Tests of Distance-Dependent Competition Indices for Predicting Growth of Japanese Larch Trees

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Abstract: We examined the usefulness of distance-dependent competition indices for predicting individual tree basal area growth in a mature Japanese larch plantation. Using data from a permanent sample plot, we calculated several traditional distance-dependent competition indices and constructed individual growth prediction models. Results of regression analyses suggested that tree size could explain a large part of variation in tree growth much better than distance-dependent competition indices. We also used local indicators of spatial association to detect "hot spots," or clusters of similar-sized trees, and "cold spots," or clusters of trees of varying sizes within sample plots. Relationships between basal area growth and diameter of trees in "hot spots" and "cold spots" were analyzed.

1. Introduction

Competition among neighboring individuals is one of the most important factors that determine individual tree growth (Tomé and Burkhart, 1989). In many studies, distance-dependent competition indices - which are intended to represent the degree of competition using subject tree size, competitor tree size, and distance to competitor - have been used in analyses (e.g., Daniels, 1976; Lorimer, 1983; Martin and Ek, 1984; Daniels *et al.*, 1986; Tomé and Burkhart, 1989; Biging and Dobbertin, 1992, 1995). In some cases, a significant effect of competition on growth has been identified. It has also been shown that distance-dependent competition indices are not so useful for explaining variations in tree growth, in spite of a large effort to calculate these indices. In many cases, initial tree size alone can explain variations in tree growth.

Because the current tree size reflects the cumulative effects of past competition and other environmental factors, there must be a strong correlation between periodic tree growth and initial tree size (Bella, 1971; Lorimer, 1983). However, Bella (1971) showed that the relative importance of competition on growth differs among different size classes within a stand. In addition, Mitsuda *et al*. (2002) showed that different types of competition indices should be used to predict tree growth for each size class within a stand. These studies suggest the importance of competitive effect represented by competition indices on growth differ among individuals within a stand in relation to the circumstances of each individual tree. Therefore, competition indices based on regression analyses, which treat all trees the same, fail to explain variations in individual tree growth within stands.

Indices representing spatial patterns of tree locations that consider tree size have recently been developed (e.g., Anselin, 1995). Shi and Zhang (2003) applied a group of such indices, which they called Local Indicators of Spatial Association (LISA), to detect local clusters of trees of similar and dissimilar sizes. Within a local cluster of trees of similar size (a "hot spot"), two-sided competition - in which neighboring trees limit each other's access to resources (Schwinning and Weiner, 1998) - should be severe. On the other hand, within a local cluster of trees of dissimilar size (a "cold spot"), one-sided competition - in which larger trees suppress smaller trees - should be severe. Thus, we may be able to reveal differences in the competitive effects on growth by identifying hot spots and cold spots within a stand using LISA.

The objectives of this study were (1) to test distance-dependent competition indices for predicting individual tree basal area growth in a mature Japanese larch plantation and (2) to examine the relative importance of competition on tree growth and how it varies with the spatial distribution of individual trees.

2. Materials and Methods

The data used in this study was collected in permanent sample plots of a Japanese larch (*Larix kaempferi*) plantation in Ashoro Research Forest, Kyushu University. Ashoro Research Forest is located from 43º 17' to 43º 19' north latitude and from 143º 29' to 143º 33' east longitude, and its elevation ranges from 100 to 500 m a.s.l. The annual mean temperature and precipitation are about 6 ºC and 800 mm, respectively.

Three 0.1 ha permanent sample plots were established in a 19-year-old Japanese larch plantation forest in 1968; since then, diameter at breast height (1.3m) of all living trees has been measured 9 times. The positions of all living trees were recorded with the 7th measurement, which was conducted in 1998, allowing us to compile stem maps (Figure 1). Moreover, the heights of all living trees have been measured since 1998. Because distance-dependent competition indices and LISA require information on tree position for calculation, we used data from the 7th (1998), 8th (2000), and 9th (2003) measurements, and defined growth period I as 1998 to 2000 and growth period II as 2000 to 2003.

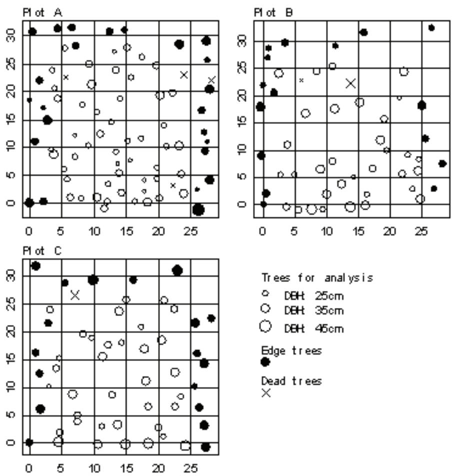

Figure 1. Stem maps of each plot in 1998. Circle size is in proportion to DBH

In 1973, trees in the three plots (A, B, and C) were thinned at different intensities; thus, the densities in each stand differ. The stand information of these sample plots is summarized in Table 1.

Table 1. Overview of permanent sample plots

Year	Age	Mean DBH (cm)			Mean Height (m)			Density (trees/0.1ha)		
		A	B	C	A	B	C	A	B	C
1998	49	27.1	29.7	32.5	28.0	29.3	31.6	79	51	54
2000	51	28.2	30.8	33.4	27.9	28.2	31.0	75	49	53
2003	54	29.1	31.4	34.4	28.3	28.7	32.5	71	49	51

First, we examined the competitive effects on growth using a traditional approach. We calculated three distance-dependent competition indices—a Horizontal Competition Index (HCI), one-sided Vertical Competition Index (VCI1), and a two-sided Vertical Competition Index (VCI2) (Mitsuda *et al*., 2002). These indices were calculated as the sums of distance-weighted size ratios (HCI) and the difference (VCI1 and VCI2) between a subject tree (i) and its competitors (j). These methods have been widely used for some time (e.g., Daniels, 1976; Lorimer, 1983; Biging and Dobbertin, 1995; Mitsuda *et al*., 2002; Yamashita *et al*., 2006; Kohama *et al*., 2006) and are defined as follows:

[1] $$HCI_i = \sum_{j \in C_i} \frac{1}{dist_{ij}} \cdot \frac{DBH_j}{DBH_j}$$

[2] $$VCI_i = \sum_{j \in C_i} \tan^{-1}\left(\frac{H_j - H_i + dgl}{dist_{ij}}\right)$$

where DBH is diameter at breast height, H is tree height, $dist_{ij}$ is distance between the subject tree and competitor, dgl is the difference of ground level between the subject tree and competitor, and C_i is a set of competitors of the subject tree i.

We selected all trees within a 3m radius of the subject tree as competitors for calculating HCI and VCI2. Only taller trees within the 3m radius were selected as competitors for the VCI1 calculation. Because we used 3m as the radius for identifying competitors, we excluded edge trees which were located within a 3m buffer from the left, top, and right edges of the plot for subsequent analyses (Figure 1). We did not set an edge buffer for the lower side because all three plots were adjacent to a forest road where trees did not exist. Trees might be large enough to affect each other over the 3m distance in these plots; however, because we excluded edge trees from the analysis, we used 3m as the radius for identifying competitors to maintain enough trees for additional analyses.

We constructed individual tree annual basal area growth models. First, we used *DBH* as the sole explanatory variable, then *DBH* and one of three competition indices as explanatory variables, and finally we examined the competitive effect on tree growth through model selection (see e.g., Burnham and Anderson, 2002). Because we pooled all the data acquired from the three sample plots and two growth periods for model construction, we included these factors as random variables affecting variations of tree growth in linear mixed-effect models (see. e.g., Faraway, 2006). We set the sample plot factor and growth period factor as random effects assuming normally distributed $N(0, \sigma^2)$. We fitted the following four linear mixed-effect models to the data by the maximum likelihood method, using R (R Development Core Team, 2007) with the lme4 package (Bates, 2007), and compared these linear mixed-effect models using the Bayesian information criterion (BIC) (Schwarz, 1978):

[3] $$G_i = \alpha + \beta_1 \times DBH_i + \alpha_{plot} + \alpha_{period}$$

[4] $$G_i = \alpha + \beta_1 \times DBH_i + \beta_2 \times HCI_i + \alpha_{plot} + \alpha_{period}$$

[5] $$G_i = \alpha + \beta_1 \times DBH_i + \beta_2 \times VCI1_i + \alpha_{plot} + \alpha_{period}$$

[6] $$G_i = \alpha + \beta_1 \times DBH_i + \beta_2 \times VCI2_i + \alpha_{plot} + \alpha_{period}$$

where G_i is annual basal area growth, α is an intercept, β_1 and β_2 are coefficients of regression, and α_{plot} and α_{period} are random effects of plot and growth period, respectively.

Next, we investigated the relationships between individual tree growth and tree size, and competition indices of trees facing severe competition with neighboring trees. We used the local forms of the Moran coefficient and the Geary ratio as LISA (Shi and Zhang, 2003). The Moran coefficient (*MC*) is defined as follows:

[7] $$MC_i = \left(DBH_i - \overline{DBH}\right) \sum_{j \in C_i} \left(DBH_j - \overline{DBH}\right)$$

where $\overline{DBH}$ is plot average *DBH*. A positive *MC* value indicates a subject tree is in a cluster of similar size, whereas a negative *MC* value indicates a subject tree is in a cluster of dissimilar size. In cold spots, the lower negative *MC* values indicate that both dominant and suppressed trees are in the more severe one-sided competition scenario.

The Geary ratio (*GR*) is defined as follows:

[8] $$GR_i = \sum_{j \in C_i} \left(DBH_i - DBH_j\right)^2$$

The *GR* value indicates variance of tree size within a cluster; a lower *GR* value means less variance of tree size and more severe competition among similar-sized trees.

To extract data acquired from hot and cold spots, we first examined trees with over five competitors, which is larger than the average number of competitors (3.83). Then, we identified observations in the lowest 10% of negative *MC* values as cold spot observation values because negative *MC* values could represent the competitive status where lager trees suppressed smaller neighbors. We also examined observations with positive *MC* values, smaller *DBH* than plot average, and the lowest 10% *GR* values as hot spot observations because lower *GR* values could represent the local size equality. After that, we calculated the coefficients of correlation between annual basal area growth and initial *DBH* and three competition indices for each dataset.

3. Results and Discussion

The BIC of the regression model using *DBH* as the sole explanatory variable (Model 1) was 1607.15, indicating Model 1 is the best fitted of the 4 regression models (Table 2). This result suggests that initial size could explain a large part of the variation in individual tree growth much better than the competition indices. Model 3, which used DBH and VCI1 as explanatory variables, is the best fitted model that includes the competition index and its BIC was approximately the same value (1607.73) as that of Model 1. The standardized regression coefficients of DBH and VCI1 in Model 3 were 0.664 and 0.093, respectively. This result also suggests that the competition index may not easily explain the variation in individual tree growth. Figure 2 shows a strong relationship between initial DBH and annual basal area growth.

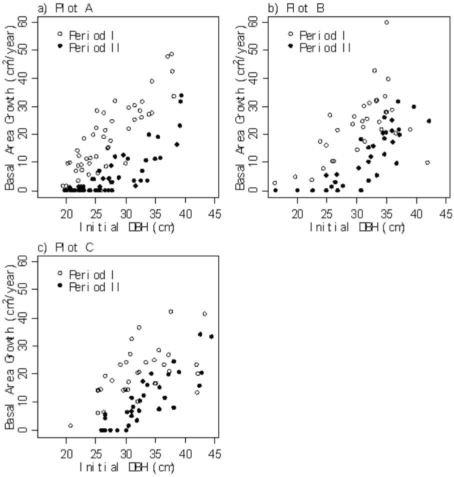

Figure 2. Relationshipt between basal area growth and initial DBH

As in our study, initial tree size has been accepted as the most effective variable in previous regression analyses. Competition indices have not been accepted, or have provided unsatisfactory explanations of the variation in individual growth in regression models (reviewed by Biging and Dobbertin, 1995). As we mentioned before, the initial tree size reflects the cumulative effects of past competition and other factors. Given that the study site is a mature plantation forest and has not been significantly disturbed for a known period of time, various factors determining individual tree growth could be represented by the actual tree size. Consequently, are competition indices useless for describing individual tree growth?

The coefficients of correlation between annual basal area growth and initial diameter were 0.62, 0.05, and 0.83 for total, hot spot, and cold spot observations, respectively (Table 3 and Figure 3). In cold spots, the coefficient of correlation between basal area and initial diameter increased to 0.83. The correlation between

Table 2. BICs of linear mixed-effect models

No.	Explanatory Variables	BIC	σ^2	
			Plot*	Period*
1	DBH (P<0.001)	1607.15	5.46	38.06
2	DBH (P<0.001), HCI (P=0.706)	1611.35	5.71	38.06
3	DBH (P<0.001), VCI1(P=0.027)	1607.73	4.69	37.29
4	DBH (P<0.001), VCI2 (P=0.706)	1610.47	5.54	37.72

* estimated variance of random effects for sample plot and growth period.

growth and competition indices was also stronger, but its coefficients of correlation showed a weaker relationship than that of initial *DBH*. Because there are both dominant trees and suppressed trees in cold spots, tree size sufficiently represents superiority over neighboring trees for a dominant tree and inferiority for a suppressed tree. In hot spots, the correlation between basal area growth and initial size become quite weak.

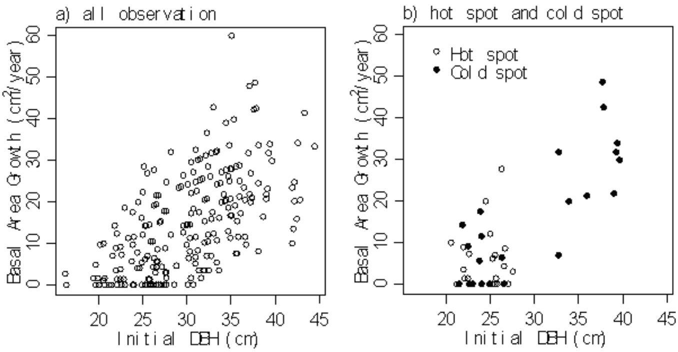

Figure 3. Relationship between basal area growth and initial *DBH* in hot spot and cold spot

Because trees in hot spots are competing with similar-sized neighbors, initial size cannot sufficiently represent competitive superiority or inferiority. This situation calls for competition indices; thus, the coefficients of correlation between annual basal area growth and HCI and VCI1 of hot spot data are not great, but show a stronger relationship than that of initial *DBH*. At the very least, we can say that competition indices are useful to describe variation in the growth of individual trees that are in severe competition with similar-sized neighbors.

In mature undisturbed stands like our study site, where dominant trees and suppressed trees have been fixed through historical competition, it is especially apparent that "big trees grow fast" (Lorimer, 1983). Inoue *et al*. (2008) showed that volume growth of young *Cryptomeria japonica* trees depends on tree size before canopy closure and the distance-dependent competition index is far better than actual tree size to describe individual tree volume growth after canopy closure. They concluded the relative importance of competition increased during the canopy closure process. Nagashima (1999) showed that height growth of *Chenopodium album* can be predicted using plant size before canopy closure, both size and the competition index can be used at the canopy closure stage, and that plant size can be used from a certain point after canopy closure. These studies suggest that competition among neighboring trees is quite important in young stands in the midst of the canopy closure process. In mature stands where much time has passed since canopy closure, the competitive effect for tree growth becomes relatively unimportant and actual tree size comes to represent competitive status. Lorimer (1983) stated that the high correlation between tree size and growth is, in part, a secondary effect of competition. In this situation, it is difficult to use distance-dependent competition indices to predict tree growth, as shown in our results.

Table 3. Coefficients of correlation between basal area growth and *DBH*, and competition indices

	All	Hot spot	Cold spot
DBH	0.62	0.05	0.83
HCI	-0.33	-0.12	-0.51
VCI1	-0.34	-0.22	-0.64
VCI2	-0.34	-0.04	-0.54
n	234	23	23

On the other hand, our results also showed that it may be possible to use distance-dependent competition indices in some situations. Using LISA, we detected clusters of trees where competition among trees of similar or dissimilar size was severe within sample plots. In these clusters, the relative importance of competition on tree growth should be higher and distance-dependent competition indices should logically show somewhat better correlations to tree growth. Although our study site is in a controlled plantation forest, spatial locations of trees are not uniform and there are some hot spots and cold spots (Figure 1). The spatial-size distribution of individuals affects the stand development through tree competition. This process has recently been intensively studied (e.g., Fajardo and McIntire, 2007). Our results also suggest that the spatial distribution of tree size should be taken into account to describe individual tree growth. In future studies, we should focus on the temporal and spatial changes in the relative importance of competition in individual tree growth. Therefore, we must continue to measure the existing permanent plots and establish new permanent plots.

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References

Anselin, L. (1995) Local indicator of spatial association-LISA, ***Geogr. Anal.* 27**: 93-115.

Bates, D. (2007) Linear mixed model implementation in lme4. http://cran.r-project.org/doc/packages/lme4.pdf, (accessed July 10, 2007).

Bella, I.E. (1971) A new competition model for individual trees, ***For. Sci.* 17**: 364-372.

Biging, G.S. and Dobbertin, M. (1992) A comparison of distance-dependent competition measures for height and basal area growth of individual conifer trees, ***For. Sci.* 38**: 695-720.

Biging, G.S. and Dobbertin, M. (1995) Evaluation of competition indices in individual tree growth models, ***For. Sci.* 41**: 360-377.

Brand, D.G. and Magnussen, S. (1998) Asymmetric, two-sided competition in even-aged monocultures of red pine, ***Can. J. For. Res.* 18**: 901-910.

Brunner, A. and Nigh, G. (2000) Light absorption and bole volume growth of individual Douglas-fir, ***Tree Physiol.* 20**: 323-332.

Burnham, K.P. and Anderson, D.R. (2002) Model selection and multimodel inference: a practical information-theoretic approach, 2nd ed. Springer, New York, 484p.

Daniels, R.F. (1976) Simple competition indices and their correlation with annual loblolly pine tree growth, ***For. Sci.*** **22**: 454-456.

Daniels, R.F., Burkhart, H.E. and Clason, T.R. (1986) A comparison of competition measures for predicting growth of loblolly pine trees, ***Can. J. For. Res.*** **16**: 1230-1237.

Fajardo, A., and McIntire, E.J.B. (2007) Distinguishing microsite and competition processes in tree growth dynamics: An a priori spatial modeling approach, ***Amer. Naturalist*** **169**: 647-661.

Faraway, J.J. (2006) Extending the linear model with R: generalized linear, mixed effects and nonparametric regression models, Chapman & Hall/CRC, Boca Raton, London, and New York, 301p.

Inoue, S., Shirota, T., Mitsuda, Y., Ishii, H. and Gyokusen, K. (2008) Effects of individual size, local competition and canopy closure on the stem volume growth in a monoclonal Japanese cedar (*Cryptomeria japonica* D. Don) plantation, ***Ecol. Res***. (in press).

Kohama, T., Mizoue, N., Ito, S., Inoe A., Sakuta, K. and Okada, H. (2006) Effects of light and microsite conditions on tree size of 6-year-old *Cryptomeria japanica* planted in a group selection opening, ***J. For. Res.*** **11**: 235-242.

Lorimer,C.G. (1983) Tests of age-independent competition indices for individual trees in natural hardwood stands, ***For. Ecol. Manag.*** **6**: 343-360.

Martin, G.L. and Ek, A.R. (1984) A comparison of competition measures and growth models for predicting plantation red pine diameter and height growth, ***For. Sci.*** **30**: 731-743.

Mitsuda, Y., Ito, S. and Takata, N. (2002) Effects of competitive and cooperative interaction among neighboring trees on tree growth in a naturally regenerated even-aged *Larix sibirica* stands in considering height stratification, ***J. For. Res.*** **7**: 185-191.

R Development Core Team (2007) R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, 2500p.

Schwarz, G. (1978) Estimating the dimension of a model, A***nn. Statist*. 6**: 461-464.

Schwinning, S. and Weiner, J. (1998) Mechanisms determining the degree of size asymmetry in competition among plants,***Oecologia* 113**:447-455.

Shi, H. and Zhang, L. (2003) Local analysis of tree competition and growth, ***For. Sci*. 49**: 938-955.

Tomé, M. and Burkhart, H.E. (1989) Distance-dependent competition measures for predicting growth of individual trees, ***For. Sci*. 35**: 816-831.

Yamashita, K., Mizoue, N., Ito, S., Inoue A. and Kaga, H. (2006) Effects of residual trees on tree height of 18- and 19-year-old *Cryptomeria japonica* planted in group selection opening, ***J. For. Res*. 11**: 227-234.

カラマツ個体成長予測における距離従属競争指数の有効性の検討

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要約 : 距離従属競争指数が成熟したカラマツ人工林の個体成長を記述する上で有効であるかどうかを検証した. 固定試験地調査により得られた成長データを利用して, 初期のサイズおよび一般的な競争指数により個体の断面積成長を説明するモデルを構築した. その結果, 初期サイズのみを用いたモデルが最も個体成長のバラツキを説明するモデルとなり, 競争指数は有効ではないという結果となった. また, 局所的な個体配置を表現する指数によって一方向的競争が激しい “cold spot” と, 二方向的競争が激しい “hot spot” を抽出し, その中での成長と初期サイズおよび競争指数との関係を解析することを試みた.

キーワード : 距離従属競争指数, 個体成長, 固定試験地, hot spot, cold spot