of Durango, Mexico. The forest regions are called San Diego de Tezanos Ejido and Lobos & Pescaderos Community, and they are in a geographical region from 24° 48.2' to 25° 19.5' N and – 105° 52.2' to – 106° 12.9' W (Fig. 1). The total area is 91,235.63 ha and the altitude ranges from 800 to 3103 m. The mean annual precipitation ranges from 1000 to 1200 mm, and the maximum occurs from June to August. The mean annual temperature ranges from 5 to 18 °C, and the lowest temperature occurs in January (– 6 °C) and the hottest in May (28 °C). The mixed-species stands are represented by seven genus: *Pinus*, *Quercus*, *Juniperus*, *Cupressus*, *Pseudotsuga*, *Arbutus*, and *Alnus*. About 90% of the stands in study area are uneven-aged and species-mixed. They were managed according to a continuous cover forestry (CCF) system with selective

harvesting treatments and natural regeneration, or a rotation forest management (RFM) system characterized by three or four thinning treatments and a shelterwood cut (Pukkala and Gadow 2011). Those systems are called Mexican Method of Forest Regulation (MMFR) and Method for Silvicultural Development (MSD). The cutting cycle is 15 years (Quiñonez-Barraza et al. 2018; for more information about these systems, please refer to Torres-Rojo et al. 2016).

The plots were established in 2008 on a symmetric grid of 3 km × 3 km and were re-measured in 2013. Each square plot (50 m × 50 m) consists of four quadrants (25 m × 25 m). The location of each tree was determined in a clockwise order from the plot center. All trees ≥ 7.5 cm in dbh were measured, mapped, and identified. The variables collected were the species (sp), total height (H, m), height to base of live crown (Hc, m), tree crown width (Cw, m), dominance tree (Do), tree location (UTM coordinate), tree distance from central tree to other trees (R, m), and tree azimuth (Az, °).

In total, the dataset included measurements of 6014 trees of 22 species. The species were grouped as follows: *Pinus* (P, seven species); other conifers (OC, three species); other broadleaves (OB, four species); and *Quercus* (Q, eight species). This criterion of species groups is used in forest management planning (detailed information of the dataset is presented in Tables 1 and 2). Using a geographic information system (GIS), tree locations were mapped for each plot, and the distances between each tree and all other trees in that plot were calculated.

## 2.2 Distance-dependent competition indices

CI's are regularly used to characterize competition, so they shall be clear, specific, and consistent in meaning and relevant to important themes and perspectives (Weigelt and Jolliffe 2003). The role of CI's in prediction models is to indicate the competitive status of a subject tree with respect to neighboring competitors (Radtke et al. 2003). The CI's describe a mosaic of forest patches, and each patch is characterized by its location in the stand and the dynamic interaction between neighbor patches (Porté and Bartelink 2002). The CI's are defined as a function of the dimension of the subject tree and the distance between that subject tree and its neighbors, and their values depend on the method used to select the neighbor trees (Biging and Dobbertin 1992). In this study, a crown-overlapping distance-weighted size ratio (DR) index proposed by Tomé and Burkhart (1989) was used:

$$CI = \sum_{j=1}^n R_{ij} f(S_{ij}) \quad (1)$$

where  $n$  is the number of competitors of a subject tree  $i$ ,  $R_{ij}$  is the size ratio between the subject tree  $i$  and its  $j$ th neighbor tree, and  $f(S_{ij})$  is a function of the distance ( $S_{ij}$ ) between the subject tree  $i$  and its neighbor tree  $j$ .

In this study, the combination of three size ratios (tree dbh  $D_j/D_i$ , tree height  $h_j/h_i$ , and tree crown width  $Cw_j/Cw_i$ ) and four distance functions ( $1/S_{ij}$ ,  $1/S_{ij}^2$ ,  $e^{-S_{ij}}$ , and  $1-e^{-S_{ij}}$ ) results in the 12 CI's. The preliminary analysis showed that the following five CI's were better than others, based on the likelihood ratio tests between the diameter growth models with equivalent neighborhood effects but using different CI's and the models without neighborhood effect, fitted for each species group (see Appendix Table 7):

$$CI1 = \sum_{j=1}^n \frac{D_j}{D_i} \frac{1}{S_{ij}} \quad (2)$$

$$CI4 = \sum_{j=1}^n \frac{D_j}{D_i} (1-e^{-S_{ij}}) \quad (3)$$

$$CI7 = \sum_{j=1}^n \frac{h_j}{h_i} e^{-S_{ij}} \quad (4)$$

$$CI8 = \sum_{j=1}^n \frac{h_j}{h_i} (1-e^{-S_{ij}}) \quad (5)$$

$$CI9 = \sum_{j=1}^n \frac{Cw_j}{Cw_i} \frac{1}{S_{ij}} \quad (6)$$

If the crown of a tree was completely in the square plot, then that tree was considered as a subject tree. Otherwise, it was not considered as a subject tree, but it might be a neighbor of other subject trees. For a given subject tree, its neighbor trees were defined by the following expression:

$$N_j = \begin{cases} 1 & \text{if } S_{ij} < \left( \frac{\delta Cw_i}{2} + \frac{\delta Cw_j}{2} \right) \\ 0 & \text{Otherwise} \end{cases} \quad (7)$$

where  $N_j$  is the neighbor tree for the subject tree  $i$  and  $\delta$  could be 1.0, 1.5, 2.0, or 2.5.

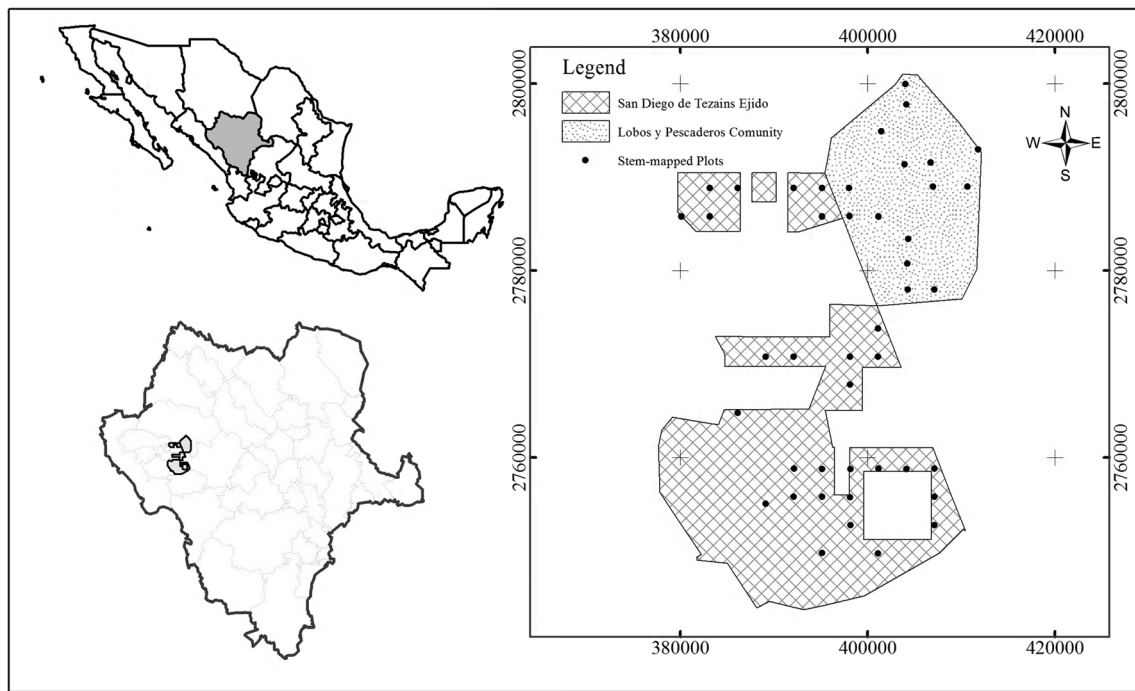
In the whole dataset, 4833 subject trees were selected and their neighboring trees were determined by  $\delta$  values. The number of subject trees by species group and neighboring trees is given in Table 3.

## 2.3 Model derivation

A distance-dependent individual tree growth model that did not explicitly use age was developed, based on the Chapman-Richards equation (Richards 1959):

$$\text{dbh} = \alpha_0 (1 - e^{-\alpha_1 t})^{\alpha_2} \quad (8)$$

where dbh is the diameter at breast height (cm) at age  $t$  (years),  $\alpha_0$ ,  $\alpha_1$ , and  $\alpha_2$  are asymptote, growth rate, and exchange rate parameters, respectively, and  $e$  is the Euler's constant.



**Fig. 1** Study area and plot locations in Durango, Mexico

**Table 1** Species included in each species group for individual-based growth models, and their number of trees ( $n$ ), minimum (min), maximum (max), mean, and standard deviation (SD) of dbh (cm) measured at 2008 and 2013

| Species group                     | Scientific name  | $n$  | 2008  |       |       |       | 2013  |       |       |       |
|-----------------------------------|--|------|-------|-------|-------|-------|-------|-------|-------|-------|
|                                   |  |      | Min   | Max   | Mean  | SD    | Min   | Max   | Mean  | SD    |
| Pinus                             | <i>Pinus arizonica</i> Engelm.                               | 466  | 3.60  | 50.02 | 19.63 | 9.99  | 7.55  | 51.90 | 21.65 | 10.19 |
|                                   | <i>Pinus ayacahuite</i> Ehrenb. ex Schtdl.                   | 412  | 3.85  | 50.08 | 14.37 | 7.19  | 7.85  | 52.20 | 16.24 | 7.23  |
|                                   | <i>Pinus durangensis</i> Martínez                            | 1241 | 3.50  | 71.50 | 15.86 | 9.16  | 7.50  | 74.10 | 17.61 | 9.35  |
|                                   | <i>Pinus engelmannii</i> Carrière                            | 32   | 8.20  | 65.50 | 19.13 | 16.07 | 9.60  | 66.80 | 21.02 | 15.95 |
|                                   | <i>Pinus leiophylla</i> Schiede ex Schtdl. & Cham.           | 335  | 3.50  | 44.90 | 20.23 | 9.41  | 7.50  | 46.85 | 22.39 | 9.37  |
|                                   | <i>Pinus lumholtzii</i> B.L.Rob. & Fernald                   | 168  | 7.50  | 40.85 | 15.23 | 6.01  | 8.70  | 42.50 | 16.69 | 6.21  |
|                                   | <i>Pinus teocote</i> Schied. ex Schtdl. & Cham.              | 1319 | 3.20  | 78.70 | 15.85 | 9.19  | 7.20  | 82.70 | 17.91 | 9.23  |
| OC                                | <i>Cupressus lusitanica</i> Mill.                            | 7    | 5.88  | 26.00 | 16.22 | 8.82  | 10.00 | 30.00 | 19.38 | 8.64  |
|                                   | <i>Juniperus deppeana</i> Steud.                             | 25   | 3.65  | 57.00 | 13.78 | 7.86  | 7.65  | 60.50 | 15.73 | 8.01  |
|                                   | <i>Pseudotsuga menziesii</i> (Mirb.) Franco                  | 13   | 7.50  | 66.30 | 16.75 | 15.02 | 9.90  | 68.30 | 18.55 | 14.92 |
| OB                                | <i>Alnus firmifolia</i> Fernald                              | 584  | 5.50  | 21.20 | 12.88 | 6.05  | 9.50  | 22.20 | 15.28 | 5.25  |
|                                   | <i>Arbutus arizonica</i> (A.Gray) Sarg.                      | 16   | 2.00  | 22.10 | 11.78 | 5.68  | 6.00  | 25.50 | 14.10 | 5.77  |
|                                   | <i>Arbutus bicolor</i> S.González, M.González & P.D.Sørensen | 28   | 3.60  | 60.20 | 14.55 | 9.80  | 7.60  | 63.20 | 16.56 | 10.11 |
| Quercus                           | <i>Arbutus madrensis</i> S.González                          | 802  | 6.90  | 38.13 | 14.42 | 6.75  | 8.30  | 39.40 | 16.39 | 6.93  |
|                                   | <i>Quercus arizonica</i> Sarg.                               | 6    | 7.90  | 20.50 | 14.76 | 3.63  | 11.60 | 24.30 | 16.88 | 3.80  |
|                                   | <i>Quercus crassifolia</i> Bonpl.                            | 308  | 7.70  | 13.70 | 9.88  | 2.40  | 8.60  | 15.30 | 11.25 | 2.51  |
|                                   | <i>Quercus durifolia</i> Seemen ex Loes                      | 22   | 8.10  | 56.10 | 16.33 | 11.70 | 8.70  | 58.30 | 17.94 | 12.22 |
|                                   | <i>Quercus jonesii</i> Trel.                                 | 9    | 8.30  | 31.50 | 21.08 | 8.37  | 11.70 | 33.20 | 23.05 | 7.77  |
|                                   | <i>Quercus mcvaughii</i> Spellens.                           | 15   | 3.50  | 45.90 | 13.02 | 6.22  | 7.50  | 49.90 | 14.63 | 6.42  |
|                                   | <i>Quercus obtusata</i> Bonpl.                               | 154  | 8.00  | 27.20 | 12.81 | 5.86  | 8.70  | 27.80 | 13.59 | 5.93  |
| <i>Quercus rugosa</i> Née         | 36   | 6.50 | 26.65 | 14.56 | 5.59  | 9.60  | 27.95 | 16.86 | 5.39  |       |
| <i>Quercus sideroxylla</i> Bonpl. | 16   | 4.70 | 80.00 | 17.35 | 12.52 | 7.50  | 85.00 | 18.99 | 12.87 |       |

**Table 2** Minimum (min), maximum (max), mean, and standard deviation (SD) of stand characteristics from 44 plots measured at 2008 and 2013

| Variable  | 2008 |        |       |       | 2013 |        |       |       |
|---|------|--------|-------|-------|------|--------|-------|-------|
|   | Min  | Max    | Mean  | SD    | Min  | Max    | Mean  | SD    |
| Trees per hectare, $N$                          | 60.0 | 1424.0 | 546.4 | 266.6 | 60.0 | 1424.0 | 546.4 | 266.6 |
| Basal area, BA ( $\text{m}^2 \text{ ha}^{-1}$ ) | 3.73 | 35.29  | 15.01 | 7.28  | 4.46 | 43.39  | 17.86 | 8.47  |
| Average dbh of dominant trees, Dd (cm)          | 18.8 | 49.3   | 31.1  | 6.7   | 20.6 | 52.5   | 33.2  | 6.8   |
| Dominant height, Hd (m)                         | 6.1  | 23.2   | 13.9  | 3.8   | 6.7  | 24.6   | 15.4  | 4.2   |

The tree dbhs at time  $t_1$  and  $t_{1+a}$  are:

$$\text{dbh}_1 = \alpha_0(1 - e^{-\alpha_1 t_1})^{\alpha_2} \quad (9)$$

$$\text{dbh}_{1+a} = \alpha_0(1 - e^{-\alpha_1 t_{1+a}})^{\alpha_2} \quad (10)$$

where  $t_{1+a} = t_1 + a$ ,  $a$  is the time interval between two measurements, for example, 5 years in this study.

Solving for  $t_1$  from Eq. 9 resulted in Eq. 11.

$$t_1 = \frac{\ln\left(1 - \left(\frac{\text{dbh}_1}{\alpha_0}\right)^{\frac{1}{\alpha_2}}\right)}{-\alpha_1} \quad (11)$$

Then, by substituting Eq. 11 into Eq. 10, we got Eq. 12, a growth model without age:

$$\text{dbh}_{(1+a)} = \alpha_0 \left(1 - e^{-\alpha_1 a} \left(1 - \left(\frac{\text{dbh}_1}{\alpha_0}\right)^{1/\alpha_2}\right)\right)^{\alpha_2} \quad (12)$$

A full dbh growth model was then derived by adding the neighborhood effects and an error term to Eq. 12:

$$\text{dbh}_{ik(1+a)} = \alpha_{i0} \left(1 - e^{-\alpha_{i1} a} \left(1 - \left(\frac{\text{dbh}_1}{\alpha_{i0}}\right)^{1/\alpha_{i2}}\right)\right)^{\alpha_{i2}} + \sum_{j=1}^4 \beta_{ij} CI_{ijk(1)} + \varepsilon_{ik(1+a)} \quad (13)$$

where  $\text{dbh}_{ik(1+a)}$  is the dbh of the  $k$ th subject tree in the  $i$ th species group at measurement  $(1+a)$ ,  $(\alpha_{i0}, \alpha_{i1}, \alpha_{i2}, \beta_{i1}, \beta_{i2}, \beta_{i3}, \beta_{i4})$  are the parameters to be estimated,  $CI_{ijk(1)}$  are the competition indices calculated for subject tree  $k$  of species group  $i$  from its neighbors that belong to species group  $j$ , and  $\varepsilon_{ik(1+a)}$  is the error for the  $k$ th tree of the species group  $i$ .  $\beta_{ii}$  describes the intra-species-group competition for species group  $i$ , and  $\beta_{ij}$  ( $i \neq j$ ) represents the inter-species-group competition (i.e., the competition of species group  $j$  on group  $i$ ).

## 2.4 Heteroscedasticity

The variance was modeled with a power of the absolute values of the variance covariate (varPower):  $\text{Var}(\varepsilon_{ik}) = \sigma^2 |v_{ik}|^{2\varphi}$ , corresponding to the variance function  $g(v_{ik}, \varphi) = |v_{ik}|^\varphi$ . The variance covariate  $v_{ik}$  is the fitted value of dbh,  $\varphi$  is an unrestricted parameter, and  $\sigma^2$  is the scale factor. This structure can

model cases where the variance increases or decreases with the fitted dbh. The varPower was included in the fitting process as a weight function (Pinheiro and Bates 2000).

## 2.5 Model fitting and evaluation

First, the full dbh growth model (Eq. 13) was fitted for each species group and for each of the preselected CIs, assuming nonequivalent neighborhood effects:  $\beta_{i1} \neq \beta_{i2} \neq \beta_{i3} \neq \beta_{i4}$ , that is, neighboring trees from different species groups have distinct values of competition effects on the subject species group  $i$ . Then, based on the fitted full model, several assumptions of equivalent inter-species-group competition effects, that is, some parameters of  $\beta_{ij}$  ( $i \neq j$ ) are equal were tested. As a special case, the assumption of an equivalent neighborhood effect:  $\beta_{i1} = \beta_{i2} = \beta_{i3} = \beta_{i4}$  was tested, that is, it is not necessary to identify species groups for neighboring trees. For comparison purpose, the dbh growth model without competition term (Eq. 12) was also separately fitted for each species group. Due to the convergence problem in the models with or without competition term, the parameters  $\alpha_0$ 's were fixed as the largest dbh for each species group in the dataset, that is, 97.7 cm, 73.3 cm, 68.2 cm, and 90.0 cm for species groups P, OC, OB, and Q, respectively. Generalized nonlinear least squares (gnls) method in the linear and nonlinear mixed effects (NLME) models package (Pinheiro et al. 2015) of the R software environment (R Core Team 2017) was used to fit the models. Four statistics, i.e., root mean square error (RMSE), the adjusted coefficient of determination ( $R^2a$ ), Akaike information criterion (AIC), and log-likelihood (LL), were used to evaluate the models.

**Data availability** The data belong to forest owner communities in Mexico and cannot be made publicly available.

## 3 Results

The parameter estimates and goodness-of-fit statistics for dbh growth model without neighborhood effects (Eq. 12) fitted for each species group are listed on Table 4. Compared to these base models, in terms of log-likelihood (LL) values or likelihood ratio tests, 5 of the 12 CIs were better as potential

**Table 3** The number of subject trees for each species group and their neighboring trees determined by different  $\delta$  values in Eq. 7

| Species group     | Subject trees (trees) | Neighbors      |      |                |      |                |      |                |      |
|-------------------|-----------------------|----------------|------|----------------|------|----------------|------|----------------|------|
|                   |                       | $\delta = 1.0$ |      | $\delta = 1.5$ |      | $\delta = 2.0$ |      | $\delta = 2.5$ |      |
|                   |                       | Trees          | %    | Trees          | %    | Trees          | %    | Trees          | %    |
| <i>Pinus</i>      | 3203                  | 11,881         | 65.8 | 16,708         | 66.4 | 19,198         | 66.6 | 21,954         | 66.8 |
| Other conifers    | 256                   | 849            | 4.7  | 1183           | 4.7  | 1326           | 4.6  | 1446           | 4.4  |
| Other broadleaves | 182                   | 758            | 4.2  | 1032           | 4.1  | 1153           | 4.0  | 1315           | 4.0  |
| <i>Quercus</i>    | 1192                  | 4568           | 25.3 | 6240           | 24.8 | 7149           | 24.8 | 8150           | 24.8 |
| Total             | 4833                  | 18,056         | 100  | 25,163         | 100  | 28,826         | 100  | 32,865         | 100  |

variable in the dbh growth models for most of species groups (Appendix Table 7). They included CI1 and CI4 associated with the dbh ratio, CI7 and CI8 associated with the height ratio, and CI9 associated with the crown width ratio. A better way to determine the neighboring trees was to set  $\delta = 1.5$  in Eq. 7 (Appendix Table 7). That is, if the distance of a tree to the subject tree is less than 1.5 times of the sum of their crown radii, then that tree is a neighboring tree of the subject tree. When the CIs were computed using different  $\delta$  values, there were no significant differences in the log-likelihood values of the model under equivalent neighborhood effect assumption for each species group. Of total 48 cases, however, we still observed little LL gain in 18 cases when changing  $\delta$  from 1 to 1.5, ten cases when changing  $\delta$  from 1.5 to 2.0, and one case when changing  $\delta$  from 2.0 to 2.5.

Parameter estimates and fitting statistics for the dbh growth models with the assumption of equivalent neighborhood effects and associated with different CIs are given in Table 5, in which nonsignificant neighborhood effect was excluded from the model. Under this assumption, nine significantly negative neighborhood effects ( $p \leq 0.05$ ) were detected and one significantly positive neighborhood effect (species group Q with the CI8) was detected. For species group P, significant and negative neighborhood effects (at  $\alpha = 0.05$ ) were detected using all CIs, except CI8 (Table 5).

Parameter estimates and fit statistics of the models fitted with the assumption of nonequivalent neighborhood effects are listed in Table 6. Variables whose associated parameter estimates were not significantly different from zero (at  $\alpha = 0.05$ ) were excluded from the model. The neighborhood effects from the same species group (con-group) were represented by the significant  $\hat{\beta}_{ii}$  values. The neighborhood effects from different species groups (hetero-group) were represented by the significant  $\hat{\beta}_{ij(i \neq j)}$  values, suggesting significant neighborhood effects from the  $j$ th species group on the dbh growth of the  $i$ th species group. When CI1 and CI7 were used as predictor variable, significant and negative con-group competition effects could be detected, but the detectable con-group competition effect was positive when CI8 was used for the species group P (Table 6). Both species groups OC and Q had significant and negative effects on the species group P. The species group OB had no significant effects on the species group P, no matter which CI was used. For the species group OC, there was a detectable negative con-group effect, and negative effect of species group P on that species group was also detected, when CI4 was used. When CI1 was used, a significantly negative effect of species group Q on species group OC could be detected. If CI7, CI8, or CI9 was used, however, no significant neighborhood effect could be detected for species group OC. For the species group OB, significantly negative con-

**Table 4** Parameter estimates and their standard errors (SE), and fitting statistics of individual dbh growth models without competition effects (Eq. 12) fitted for each species group

| Group | Parameter  | Estimate | SE     | RMSE (cm) | $R^2a$ | AIC    | LL    |
|-------|------------|----------|--------|-----------|--------|--------|-------|
| P     | $\alpha_1$ | 0.0066   | 0.0003 | 1.2602    | 0.9819 | 10,935 | -5462 |
|       | $\alpha_2$ | 1.3838   | 0.0661 |           |        |        |       |
| OC    | $\alpha_1$ | 0.0042   | 0.0009 | 1.2972    | 0.9773 | 935    | -463  |
|       | $\alpha_2$ | 0.7374   | 0.0879 |           |        |        |       |
| OB    | $\alpha_1$ | 0.0072   | 0.0015 | 1.3326    | 0.9790 | 627    | -309  |
|       | $\alpha_2$ | 0.9963   | 0.1703 |           |        |        |       |
| Q     | $\alpha_1$ | 0.0093   | 0.0007 | 1.0918    | 0.9897 | 3709   | -1849 |
|       | $\alpha_2$ | 4.1389   | 1.1978 |           |        |        |       |

P, OC, OB, and Q are the species groups *Pinus*, other conifers, other broadleaves, and *Quercus*, respectively; RMSE is the root mean square error;  $R^2a$  is the adjusted coefficient of determination; AIC is the Akaike information criterion; LL is the log-likelihood

**Table 5** Parameter estimates and their asymptotic standard error (in parentheses), and fit statistics of individual dbh growth models fitted for each species group and by CIs, under the assumption of equivalent neighborhood effect

| Group      | Parameter  | CI1              | CI4              | CI7              | CI8             | CI9              |
|------------|------------|------------------|------------------|------------------|-----------------|------------------|
| P          | $\alpha_1$ | 0.0063 (0.0003)  | 0.0067 (0.0003)  | 0.0064 (0.0003)  | 0.0066 (0.0003) | 0.0065 (0.0003)  |
|            | $\alpha_2$ | 1.2548 (0.0546)  | 1.356 (0.0641)   | 1.2705 (0.0562)  | 1.3838 (0.0661) | 1.3236 (0.0609)  |
|            | $\beta_1$  | -0.0354 (0.0089) | -0.009 (0.0005)  | -0.1675 (0.0438) |                 | -0.0191 (0.0082) |
|            | $R^2a$     | 0.9819           | 0.9819           | 0.9819           | 0.9819          | 0.9819           |
|            | AIC        | 10,928           | 10,935           | 10,923           | 10,935          | 10,931           |
|            | RMSE (cm)  | 1.2591           | 1.2616           | 1.2588           | 1.2602          | 1.259            |
|            | LL         | -5458*           | -5452*           | -5456*           | -5462           | -5460*           |
|            | OC         | $\alpha_1$       | 0.0043 (0.0009)  | 0.0054 (0.001)   | 0.0042 (0.0009) | 0.0042 (0.0009)  |
| $\alpha_2$ |            | 0.7162 (0.0782)  | 0.7713 (0.0821)  | 0.7374 (0.0879)  | 0.7374 (0.0879) | 0.7374 (0.0879)  |
| $\beta_2$  |            | -0.0505 (0.0248) | -0.0597 (0.0202) |                  |                 |                  |
| $R^2a$     |            | 0.9775           | 0.9780           | 0.9773           | 0.9773          | 0.9773           |
| AIC        |            | 934              | 930              | 935              | 935             | 935              |
| RMSE (cm)  |            | 1.2933           | 1.2788           | 1.2972           | 1.2972          | 1.2972           |
| LL         |            | -461*            | -461*            | -463             | -463            | -463             |
| OB         |            | $\alpha_1$       | 0.0073 (0.0014)  | 0.0076 (0.0015)  | 0.0072 (0.0015) | 0.0072 (0.0015)  |
|            | $\alpha_2$ | 0.8724 (0.1098)  | 0.9063 (0.1187)  | 0.9962 (0.1703)  | 0.9962 (0.1703) | 1.0465 (0.1718)  |
|            | $\beta_3$  | -0.0849 (0.0245) | -0.0434 (0.0168) |                  |                 | -0.0568 (0.0257) |
|            | $R^2a$     | 0.9797           | 0.9790           | 0.9790           | 0.9790          | 0.9795           |
|            | AIC        | 617              | 624              | 627              | 627             | 624              |
|            | RMSE (cm)  | 1.3110           | 1.3349           | 1.3326           | 1.3326          | 1.3172           |
|            | LL         | -303*            | -305*            | -309             | -309            | -306*            |
|            | Q          | $\alpha_1$       | 0.0093 (0.0007)  | 0.0094 (0.0007)  | 0.0093 (0.0007) | 0.0092 (0.0007)  |
| $\alpha_2$ |            | 4.1389 (1.1978)  | 4.1384 (1.1973)  | 4.1384 (1.1967)  | 5.2704 (2.1565) | 4.1384 (1.1967)  |
| $\beta_4$  |            |                  |                  |                  | 0.0150 (0.0055) |                  |
| $R^2a$     |            | 0.9897           | 0.9897           | 0.9897           | 0.9898          | 0.9897           |
| AIC        |            | 3709             | 3709             | 3709             | 3703            | 3709             |
| RMSE (cm)  |            | 1.0918           | 1.0918           | 1.0918           | 1.0888          | 1.0918           |
| LL         |            | -1849            | -1849            | -1849            | -1847*          | -1849            |

P, OC, OB, and Q are the species groups *Pinus*, other conifers, other broadleaves, and *Quercus*, respectively;  $\beta_i$  is the neighborhood effect parameter,  $i = 1, 2, 3$ , and 4, for species groups P, OC, OB, and Q, respectively; AIC is the Akaike information criterion;  $R^2a$  is the adjusted coefficient of determination; RMSE is the root mean square error, LL is the log-likelihood. Asterisk indicates that the model involving equivalent neighborhood effects was better than the model without neighborhood effect (Eq. 12), using a likelihood ratio test at  $\alpha = 0.05$

group effects could be detected, when CI1, CI4, or CI8 was used. When CI1 was used, significantly negative hetero-group effects from all other three species groups on the species group OB could be detected. If CI7 or CI9 was used, however, only a negative effect of species group OC on species group OB could be detected. For the species group Q, only a positive hetero-group effect from the species group P was detected when using CI4 or CI8. The residual plots for the final models using CI1 are showed in Fig. 2.

## 4 Discussion

A series of dbh growth models were fitted for each species group, assuming no neighborhood effects (Eq. 12), equivalent

neighborhood effects, and nonequivalent neighborhood effects (Eq. 13). The methods of selecting neighboring trees and calculating CIs were compared based on the model fit statistics. Our results showed that it would be better to select neighboring trees in such way that distance between a subject tree and its neighbor was less than 1.5 times of their crown radii (i.e.,  $\delta = 1.5$  in Eq. 7). In the preliminary analysis, among the 12 competition indices, we found that using the dbh ratio-associated CI1 or CI4, the height ratio-related CI7 or CI8, or crown width ratio-connected CI9 could detect more significant neighborhood effects. Further analysis indicated that CI1 was preferred, in terms of fit statistics. No matter assuming equivalent or nonequivalent neighborhood effects, including neighborhood effects in the dbh growth models significantly improved the model performance. In either case, the values of

**Table 6** Parameter estimates and their asymptotic standard error (in parentheses), and fit statistics of individual tree dbh growth models fitted for each species group under the assumption of nonequivalent neighborhood effects and using different CIs

| Group        | Parameter    | CI1              | CI4              | CI7              | CI8              | CI9              |
|--------------|--------------|------------------|------------------|------------------|------------------|------------------|
| P            | $\alpha_1$   | 0.0064 (0.0003)  | 0.0066 (0.0003)  | 0.0064 (0.0003)  | 0.0065 (0.0003)  | 0.0066 (0.0003)  |
|              | $\alpha_2$   | 1.2559 (0.0546)  | 1.3350 (0.0596)  | 1.2738 (0.0564)  | 1.3989 (0.0692)  | 1.3520 (0.0622)  |
|              | $\beta_{11}$ | -0.0208 (0.0101) |                  | -0.1307 (0.0478) | 0.0196 (0.0075)  |                  |
|              | $\beta_{12}$ | -0.1688 (0.0487) | -0.0997 (0.0349) | -0.7729 (0.2906) | -0.1082 (0.0476) | -0.1184 (0.0415) |
|              | $\beta_{14}$ | -0.0776 (0.0213) | -0.0351 (0.0114) | -0.3203 (0.1210) | -0.0339 (0.0128) | -0.0357 (0.0166) |
|              | $R^2a$       | 0.9820           | 0.9819           | 0.9820           | 0.9820           | 0.9820           |
|              | AIC          | 10,913           | 10,921           | 10,922           | 10,927           | 10,926           |
|              | RMSE (cm)    | 1.2558           | 1.2585           | 1.2566           | 1.2559           | 1.2580           |
|              | LL           | -5448*           | -5454*           | -5452*           | -5455*           | -5456*           |
|              | OC           | $\alpha_1$       | 0.0040 (0.0009)  | 0.0053 (0.0010)  | 0.0042 (0.0009)  | 0.0042 (0.0009)  |
| $\alpha_2$   |              | 0.6924 (0.0734)  | 0.7756 (0.0848)  | 0.7383 (0.0881)  | 0.7383 (0.0881)  | 0.7383 (0.0881)  |
| $\beta_{21}$ |              |                  | -0.0579 (0.0257) |                  |                  |                  |
| $\beta_{22}$ |              |                  | -0.1113 (0.0553) |                  |                  |                  |
| $\beta_{24}$ |              | -0.1291 (0.0512) |                  |                  |                  |                  |
| $R^2a$       |              | 0.9770           | 0.9779           | 0.9773           | 0.9773           | 0.9773           |
| AIC          |              | 934              | 931              | 935              | 935              | 935              |
| RMSE (cm)    |              | 1.3060           | 1.2825           | 1.2972           | 1.2972           | 1.2972           |
| LL           |              | -461             | -460             | -463             | -463             | -463             |
| OB           |              | $\alpha_1$       | 0.0069 (0.0013)  | 0.0082 (0.0016)  | 0.0058 (0.0012)  | 0.0144 (0.0026)  |
|              | $\alpha_2$   | 0.8301 (0.0998)  | 0.9387 (0.1282)  | 0.8422 (0.1169)  | 2.5370 (1.1945)  | 0.8560 (0.1205)  |
|              | $\beta_{31}$ | -0.0717 (0.0355) | -0.0469 (0.0213) |                  |                  |                  |
|              | $\beta_{32}$ | -0.3262 (0.1320) |                  | -1.2674 (0.6372) |                  | -0.3524 (0.1764) |
|              | $\beta_{33}$ | -0.0723 (0.0341) | -0.2980 (0.1132) |                  | -0.2079 (0.0524) |                  |
|              | $\beta_{34}$ | -0.1260 (0.0718) |                  |                  |                  |                  |
|              | $R^2a$       | 0.9798           | 0.9787           | 0.9783           | 0.9794           | 0.9784           |
|              | AIC          | 619              | 622              | 625              | 627              | 625              |
|              | RMSE (cm)    | 1.3077           | 1.3428           | 1.3558           | 1.3193           | 1.3527           |
|              | LL           | -302*            | -305*            | -309             | -307*            | -307             |
| Q            | $\alpha_1$   | 0.0093 (0.0007)  | 0.0094 (0.0007)  | 0.0093 (0.0007)  | 0.0092 (0.0007)  | 0.0093 (0.0007)  |
|              | $\alpha_2$   | 4.1389 (1.1978)  | 4.1384 (1.1973)  | 4.1384 (1.1967)  | 5.0671 (1.9593)  | 4.1384 (1.1967)  |
|              | $\beta_{41}$ |                  |                  |                  | 0.0211 (0.0066)  |                  |
|              | $R^2a$       | 0.9897           | 0.9897           | 0.9897           | 0.9898           | 0.9897           |
|              | AIC          | 3709             | 3709             | 3709             | 3700.4           | 3709             |
|              | RMSE (cm)    | 1.0918           | 1.0918           | 1.0918           | 1.0886           | 1.0918           |
|              | LL           | -1849            | -1849            | -1849            | -1844*           | -1849            |

P, OC, OB, and Q are the species groups *Pinus*, other conifers, other broadleaves, and *Quercus*, respectively; con-group and hetero-group neighborhood effects were represented by  $\beta_{ij}$ ,  $i = 1, 2, 3, 4$  and  $j = 1, 2, 3, 4$ , for species group P, OC, OB, and Q, respectively (i.e.,  $\hat{\beta}_{12}$  represents the competition of species group OC on species group P); AIC is the Akaike information criterion;  $R^2a$  is the adjusted coefficient of determination; RMSE is the root mean square error; LL is the log-likelihood. Asterisk indicates that the models under the assumption of nonequivalent neighborhood effect was better than the models under equivalent neighborhood effect assumption, based on a likelihood ratio test at  $\alpha = 0.05$

$R^2a$  in our models were greater than 0.977 (Tables 5 and 6). In previous studies using the distance-dependent or distance-independent CIs, all  $R^2$  values were less than 0.69 for modeling either dbh increment (Bella 1971; Daniels 1976; Tomé and Burkhardt 1989; Zhao et al. 2006), basal area increment (Andreassen and Tomter 2003; Corral et al. 2005; Monserud and Sterba 1996; Perin et al. 2016; Tenzin et al. 2017; Tomé

and Burkhardt 1989), or height annual increment (Daniels 1976; Martin and Ek 1984).

In general, distance-dependent individual tree growth models more adequately described interactions among species or species groups, especially in mixed-species stands, than distance-independent models or models without any CIs (Sharma et al. 2016). In the current study, our crown-



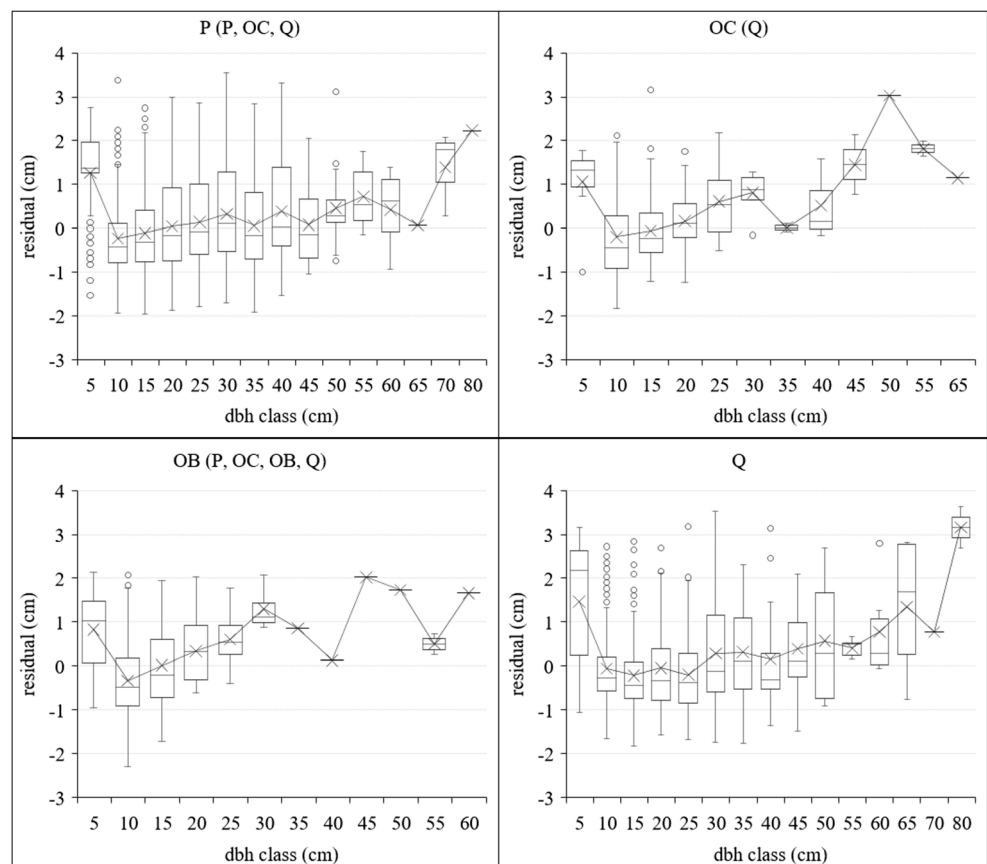
overlapping distance-dependent models described tree dbh growth well for all four species groups. The results of the likelihood ratio tests indicated that the models assuming non-equivalent neighborhood effects performed better than the ones assuming equivalent neighborhood effects for species groups P and OB. For species groups OC and Q, even though assuming nonequivalent neighborhood effects did not further improve model performance, we can still distinguish some intra-species-group (or con-group) and inter-species-group (or hetero-group) competition effects (Tables 5 and 6). Our results further demonstrated that distinguishing neighbor trees by species groups is necessary for modeling mixed-species stands (Zhao et al. 2006). The significant estimates of  $\hat{\beta}_{ii}$  and  $\hat{\beta}_{ij(i \neq j)}$  in the model 13 (Eq. 13) suggested intra-species-group (or con-group) competition and inter-species-group (or hetero-group) competition, respectively. Our models indicated there were significant and negative con-group competition for species groups P, OC, and OB (Table 6). Both species groups OC and Q had negative competition effects on species group P, but species group P had no significant effect on species group OC or Q. All species groups P, OC, and Q have negative effects on tree growth of species group OB, but species group OB did not have significant effect on other three species groups. This demonstrated that a distance-dependent individual tree modeling approach is effective to identify tree

complex competing statuses in mixed-species stands with high tree species diversity (Maleki et al. 2015; Zhao et al. 2006). In order to study the dynamics of mixed-species forests, the repeated measures of stem-mapped permanent plots provide the best source of data to characterize the competition effects (Zhao et al. 2006).

For the species groups with significant hetero-group effects, e.g., species groups OC and Q that negatively affected on species group P (Table 6), they shared the growing space and competed for the available resources on a given site (del Río et al. 2016). Distinguishing the species groups in neighboring trees in the distance-dependent growth models could describe the different competition status among the species groups. For example, species group Q seems to have an advantageous competition in the mixed-species stands. This species group had significantly negative effects on the other three species groups, but other species groups did not have significant influence on its growth. The partial reason is that this species group is intermediate shade-tolerant, (Zeide 1985), and it seems to be less sensitive to competition (Zhang et al. 2017).

Under the assumption of equivalent competition effects among species groups, if the CI8 was used, there were no significant competition effects detected for species group. However, under the assumption of nonequivalent competition

**Fig. 2** Box-and-whisker plots of residuals of the final dbh growth models by species group and using CI1, with detectable con-group and hetero-group neighborhoods effects. P, OC, OB, and Q are the species groups *Pinus*, other conifers, other broadleaves, and *Quercus*, respectively



effects, significant con-group competition was detectable for species group P and species groups OC and Q negatively affected the species group P growth. On the other hand, if the CI7 and CI8 were used, there were no significant equivalent competition effects detected for species group OB, but significant hetero-group competition was detectable for species group OC and a negative con-group effect with CI7 and CI8, respectively (Table 6).

When CI1 was used, the final growth models included one con-group and two hetero-group effects for species group P, one con-group and three hetero-group effects for species OB, one hetero-group effect for species group OC, and no competition effect terms for species group Q. All the significant competition terms were negative. The residual plots showed that the final models generally fitted the data well, although dbh growth was underestimated for the extremely large dbh classes (Fig. 2). The developed models have the capacity to predict tree diameter growth for each species group in the mixed-species stands in Durango, Mexico, and could be used in the forest management programs in this area. Especially when age information was not available in plot inventory data, our age-independent models are very useful for predicting tree dbh growth in mixed-species stands in the research area.

## 5 Conclusion

Neighborhood effects on tree dbh growth in natural mixed-species stands in Mexico were evaluated using an age-independent spatially explicit diameter growth model. Our

results demonstrated that it is necessary to identify the neighboring trees by species groups: *Pinus*, other conifers, other broadleaves, and *Quercus*. The fitted growth models had high value of the coefficient of determination ( $> 97.72\%$ ). In general, the assumption of nonequivalent neighborhood effects was supported. The negative con-group neighboring effects existed for all species groups, except for species group *Quercus*. All detectable hetero-group effects were negative, except that species group *Pinus* had positive effects on species group *Quercus*. The resultant age-independent dbh growth models can be used to predict tree diameter growth for Mexican mixed-species forests and the competition can be incorporated as distance-dependent competition indices. The choice of competition indices may influence the prediction of some species groups. Our study showed that the dbh ratio-associated competition indices (i.e., CI1 and CI4) were preferred over others.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

## Appendix 1

**Table 7** The values of the log-likelihood for individual dbh growth models fitted for each species group and all CIs, under assumption of equivalent neighborhood effect for  $\delta = 1.5$  value

| Group | CI1    | CI2   | CI3    | CI4    | CI15   | CI16   | CI17   | CI18   | CI19   | CI10   | CI11   | CI12  |
|-------|--------|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-------|
| P     | -5458* | -5463 | -5453* | -5452* | -5460* | -5463  | -5456* | -5462  | -5460* | -5462  | -5458* | -5463 |
| OC    | -461*  | -462  | -462   | -461*  | -462   | -462   | -463   | -463   | -463   | -462   | -463   | -462  |
| OB    | -303*  | -305* | -305*  | -305*  | -307   | -307   | -309   | -309   | -306*  | -307   | -308   | -308  |
| Q     | -1849  | -1848 | -1849  | -1849  | -1848  | -1847* | -1849  | -1847* | -1849  | -1847* | -1849  | -1849 |

P, OC, OB, and Q are the species groups *Pinus*, other conifers, other broadleaves, and *Quercus*, respectively. Asterisk indicates that neighborhood effect was significant at  $\alpha = 0.05$ , based on the log-likelihood ratio tests between these models with the models without neighborhood effects (Table 4). In the same way, the competition indices were also calculated with  $\delta = 1.0, 2.0, 2.5$ , respectively. Then the diameter growth model under the assumption of equivalent neighborhood effects was fitted to each species group, using these competition indices. The results of the likelihood ratio test indicated that  $\delta = 1.5$  was the best and CI1, CI4, CI7, CI8, and CI9 were better for most of species groups, in terms of the Log-likelihood value (the higher is the better) and the number of species groups for which the significant competition effect was detected

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