The Impact of Competition for Growing Space on Diameter, Basal Area and Height Growth in Pine Trees

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Abstract

Competition between trees exists due to limited resources required for tree growth. The growth dependent competitive situation of each tree is described in growth models by calculating distance dependent and distance independent competition indices, CIs. The first aim of the research was to compare distance dependent and distance independent CIs and find the best variant with highest predictive capacity to simulate basal area and height growth of pine trees under Lithuanian conditions. The second aim was to describe the impact of competition on the tree diameter and height growth of pine trees by using those CIs that showed the highest predictive capacity. The research was based on data collected from eighteen permanent sample plots. The study evaluated 2 distance independent and 18 distance dependent CIs using partial correlation analysis.

The results showed that the distance dependent CIs had a higher predictive capacity for basal area growth of pine trees. The CI proposed by Biging and Dobbertin (1992) combined with the selection method of an inverse search cone at height to crown base with opening angle of 80 degrees is recommended for developing basal area increment models used in single tree level growth simulators in Lithuania.

While modelling tree height growth, distance dependent CIs did not show better results than the distance independent CIs. Hegyi's (1974) distance independent CI scored the highest partial correlation coefficients in predicting mean annual height increment. Generally, poor ability of competition indices to predict periodic mean annual height increment was observed under growth conditions prevalent in Lithuania.

The results also showed that an increase in competition always had a negative impact on tree diameter growth, but a low level of competition increased tree height growth compared to no competition and additional competition had a negative impact to tree height growth.

Key words: basal area, competition-dependent, competition indices, diameter, distance dependent, distance independent, growth, height, increment, tree.

Introduction

Prior to the formulated introduction and use of single tree level (STL) simulators to forest management in Lithuania (Linkevičius et al. 2011) research had to define the most appropriate competition indices (CIs) for Lithuanian growth conditions. As Pretzsch (2009) argues, CIs are crucial in forest management because they comprise the core of STL simulators by adjusting the growth of subject trees to certain growth conditions in the stands. Thus, the main tasks of this study are to estimate the impact of competition for growing space on diameter, basal area and height growth of trees and to recommend the best CI for developing Lithuanian basal area and height increment models used in STL simulators.

Competition between trees exists when resource (sunlight, water and nutrients) availability falls below the sum requirement of the stand population for optimal growth (Brand and Magnussen 1988). The competitive stress of a target tree is estimated by calculating its CIs, as they "quantify the space occupation and spatial constellation of individual trees within a stand and indicate the associated access to resources in one or a few surrogate variables" (Pretzsch 2009:334). Functions that quantify the competition range from simple formulations, expressing the hierarchical position, to complex indices that incorporate the size of, distance to, and number of local neighbours (Burkhart and Tome 2012). Munro (1974) classifies all CIs into two major groups: distance independent and distance dependent.

Distance independent CIs are based on functions of stand or tree level variables in relation to the average or maximum tree value of the stand and do not require individual tree coordinates (Burkhart and Tome 2012). For example, the Crown Competitor Factor, developed by Krajicek et al. (1961) and based on potential crown extension, is the sum of the maximum crown areas for all trees in the stand divided by stand area. The CI Basal Area of Larger trees sums the basal areas of all trees larger than the target tree (Wykoff et al. 1982). Relative size indices estimate the hierarchical position of certain trees within the stand by comparing the diameters, heights or crown variables of trees (Hegyi 1974, Wensel et al. 1987, Biging and Dobbertin 1995).

Distance dependent CIs take into account relative or absolute tree positions. Indices are calculated in two steps: the competing trees are determined by applying competitor selection methods and then the strength of competition from each tree is estimated (Pretzsch 2009).

Competitor selection methods can be divided into five groups: 1) Fixed area (Hegyi 1974, Pukkala and Kolström 1987) or a fixed number of nearest neighbours (Soares andTome 1999); 2) Area of influence overlap (Opie 1968, Bella 1971); 3) Competition elimination angle (Lee and Gadow 1997); 4) Angle count sampling with basal area factor, (Hamilton 1969, Daniels 1976, Glover and Hool 1979); and 5) Angle gauge (Biging and Dobbertin 1992, Pretzsch 1995 and Schröder 2004).

Most of the indices that estimate strength of competition can be grouped into three approaches:

• *influence zone* estimating competition according to the degree to which each tree must share its maximal zone of influence with the zones of other trees (Opie 1968);

• *growing space polygons* constructed around the subject tree (Moore et al. 1973, Adlard 1974, Alemdag 1978 and Pelz 1978);

• *size relation* based on relative size and distances between the subject tree and competitors. Relative size is expressed by tree diameter at breast height (Hegyi 1974, Daniels 1976), tree height (Hegyi 1974, Braathe 1980), horizontal and vertical angles captured at the subject tree (Pukkala and Kolström 1987, Rouvinen & Kuuluvainen 1997, Prevosto et al. 2000) and crown dimensions (Biging and Dobbertin 1992, Pretzsch 1995, Schröder 2004).

Previous analysis of CIs (Biging and Dobbertin 1992, Biging and Dobbertin 1995, Bachmann 1998) has identified that various authors have developed more than one hundred of these indices. Clearly, not all of these can be analysed in this study, so we selected CIs for further analysis based on results already presented by other authors.

a) Distance independent CIs. Lorimer (1983), Martin and (Ek 1984), Daniels et al. (1986), Corona and Ferrara (1989), Biging and Dobbertin (1995) and Castagneri et al. (2008), all conclude that distance independent CIs in pure stands performed as well as distance dependent CIs, and in some cases showed better results. So, distance independent CIs should not be excluded from this study. The distance independent CI 'basal area of larger trees', developed by Wykoff et al. (1982) was positively evaluated by Lorimer (1983) and Lee and Gadow (1997). Castagneri et al. (2008) found the distance independent CI developed by Hegyi (1974) to be better than more complex distance dependent CIs. So, these two distance independent CIs were selected for analysis.

b) Distance dependent CIs. Pukkala and Kolström (1987), Biging and Dobbertin (1992), Bachmann (1998) and Schröder (2004) showed the advantages of angle gauge methods over the other selection methods. Biging and Dobbertin (1992) found that the selection method with an inverse cone set on the stem base at an opening angle of 50-60 degrees (Pretzsch 1995) was better than other selection methods. Bachmann (1998) concluded that using an inverse cone (Pretzsch 1995) at the height of the greatest crown width with an opening angle of 60 degrees was most appropriate. Schröder (2004) proved that a selection method involving an inverse search cone set at the height to crown base with an opening angle of 80 degrees was the best in the particularities of East Germany's soil and environment. So, this study focuses on the angle gauge methods described by Biging and Dobbertin (1992), Pretzsch (1995) and Schröder (2004).

In estimating the strength of competition, Hegyi's (1974) approach was positively evaluated by Daniels (1976), Pukkala and Kolström (1987) and Holmes and Reed (1991). Biging and Dobbertin (1992) showed that the inclusion of estimated crown parameters (crown volume, crown surface area or horizontal area) substantially improved the performance of distance dependent measures. After evaluating many distance dependent CIs, Bachmann (1998) found that the index developed by Pretzsch (1995) was the most appropriate for tree growth modelling. Nagel (1999) proposed a CI based on horizontal crown area of competing trees estimated at the height of the greatest crown width i.e. at 66% of subject tree crown length. Schröder (2004) found that a size ratio CI based on vertical crown areas performed very well in two-storey stands. Thus, the methods proposed by Hegyi's (1974), Biging and Dobbertin (1992), Pretzsch (1995), Nagel (1999) and Schröder (2004) were selected for estimating the strength of competition.

It is important to point out that each angle gauge selection method combined with each competition estimation method results in a different competition index that is evaluated separately.

Our research study hypothesis was "Distance dependent competition indices yield higher partial correlation coefficients with tree basal area and height increment than distance independent competition indices".

Materials and Methods

Experimental data applied in the research. The study used data from two types of permanent experimental plots (PEPs) established by the Lithuanian Research Centre for Agriculture and Forestry. The first consisted of 16 PEPs – numbers 81-96 – established in 1983-1985 in older (7-75 years old), naturally regenerated, single layer stands that grow on typical pine sites (Кулешис 1989). The second consisted of 2 PEPs – numbers 201 and 206 – established in 1990 and 1992 respectively, in artificially regenerated, young pine stands (Kuliešis and Saladis 1998). All 18 PEPs are located in Lithuanian regions 3 and 4 (see Figure 1).

The rectangular design of PEPs 81-96 is basically the same, although the side measurements vary from 31-80m and the areas from 0.10-0.64ha. Each PEP has nine subplots sited on a 3x3 grid. Every subplot has co-ordinates (latitude and longitude) based on a precisely measured centre. The distance and the azimuth (horizontal angle measured clockwise from true north)

Figure 1. Lithuania pine productivity by regions and permanent experimental plots
Source: The first author's own work set in regions defined by Kuliešis 1997:60
Key:
Regions: 1-4
▲ – permanent experimental plots: 81-206
– Pine forests

from the centre of the subplot to the subject tree were recorded (see Кулешис 1989). The counting of trees in these PEPs started, according to their azimuth values, from the subplot's north-west corner and continued in a clockwise direction.

The experimental design of PEPs 201 and 206 is remarkably different. These plots were established to investigate the impact of thinning on the growth of pine stands. Thus, the PEPs were divided into 10 subplots, each of which was grown with various densities of trees. For this study, only 2 subplots in each of PEP 201 and 206 with no thinning intervention or control plots were taken into account. The trees in the subplots of PEPs 201 and 206 were counted in a continuous 'snaking' line moving from the bottom right corner to the top left corner. Coordinates of trees were estimated by measuring the distances between and inside the rows (Kuliešis and Saladis 1998).

Table 1 shows information about the characteristics of the experimental plots. The size of the experimental plots varied from 0.1 to 0.6 ha due to the different densities of the naturally regenerated stands. In order to have a 5% representative sample, at least 200 trees are required in the last periodic measurement (Antanaitis et al. 1975). The highest initial densities occurred in the youngest plots, 201(5,403 trees ha^{-1}) and 206 (4,906 trees ha^{-1}) and the lowest densities in the oldest plots 81 (474 trees ha^{-1}) and 91 (431 trees ha^{-1}).

The vegetation types of the experimental plots show the wide range of site conditions: they include *Cladoniosa, Vacciniosa, Vaccinio-myrtillosa,* and *Myrtillosa.* These are the main vegetation types for pine stands in Lithuania. When the experiment began in 1983 the age of the stands in the experimental plots ranged from 7 to 75 years. So the age coverage interval, in 2013, has increased to more than 100 years. All stands were single-layered monocultures of pine, with a pine proportion close to 100% (10P). However, some regeneration of spruce, birch, aspen, oak and maple was recorded.

The trees in the experimental plots were measured by applying a Lithuanian unified forest measurement methodology, defined by Kuliešis and Saladis (1998). Additionally, an up-to-date description of the field measurements, the modelling of missing tree level variables and the estimation of stand level variables is given in Kuliešis et al. (2012). The following measurements were recorded: species, status (alive, damaged or dead), tree coordinates, diameter at breast height, height, height to crown base, crown width (cw), age and horizontal position. Tree diameter at breast height was measured for all growing trees and height, height to crown base and crown width were measured only for sample trees (one of every five trees in a PEP).

Table 1. Characteristics of permanent experimental plots

Plot	Size ha	Vegetation types	Year of establishment	Age	Storey	Species	Trees ha^{-1}	Regeneration
			Experimental data					
81	0.54	*Myrtillosa*	1983	75	I	10P	474	Spruce, Oak
82	0.25	*Myrtillosa*	1983	31	I	10P	1000	Spruce, Birch, Aspen
83	0.64	*Vaccinio-myrtillosa*	1983	61	I	10P	592	Spruce, Birch, Oak, Maple
84	0.42	*Vaccinio-myrtillosa*	1983	40	I	10P	995	Spruce
85	0.42	*Vaccinio-myrtillosa*	1984	50	I	10P	964	
86	0.25	*Vacciniosa*	1984	48	I	10P	2328	
87	0.25	*Vaccinio-myrtillosa*	1984	50	I	10P	1560	Spruce
88	0.17	*Vaccinio-myrtillosa*	1984	29	I	10P	3041	
89	0.25	*Vaccinio-myrtillosa*	1984	39	I	10P	1644	
90	0.42	*Vaccinio-myrtillosa*	1984	66	I	10P	814	
91	0.51	*Vaccinio-myrtillosa*	1984	72	I	10P	431	Spruce, Oak
92	0.42	*Vacciniosa*	1984	60	I	10P	1017	
93	0.16	*Vacciniosa*	1984	38	I	10P	1850	
94	0.49	*Vacciniosa*	1984	67	I	10P	716	
95	0.36	*Cladoniosa*	1984	68	I	10P	925	Birch
96	0.10	*Vacciniosa*	1984	44	I	10P	2865	
201	0.36	*Vaccinio-myrtillosa*	1990	8	I	10P	5403	
206	0.22	*Vaccinio-myrtillosa*	1992	7	I	10P	4906	
			Validation data					
5	0.25	*Vaccinio-myrtillosa*	1983	34	I	10P	2096	
7	0.40	*Vaccinio-myrtillosa*	1983	60	I	7P2S1B	583	Spruce

P – pine *Pinus sylvestris*, S – spruce *Picea abies*, B – birch *Betula pendula*

Tree diameters (d), at breast height (1.3 meter up from the root collar), were measured using a calliper with a 1mm degree of graduation. In order to assure that measurements were done always in the same direction, the perpendicular arms of the tree calliper were directed at the centre of the subplots.

A clinometer (±0.5 degree of precision) was used to measure tree height (h) and tree height to crown base (hcb). Crown width (cw) measurements followed the methodology explained by Röhle (1986), in which the four cardinal directions (north, east, south and west) of the crown radius were measured using a tape measure (± 0.1m degree of graduation). Tree measurements occurred at periodic five-year intervals - 1984, 1989, 1994, 1998, 2004 and 2009 (for PEPs 81-96); 1994, 1998, 2004 and 2009 for PEP 201; 1998, 2004 and 2009 for PEP 206. The study used MS Excel to record and calculate individual diameter (d) and height (h) increments.

The database of tree measurements, and tree characteristics data, compiled since 1983 by the Lithuanian Research Centre for Agriculture and Forestry comprises 38,600 (d measurements), 11,000 (h) and 8,000 (hcb). In 2009, crown widths (n=2,450) were measured for the first time.

Analysis of competition for growing space. The impact of competition on the mean annual increment in diameter, basal area and height was analysed by applying the methods for evaluating CIs referred to above (using the *CroCom* analytical programme). In the distance dependent analysis, this study focuses only on angle gauge selection methods. The search cone area is calculated by using the following formula:

$$dist_{tj} < (h_i - hcb_j) \cdot \tan\left(90 - \frac{\alpha}{2}\right)^{-1}, \qquad (1)$$

where: $dist_{ij}$ = distance between competitor and target trees in metres, h_i = height of target tree in metres, hcb_j = tree height to crown base of competitor tree j in metres, α = cone opening angle in degrees.

When setting the search cone two important features should be taken into account. The first is the location of where the bottom of the inverse cone is set and the second is the opening angle of the search cone. This study focuses on three separate positions (see Figure 2) to set the inverse cone: a) at the height of the crown base, b) at the height of widest crown width, and c) at the stem base. The opening angle of the search cone is either 60 or 80 degrees. Trees that fall inside the search cone area are identified as competitors.

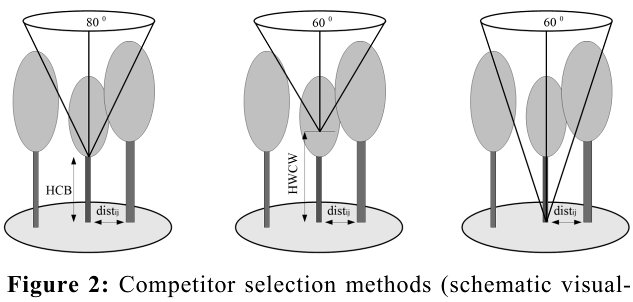

Figure 2: Competitor selection methods (schematic visualizations): (a) height to crown base 80 degrees (HCB 80), (b) height to the widest crown width 60 degrees (HWCW 60), (c) stem base 60 degrees (SB 60), distij=distance between target and competitor trees.
Source: based on competitor selection methods proposed by (a) Nagel et al. 2002; (b) Pretzsch 1995, and (c) Biging and Dobbertin 1992.

In the context of estimating the strength of competition, two distance independent CIs, developed by Wykoff et al. (1982) and Hegyi (1974) were selected for analysis. In additional, six distance dependent CIs proposed by Hegyi (1974), Biging and Dobbertin (1992), Pretzsch (1995), Schröder (2004) and Nagel (1999) were taken into account. The indices developed by Wykoff et al. (1982) and Hegyi (1974) are based on the relative sizes of tree diameters at breast height. The CIs developed by Pretzsch (1995), Schröder (2004) and Nagel (1999) and the two developed by Biging and Dobbertin (1992), are based on the relative sizes of crown parameters such as crown volume, and horizontal and vertical crown areas. Table 2 shows the formula for each of the six CIs selected.

Table 2. Competition Index Formulae to Estimate Competition between Trees

No.:	DEVELOPED BY	COMPETITION INDEX
	Distance independent	
CI1	Wykoff et al. (1982)	$CI_1 = \sum_{j=1}^{Kj} BAL$
CI2	Hegyi (1974)	$CI_2 = \sum_{j=1}^{Kj} \frac{d_j}{d_i}$
	Distance dependent	
CI3	Hegyi (1974)	$CI_3 = \sum_{j=1}^{Kj} \frac{d_j}{d_i \cdot (dist_{ij} + 1)}$
CI4	Biging and Dobbertin (1992)	$CI_4 = \sum_{j=1}^{Kj} \frac{hca_j^{(SH)}}{hca_i}$
CI5	Biging and Dobbertin (1992)	$CI_5 = \sum_{j=1}^{Kj} \frac{cv_j^{(SH)}}{cv_i}$ $cv = a_1 \cdot d^{a_2} \cdot h^{a_3} \cdot cr^{a_4}$
CI6	Pretzsch (1995)	$CI_6 = \sum_{j=1}^{Kj} \beta \frac{hca_j^{(HSCB_i)}}{hca_i}$
CI7	Schröder (2004)	$CI_7 = \sum_{j=1}^{Kj} \frac{vca_j}{vca_i \cdot (dist_{ij} + 1)}$
CI8	Nagel (1999)	$CI_8 = \sum_{j=1}^{Kj} hca_j (HWCW_i)$

Key: CI = competition index, BAL = basal area of larger trees [cm^2], K = number of trees per plot, i = subject tree, j = competitor(s), d = diameter at breast height [cm], $dist_{ij}$ = distance between competitor and target trees [m], hca = tree horizontal crown area [m^2], cv = crown volume [m^3], h = tree height [m], cr = tree crown ratio, SH = height of intersection of search cone and tree axis, β = gradient of straight line connecting base of search cone and top of competitor tree, vca = vertical crown area [m^2], $HSCB$ = height of search-cone base, $HWCW$ = height of greatest crown width in 66 % of subject tree height [m], a_1, a_2, a_3, a_4 = regression coefficients.

Each of the three competitor selection methods (stem base; height to crown base and height to widest crown width) were combined with six methods for distance dependent estimations of strength of competition (n=3x6=18 CIs). An additional 2 distance independent meant that a total of 20 CIs were chosen for more detailed statistical analysis (see Table 3).

Partial methods to evaluate competition between trees. At each five-year interval measurements of competition between trees in each PEP were assessed separately by partial correlation analysis. Measurements for trees growing at the edges of the PEPs were not included in this competition assessment. The reason for this is that competitor trees growing outside the PEPs were not measured and this absence of data had a negative effect on the competition values for trees growing at the edges. Consequently, buffer zones were established around the edges of the PEPs, 10m wide for PEPs 81-96, and 5m for PEPs 201 and 206. Only those trees growing within the buffer zones were included in the competition analysis for both distance independent and distance dependent analysis.

Previous studies have shown that the correlations of the periodic mean annual basal area and height increment with the CIs were found to be non-linear (Biging and Dobbertin 1992, Schröder 2004). So, the values of the CIs were transformed into a natural logarithmic form.

The partial correlation analysis was undertaken in three steps. First, using simple linear regression, periodic annual basal area or height increments were modelled from tree basal area or tree height respectively. Second, the residuals between the estimated and the modelled values were calculated. Logarithmic CIs were modelled from tree basal area or from tree height and the residuals between the estimated and the modelled values were also recorded. Third, in order to show the strength of the relationships between the residuals, that were estimated in the first and second step, separately for tree basal area or for tree height, Pearson's correlation coefficient (r) was estimated (significance value of d≤0.05). After estimating Pearson's correlation coefficient for all plots and for all measurements that come each measurement year, the mean partial correlation coefficients for each CI and selection method combination were calculated. In the same manner, the mean significances of correlation for each CI and the selection method combination were calculated (and labelled 'share of significant cases' in Tables 3 and 4). The mean values for each CI were estimated (using SPSS) from 87 separate analyses from the 18 PEPs and from measurements of the six measurement years, which amounted to 1,740 separate analysis.

Table 3. Combinations of the Competitor Selection Methods and the Competition Indices analysed in this study

Code	CI*	Type	Competitor Selection Method
CI_1-DI	CI_1	Distance Independent	None
CI_2-DI	CI_2	Distance Independent	None
CI_3-HCB80	CI_3	Distance Dependent	Height to Crown Base with opening angle 80° (HCB 80)
CI_4-HCB80	CI_4	Distance Dependent	Height to Crown Base with opening angle 80° (HCB 80)
CI_5-HCB80	CI_5	Distance Dependent	Height to Crown Base with opening angle 80° (HCB 80)
CI_6-HCB80	CI_6	Distance Dependent	Height to Crown Base with opening angle 80° (HCB 80)
CI_7-HCB80	CI_7	Distance Dependent	Height to Crown Base with opening angle 80° (HCB 80)
CI_8-HCB80	CI_8	Distance Dependent	Height to Crown Base with opening angle 80° (HCB 80)
CI_3-HWCW60	CI_3	Distance Dependent	Height to Widest Crown Width with opening angle 60° (HWCW 60)
CI_4-HWCW60	CI_4	Distance Dependent	Height to Widest Crown Width with opening angle 60° (HWCW 60)
CI_5-HWCW60	CI_5	Distance Dependent	Height to Widest Crown Width with opening angle 60° (HWCW 60)
CI_6-HWCW60	CI_6	Distance Dependent	Height to Widest Crown Width with opening angle 60° (HWCW 60)
CI_7-HWCW60	CI_7	Distance Dependent	Height to Widest Crown Width with opening angle 60° (HWCW 60)
CI_8-HWCW60	CI_8	Distance Dependent	Height to Widest Crown Width with opening angle 60° (HWCW 60)
CI_3-SB60	CI_3	Distance Dependent	Stem base with opening angle 60° (SB 60)
CI_4-SB60	CI_4	Distance Dependent	Stem base with opening angle 60° (SB 60)
CI_5-SB60	CI_5	Distance Dependent	Stem base with opening angle 60° (SB 60)
CI_6-SB60	CI_6	Distance Dependent	Stem base with opening angle 60° (SB 60)
CI_7-SB60	CI_7	Distance Dependent	Stem base with opening angle 60° (SB 60)
CI_8-SB60	CI_8	Distance Dependent	Stem base with opening angle 60° (SB 60)

* see Table 2 for explanations of CI_1-CI_8

The impact of competition on (i) relative diameter and (ii) relative height increments. Once the most influential CIs for the periodic mean annual basal area and height increment had been identified, it was necessary to show how the relative values of the periodic mean annual increments of diameter (i) change when competition between trees increases. To achieve this, all the sample trees were grouped according to the values of the most influential distance dependent CIs. The first group comprised trees with a CI value d≤2; the second group comprised trees with a CI value > 2 but d≤4. The last group comprised trees with a CI > 24 but d≤26.

To show how relative periodic mean annual height increments (ii) change with increasing competition, all the sample trees were grouped according to the values of the most influential distance dependent CIs (CI Group). The first, CI Group 1 comprised sample trees with a CI value d≤1; CI Group 2 with a CI value of > 1 d≤2; CI Group 3 > 2 d≤3, CI Group 4 > 3d≤4, CI Group 5 >4d≤6. The last CI Group comprised sample trees with a CI value > 58 d≤60. The quantity and sample population size of the groups were based on several conditions. Firstly, a sufficient quantity of groups was needed to build a valid model; secondly, there needed to be a sufficiently large sample population (trees) in each group to be able to derive a representative arithmetic mean with a confidence level equal to 95% (Čekanavičius and Murauskas 2000). Next, for each CI Group, the mean values of the periodic mean annual diameter or height increments were calculated. In the final step, regression analysis was conducted between mean CI values in each group and relative values (the ratio between value in group and maximum value of groups) of the periodic mean annual diameter or height increments in each group respectively by fitting the appropriate regression curve (see Figure 3).

Results

The principles of partial correlation analysis. Figure 3 shows, as an example, the results from PEP 88, 1994 data and CI_4 combined with the HCB 80 selection method. In Figure 3a, the simple linear regression shows that logarithmic CI_4 with selection method HCB 80 explained 57% of the periodic mean annual tree basal area increment (i_{ba}) variation (R^2 = 0.57).

However, as shown in Figure 3b, the control variable basal area (ba) explained 53% of i_{ba} variation (R^2 = 0.53). Figure 3c shows a strong relationship between CI_4 and basal area (R^2 = 0.57). Thus, as shown in Figure 3d, CI_4 explained the additional 21% of the varia-

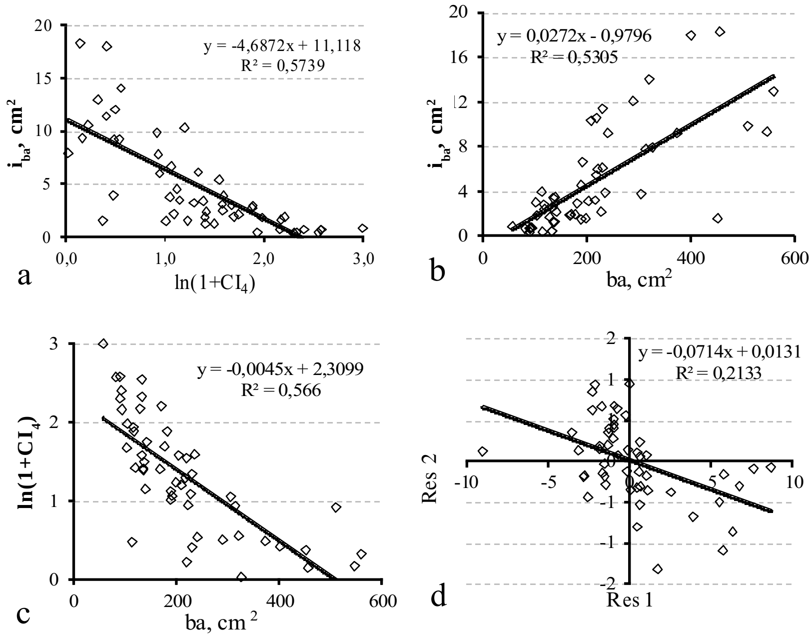

Figure 3. Partial correlation analysis in permanent experimental plot 88 and 1994 inventory, and CI_4 combined with the HCB 80 competitor selection method. Linear regression: (a) periodic mean annual basal area increment (i_{ba}) and logarithmic CI_4, (b) periodic mean annual basal area increment (i_{ba}) and basal area, (c) logarithmic CI_4 and basal area, (d) residuals observed from (b, Res_1) and (c, Res_2) linear regressions

tion in i_{ba} that is not explained by the basal area of the tree. By plotting the residuals obtained from the i_{ba} and ba regression (Res_1) against the residuals of the CI_4 and ba regression, the square of Pearson's correlation coefficient assumes a value of $R^2 = 0.21$ with significance level equal to 0.00053 (Res_2).

Partial impact of competition on periodic mean annual basal area (i_{ba}) increment. Table 4 shows the ranking of all selection methods with all CIs according to their statistical influence on i_{ba}. Our analysis showed that the selection method HCB 80 combined with CI_4 (coded as CI_4- HCB 80) was the most effective for i_{ba} modelling. This combination scored the highest mean partial correlation coefficient of -0.168 and the largest share of significant cases (39.08%). Index CI_5 combined with selection method HCB 80 (CI_5-HCB 80) was ranked second. The mean partial correlation coefficient for this combination was -0.161 and the proportion of significant cases was 34.48%. Index CI_6 combined with selection method HCB 80 (CI6-HCB 80) was ranked third. Its mean partial correlation coefficient was lower than previous combinations (-0.152), but the share of significant cases remained high at 34.48%. Index CI_8 combined with selection method SB 60 (CI_8-SB 60) showed the poorest performance of the distance dependent indices. Its mean partial correlation coefficient was only -0.073 and the share of significant cases was 21.84%. The distance independent indices CI_2 and CI_1 (CI_2-DI and CI_1-DI) had low impacts on i_{ba} and were ranked lowest with mean partial correlation results of -0.063 and 0.067 respectively and proportion of significant cases of 14.94% and 8.05%, respectively.

In summary, the partial influence of 18 distance dependent and 2 distance independent CIs on the periodic mean annual basal area increment was assessed. The distance dependent index CI_4 combined with the selection method HCB 80 had the highest mean partial correlation value and highest mean share

Table 4. Ranking of competition indices (CI) according to their effect on the periodic mean annual basal area increment. Summarized mean results from all experimental plots and inventories

I_{ba}=f(ba) mean R^2	Ranking CI	Code	Partial correlation	
			Mean Pearson Coefficient (*r*)	Share of significant cases %
0.521	1	CI_4-HCB 80	-0.168	39.08
	2	CI_5-HCB 80	-0.161	34.48
	3	CI_6-HCB 80	-0.152	34.48
	4	CI_7-HCB 80	-0.151	29.89
	5	CI_6-SB 60	-0.147	33.33
	6	CI_6-HWCW 60	-0.145	25.29
	7	CI_7-HWCW 60	-0.137	26.44
	8	CI_8-HWCW 60	-0.136	28.74
	9	CI_5-SB 60	-0.135	29.89
	10	CI_7-SB 60	-0.134	32.18
	11	CI_8-HCB 80	-0.132	28.74
	12	CI_3-HCB 80	-0.129	24.14
	13	CI_3-HWCW 60	-0.128	26.44
	14	CI_4-SB 60	-0.114	28.74
	15	CI_4-HWCW 60	-0.113	16.09
	16	CI_3-SB 60	-0.102	19.54
	17	CI_5-HWCW 60	-0.089	10.34
	18	CI_8-SB 60	-0.073	21.84
	19	CI_2-DI	-0.063	14.94
	20	CI_1-DI	0.067	8.05

HCB 60 is height to crown base (opening angle of 60°)
HWCW 60is height to widest crown width (opening angle of 60°)
SB 60 is stem base (opening angle of 60°)
SB 80 is stem base (opening angle of 80°)

of significant cases. Distance independent CIs showed the smallest mean partial capacity to predict the mean annual basal area increment, however the difference in the mean partial correlation coefficient between the best distance dependent CI and the best distance independent CI was only 0.105. No CI performed significantly better than any of the others. The hypothesis "Distance dependent competition indices had higher partial correlation with tree basal area increment than distance independent competition indices" formulated at the beginning was confirmed by these results.

Partial impact of competition on periodic mean annual height (i_h) increment. Table 5 shows the ranking of all of the selection methods associated with all of the CIs, according to their influence on the periodic mean annual height increment (i_h). Contrary to all expectations, the distance independent index CI_2 (coded as CI_2-DI) showed the highest mean partial correlation coefficient of -0.264 and the highest share of significant cases of 27.59%. The other distance independent index CI_1 (CI_1-DI) was ranked as 11th with a mean partial correlation coefficient of -0.148 and a share of significant cases of 18.39%. The best distance dependent index was ranked as 2nd and was CI_4 combined with selection method SB 60 (CI_4-SB 60) with a mean partial correlation coefficient of -0.221 and a share of significant cases of 20.69%. Its mean partial correlation coefficient was lower than the respective value of the distance independent index CI_2 by 0.043. The distance dependent index CI_5 combined with selection method SB 60 (CI_5-SB 60) was ranked as 3rd with a mean partial correlation coefficient of -0.211 and a share of significant cases of 20.69%. The least influential CI of all, ranked as 20th, was the distance dependent index CI_8 combined with selection method SB 60 (CI_8-SB 60), its partial correlation coefficient was 0.0528 and its share of significant cases was 1.15 %.

Therefore, the results showed that the formulated hypothesis "Distance dependent competition indices had higher partial correlation with tree height increment than distance independent competition indices" is incorrect and, thus, had to be rejected.

Table 5: Ranking of competition indices (CI) according to their effect on the periodic mean annual height increment. Summarized mean results from all experimental plots and inventories

i_h=f(h) mean R^2	Ranking CI	Code	Partial correlation	
			Mean Pearson Coefficient (*r*)	Share of significant cases %
0.118	1	CI_2-DI	-0.264	27.59
	2	CI_4-SB 60	-0.221	20.69
	3	CI_5-SB 60	-0.211	20.69
	4	CI_3-SB 60	-0.209	24.14
	5	CI_6-SB 60	-0.194	20.69
	6	CI_7-HCB 80	-0.190	14.94
	7	CI_7-SB 60	-0.187	18.39
	8	CI_6-HCB 80	-0.186	18.39
	9	CI_5-HCB 80	-0.159	14.94
	10	CI_3-HCB 80	-0.148	9.20
	11	CI_1-DI	-0.148	18.39
	12	CI_4-HCB 80	-0.142	11.49
	13	CI_6-HWCW 60	-0.137	12.64
	14	CI_7-HWCW 60	-0.129	12.64
	15	CI_4-HWCW 60	-0.125	8.05
	16	CI_5-HWCW 60	-0.116	6.90
	17	CI_3-HWCW 60	-0.114	8.05
	18	CI_8-HWCW 60	-0.026	4.60
	19	CI_8-HCB 80	0.016	0.00
	20	CI_8-SB 60	0.052	1.15

HCB 60 is height to crown base (opening angle of 60°)
HWCW 60 is height to widest crown width (opening angle of 60°)
SB 60 is stem base (opening angle of 60°)
SB 80 is stem base (opening angle of 80°)

Impact of competition on relative diameter and relative height increment. Figure 4 shows the influence of competition on relative values of periodic mean annual diameter ($i_{\bar{d}}$) and periodic mean annual height ($i_{\bar{h}}$) increment. Figure 4a shows that as CI values increase, $i_{\bar{d}}$ values decrease.

Figure 4b shows a different influence of competition on the relative values of periodic mean annual height increment ($i_{\bar{h}}$). The relative values reach a local maximum when competition is slightly higher than zero. After this maximum, the relative periodic mean annual height increment steadily decreases with increasing competition.

In summary, competition has a consistent negative impact on tree diameter growth; with increasing competition the diameter increment decreases. Contra-

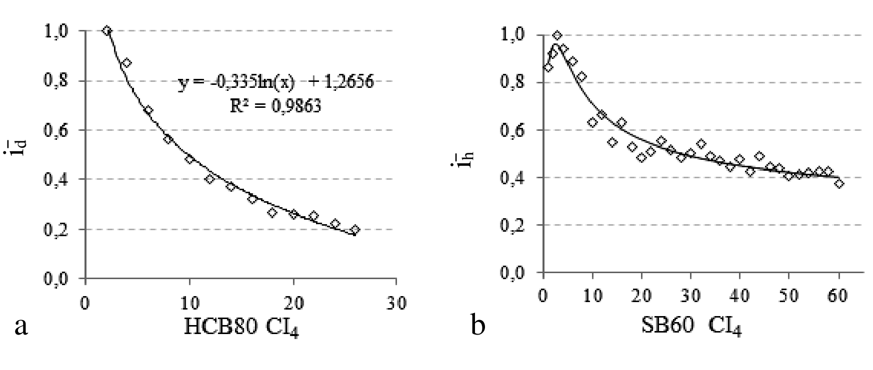

Figure 4. Influence of competition on (a) relative values of mean annual periodic diameter ($i_{\bar{d}}$) and (b) height increment ($i_{\bar{h}}$)

ry to this, a small amount of competition stimulates tree height growth, but stronger competition also has a negative impact on tree growth.

Discussion

The partial impact of competition on the periodic mean annual basal area increment. It was hypothesised that "distance dependent competition indices yield had higher partial correlation coefficients with tree basal area increment than distance independent competition indices". This hypothesis was driven by the assumption that the inclusion of tree positions increases the predictive capacity of CIs. The results clearly show the dominance of distance dependent indices over distance independent indices to predict the periodic mean annual basal area increment. The mean partial correlation coefficient of the best distance dependent index was 2.5 times higher than the best distance independent index and the proportion of significant cases of the best distance dependent index was 2.70 times higher than the best distance independent index. Yet, the difference between the poorest distance dependent and the best distance independent index was hardly noticeable. This reveals two very important findings. First, distance independent indices are also appropriate for modelling the growth of pure stands. Second, the predictive values of distance dependent indices are highly dependent on the selection method and CI used.

The selection method HCB 80 is the most suitable one for Lithuanian conditions. This method creates an average size of search cone because its positioning height increases over time, with the increasing height to crown base. The selection method HWCW 80 creates the shortest size of search cone that does not significantly increase in length over time. Particularly in older stands, this method probably does not include some important competitors and leads to index values that are too low. Selection method SB 60 creates the longest search cone that identifies the highest number of competitors. This leads to the risk that it includes trees that have no influence on the subject tree and thus increases the value of CI to an implausible level.

Since the 1950s, many CI formulae have been developed and they have become increasingly advanced. However, this progress also has a negative side in that more and more information describing tree properties is needed. Early CI formulae only required data on tree diameter at breast height. Today most indices require all tree crown parameters, as well as stem coordinates, and despite this, the results of index-based increment estimation have improved only slightly. It is very expensive to gather this type of data in practice if traditional methods of dendrometry are used. So models to simulate the data required have been developed.

Lorimer (1983), Martin and Ek (1984), Daniels et al. (1986), Corona and Ferrara (1989), Biging and Dobbertin (1995) show that distance independent CIs in pure stands performed as well as distance dependent CIs, and in some cases showed better results. An explanation could be that most of these authors compared indices that were not based on crown parameters. When comparing distance dependent and distance independent indices, only slight improvements were achieved by adding tree coordinates (Hegyi 1974). Biging and Dobbertin (1992), Bachmann (1998), Schröder (2004) and others describe the slight advantage of distance dependent indices based on crown variables, especially crown cross sectional area. Their results are clearly in line with our findings.

Based on the partial correlation results (Table 4), CI_4 proposed by Biging and Dobbertin (1992) combined with the selection method of an inverse search cone at height to crown base with an opening angle of 80 degrees is recommended for developing basal area increment models used in single tree level growth simulators. However, the difference between first three places was small. Thus, the other indices CI_5 and CI_6 used with the same selection method could be applied for modelling purposes depending on the model constructed.

Our study has some limitations. The selection of CIs was based on the results of previous studies and not all of the available indices were tested. No distance independent CI based on crown variables was tested. Furthermore, even the best distance dependent CI did not perform outstandingly, but scored only satisfactory results. Finally, CIs were only tested in pure stands and only for one tree species.

Further research should focus, not on the development of new formulae, or on the inclusion of additional tree information, but, rather, on the aggregation of the indices already developed. For example, algorithms to eliminate passive competitors in the formulae might be useful.

The partial impact of competition on the periodic mean annual height increment. The major finding on this issue was that Hegyi's (1974) distance independent CI scored better partial correlation results than all of the distance dependent indices. Thus, the research hypothesis had to be rejected, contrary to prior expectations. A very important result was that the more competitors that were included, the better were the results obtained (Table 5). The summary, given in Table 5, underlines the poor performance of CIs to predict tree height increment under conditions similar to this study, i.e. in pure and single-storeyed stands of a light demanding species like pine.

Contradictory and unusual results were found in the literature while analysing the research question. Wykoff et al. (1982) developed their height growth model without CIs. The early findings of Martin and Ek (1984) showed that no significant improvement in the height growth models could be achieved by including CIs. Biging and Dobbertin (1992) contradicted these results by stating that the inclusion of CIs considerably improves height growth predictions. Pretzsch (2002) applied a CI as a modifier in his height growth model, yet used the crown surface area of trees as well. Nagel et al. (2002) employed an individual tree height ratio to stand top height rather than a CI to reduce potential height growth.

The impact of competition on relative diameter and relative height increment. The results suggested that competition generally has a negative impact on tree diameter growth. Tree diameter increment decreases with increasing competition. A small amount of competition, however, stimulates tree height growth.

These findings were in line with our expectations, and set the basis for constructing diameter and height increment models. Logarithmic transformations of CIs make their relation with diameter or basal area increment accessible for linear regression analysis, but this transformation was of little help in the case of tree height increment (when transforming nonlinear function, visualized in Figure 6b). This could be one of the reasons for the poor performance of CIs in predicting the height increment of trees.

The results of our study are comparable to Pretzsch's (2009) results: he found that the maximum diameter increment is reached with no competition, and maximum tree height increment takes place under a moderate level of competition. This shows that under light competition, trees allocate their resources to increase height increment.

The main limitation of our study was that the results are valid only for the CIs and selection methods that we investigated. The indices with the lowest partial correlation values showed a very weak relationship, or no relation, between index values and relative diameter or height increment. Further, the modelling approach taken in Figure 6, serves mainly for assessing and visualizing the character of relationships between the competition and relative diameter and height increment. The authors are aware of the dangers of giving bias to the models, especially at the beginning and the end of the model development process when the arithmetic grouping of data is applied. A representative model should be based on individual sample values because arithmetic grouping destroys the variance of the data.

Conclusions

1. Distance dependent competition indices show higher partial correlation coefficients, and thus a higher capacity to predict mean annual basal area increment, than distance independent indices in pure pine stands. Competition indices based on crown parameters combined with the selection method of an inverse search cone at height to crown base with opening angle of 80 degrees showed the highest influence on periodic mean annual basal area increment. Competition index CI_4 proposed by Biging and Dobbertin (1992) combined with the same selection method is recommended for developing basal area increment models used in single tree level growth simulators.
2. Hegyi's (1974) distance independent CI scored the highest partial correlation coefficients in predicting mean annual height increment and outperformed distance dependent competition indices in pure pine stands. We observed the generally poor ability of competition indices to predict periodic mean annual height increment.
3. Competition has a purely negative impact on tree diameter growth. With increasing competition diameter increment steadily decreases. A small amount of competition stimulates tree height growth. However, stronger competition has a negative impact on tree height growth as well.
4. Competition indices form the core of single tree level models, and indeed are used to develop basal area as well as height increment models. Thus, the results of this study open the way for opportunities to develop a single tree level model for pine trees in Lithuania.

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ВЛИЯНИЕ КОНКУРЕНЦИИ ЗА ПРОСТРАНСТВО ДЛЯ РОСТА НА РОСТ ДЕРЕВЬЕВ СОСНЫ ПО ДИАМЕТРУ, ПЛОЩАДИ ПОПЕРЕЧНОГО СЕЧЕНИЯ И ВЫСОТЕ

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Резюме

Деревья, растущие в древостое, конкурируют из-за ограниченных ресурсов, необходимых для их роста. Конкурентная ситуация для каждого дерева в моделях роста может быть описана используя индексы конкуренции (ИК), зависимые и независимые от расстояния. Первой целью исследования является выявление ИК с самой высокой способностью предсказания прироста площади поперечного сечения и высоты деревьев сосны в лесах Литвы. Второй целью является описание воздействия конкуренции на рост деревьев сосны по диаметру и высоте с помощью таких ИК, которые показали самую высокую предсказуемость влияния конкуренции на рост. Для исследования использованы данные, собранные на восемнадцати постоянных опытных участках. Исследование проведено посредством анализа частичной корреляции по 2 независимым от расстояния и 18 зависимым от расстояния ИК.

Полученные результаты показали, что зависимые от расстояния ИК имели более высокий потенциал предсказания прироста по площади поперечного сечения деревьев сосны. ИК, предложенный Бигинг и Доббэртин (1992) в сочетании с методом отбора, когда обратный конус для определения конкурентов установлен на высоте основания кроны с углом охвата 80 градусов рекомендуется для разработки моделей прироста площади поперечного сечения деревьев сосны с их использованием в моделях роста на уровне дерева.

При моделировании роста высоты деревьев, ИК, независимые от расстояния, уступали по результатам ИК, зависимым от расстояния. Независимый от расстояния ИК по Hegyi (1974) набрал наивысший результат частичной корреляции в предсказании среднегодового прироста по высоте. Как правило, небольшие возможности ИК по предсказанию периодического среднегодового прироста по высоте наблюдались при условиях роста сосновых древостоев Литвы.

Результаты также показали, что увеличение конкуренции всегда оказывает негативное воздействие на рост диаметра дерева. Низкий уровень конкуренции увеличивает рост дерева по высоте по сравнению с отсутствием конкуренции. Но дополнительная конкуренция оказывает негативное влияние на рост дерева по высоте.

Ключевые слова: площадь поперечного сечения, индексы конкуренции, зависимые от расстояния, индексы конкуренции, независимые от расстояния, диаметр, высота, рост, прирост, дерево.