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Distance-dependent and distance-independent models of Douglas-fir and western hemlock basal area growth following silvicultural treatment

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Abstract

Distance-independent and distance-dependent individual-tree basal area growth equations for Douglas-fir and western hemlock growth following thinning and fertilization treatments were developed using regression analysis. Distance-independent models included only non-spatial competition and thinning indices, while distance-dependent models included both spatial and non-spatial indices. The distance-independent models with the highest adjusted multiple coefficient of determination (adjusted R^2) for both species included diameter at breast height, crown class, percent basal area removed in thinning, plot basal area greater than the subject tree and stand age as independent variables. The distance-dependent models with the highest adjusted R^2 included all of these variables in addition to a variant of the area potentially available index, which is based on the spatial tessellation of the point pattern of trees in the stand. Addition of this spatial index produced only a small ($< .01$) increase in adjusted R^2 for models of both species. The relatively small amount of increase was due to three factors; thinning resulted in an even distribution of growing space among residual trees, tree size explained much of the variation in local competitive stress and the competitive neighborhood of individual trees was large relative to the size of the sample plots. The results suggest that the additional effort and expense required to obtain spatially referenced stand data for developing empirical forest growth models in similar stands is not justified.

Keywords: *Pseudotsuga menziesii*; *Tsuga heterophylla*; Growth and yield; Thinning; Spatial competition indices; Tessellation

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1. Introduction

Individual-tree based growth models provide a powerful framework for integrating existing data and knowledge in order to make projections of future forest dynamics. These models are particularly useful in assessing the possible stand structures resulting from new silvicultural regimes. For example, long rotations with repeated commercial thinning are currently being proposed to maintain high rates of tree growth while producing diverse mutlicohort stands in the Pacific Northwest (Carey and Johnson, 1995, Kuehne, 1994). Empirical studies of such regimes require a significant investment and may not yield results for a long period of time. Forest managers,

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however, must make decisions in the near term. In order to evaluate the ecological and economic consequences of long-rotation forestry, forest simulation models will need to incorporate the variation in growth rates caused by thinning in mature stands. The objective of this study was to determine, for Douglas-fir and western hemlock in a mixed stand, whether distance-dependent growth models provided significantly better prediction of individual tree, basal area increment following silvicultural treatment than provided by distance-independent models.

Individual-tree growth models predict basal area increment over a given time period from variables such as tree size, vigor, age and competitive stress measured at the beginning of that period. The competition indices used in these models are actually measures of local crowding, or competition for growing space (Ford and Sorrenson, 1992). Distance-independent models are distinguished from distance-dependent models by the type of competition index used. Distance-independent models utilize only non-spatial competition indices, based on the size distribution of trees within a given area. Distance-dependent models include spatial competition indices that incorporate both the size and spatial distribution of competitors. For a given tree, competitors are identified based on their size and proximity, and the contributions of individual trees to the competition index are weighted by their size and distance from the subject tree. Distance-dependent models have an intuitive appeal; since trees are sessile organisms, their growth should be most influenced by competition from neighboring trees. One major drawback to distance-dependent models is that a significant amount of effort and expense is required to obtain spatially referenced stand data.

Previous research has produced many different types of spatial and non-spatial competition indices. Comparative studies have shown that many of these indices are similar in their capacity to predict growth (Almendag, 1978, Lorimer, 1983, Holmes and Reed, 1991). This study expands on the body of existing work by testing spatial competition indices in a naturally regenerated, mixed-species conifer stand in the Pacific Northwest. This is also the first study, to our knowledge, that compares a number of spatial and non-spatial thinning indices. To avoid an excessively large pool of highly correlated independent variables, an initial set of competition indices was selected from the existing literature on competition and growth modeling based on their effectiveness in modeling basal area growth in past studies. In addition, a new variant of an existing index was created, based on field observations.

The growth models in this study were fitted using plot-level data from a single stand that had been subjected to a range of thinning and fertilization treatments. Examining a variety of treatments applied to one stand allowed us to focus on the effects of the treatments and avoided possible confounding effects of differences in overall stand characteristics and site productivity. Although the equations generated from these data are not directly applicable to other stands, the modeling process provided insights into factors affecting growth within the study site. This knowledge can be applied to decision making and modeling efforts on a larger scale. Similarly, the methodology used to develop these models could be applied across a range of stands and treatments.

2. Study site and data

The data for this project came from an even-aged, naturally regenerated, mixed-species stand near Jordan River on the southwest coast of Vancouver Island. Major tree species were Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*), with minor components of Sitka spruce (*Picea sitchensis*) and western redcedar (*Thuja plicata*). The study site is within the Coastal Western Hemlock biogeoclimatic zone. This zone covers most of the low-to-mid elevation areas along the British Columbia coast and is characterized by a mesothermal climate, with mild winters and cool summers (Pojar et al., 1991).

The data used in this study were part of Experimental Project 703, an extensive study of forest growth and yield in southwest British Columbia conducted by the British Columbia Ministry of Forests. An overview of the study and details about the experimental design can be found in Darling and Omule (1989). Information pertinent to the Jordan River installation is summarized here.

In 1974, thirty 0.07 ha permanent plots were established in the Jordan River stand. The plots were subjected to a two-way treatment design that included three levels of thinning (0, 20, 35 and 50% of live basal area removed) and three levels of fertilization (0, 225, 450 and 675 kg N/ha). Each plot was surrounded by a 0.07 ha buffer zone that received a treatment identical to the interior plot. The 30 plots were divided equally into a high basal area and a low basal area group before treatment. Each two-way combination of treatments was represented by one plot from each of these groups. The exception was the no thinning–675 kg fertilization combination, which was not included in the design.

Initial measurements were taken before and after treatment in 1974. The interior plots were stem mapped at that time using aerial photographs. The plots were remeasured in 1977, 1980, 1983, 1986 and 1992. Species, diameter at breast height (DBH) and crown class were recorded for each tree at each measurement period. A three-year basal area increment was calculated for each of the five intervals between these measurements. Since the last measurement interval was six years in length, the basal area increment was divided by two to produce the mean three-year increment for this period. For trees that died between 1974 and 1992, growth increments were only calculated for the time periods in which the trees were alive. Heights were taken on a subset of the trees at each measurement. These subsets were used to develop height–diameter regression equations, from which estimated heights were generated for the other trees in the data set.

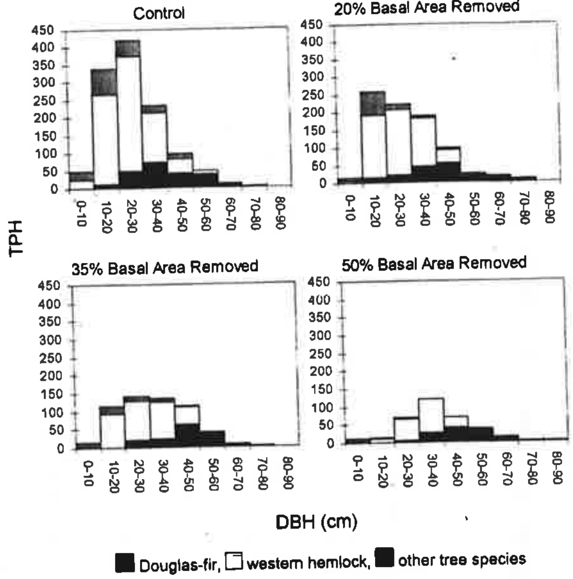

Fig. 1. Diameter distribution of residual trees immediately following treatment at each of four thinning levels. Size categories are indicated on the *x*-axis of each chart, with the trees per hectare in each size category on the *y*-axis. Species composition in each size category is indicated by shading.

3. Initial stand conditions

Plot data collected before and after thinning provided information about the treatments and their impact on the residual forest structure of the Jordan River stand. Stand structure in the control plots was characteristic of mixed Douglas-fir–western hemlock stands (Wierman and Oliver, 1979) (Fig. 1). Smaller western hemlock were stratified beneath the larger Douglas-fir, although there were some relatively large (40–60 cm DBH) western hemlock present. Trees removed were mostly western hemlock and ''other'' species (mainly western redcedar) in the 10–30 cm DBH range. Few Douglas-fir were removed and the amount of Douglas-fir removed did not vary greatly over the different thinning intensities. The actual d/D ratios (quadratic mean diameter of trees removed/quadratic mean diameter of stand before thinning) were 0.90 in the 20% basal area removal plots, 0.83 in the 35% basal area removal plots and 0.74 in the 50% basal area removal plots.

The horizontal spatial pattern of each plot immediately following the treatments was examined using the L(h) statistic (where h = distance), a transformation of the K(h) statistic Ripley (1977). The L(h) statistic was computed at distances ranging from 0.25 to 10 m at 0.25 m intervals in order to examine the pattern across a range of spatial scales. A 99% confidence interval was generated for each of these distances using Monte Carlo simulation of a random spatial pattern (Besag and Diggle, 1977, Moeur, 1993). Using these confidence intervals, the spatial pattern at each distance was classified as either random, regular or aggregated. This analysis showed that the spatial pattern of trees in most of the control plots was not significantly different from random. The thinning treatments, however, resulted in significantly regular distribution of residual trees. At the two highest thinning levels, all plots exhibited a significantly regular pattern at some distance between 0.25 and 10 m.

4. Methods

4.1. Non-spatial competition indices

Non-spatial competition indices used in this study included plot level measurements of trees per hectare (TPH), basal area per hectare (BAH) and the crown competition factor (CCF) of Krajicek et al. (1961). Asymmetric or one-sided competition can be represented by including only trees larger than the subject tree when computing the index. Plot level measurements of TPH with basal area larger than the subject tree (TPHL), total basal area of trees with a basal area larger than the subject tree (BAL) and total crown competition factor for trees with a basal area larger than the subject tree (CCFL) were calculated for each tree. Several variants of the relative size index were also computed by taking the ratio of individual tree size to the mean size for the plot (Glover and Hool, 1979), including relative DBH (RDBH), relative basal area (RBA) and relative height (RHT).

4.2. Spatial competition indices

The original form of the distance-weighted size ratio index was proposed by Hegyi (1974). It is based on the ratio of size measurements between the competitor tree and the subject tree, summed over all competitors. This ratio is divided by some function of the distance from subject to competitor, thereby giving a larger weight to closer competitors. The following equation was used to calculate the size-ratio index:

$$\mathrm{DWSR} = \sum_{j=1}^{n} (\mathrm{DBH}_j/\mathrm{DBH}_i)/(DST_{ij} + 1) \qquad (1)$$

where DBH_j is the diameter at breast height of competitor tree j, DBH_i is the diameter at breast height of subject tree i and DST_{ij} is the distance between subject tree i and competitor tree j.

Trees were included as competitors if their heights subtended a vertical angle sweep taken at 0.66 of the height of the subject tree. These criteria can be expressed mathematically as follows:

$$\mathrm{DST}_{ij} < \frac{\mathrm{HT}_j - \mathrm{HT}_i \cdot 0.66}{TAN(\Theta)} \qquad (2)$$

where DST_{ij} is the distance between subject tree i and competitor tree j, HT_j is the height of competitor j, HT_i is the height of subject tree i, and Θ is the selection angle from the horizontal.

This method is appealing because it takes both subject and competitor tree size into account, along with the distance between subject and competitor. Smaller trees will be influenced by shade from competitors a greater distance away than will larger trees. Smaller trees will also exert competitive influence over a smaller distance than larger trees. This produces a selection criteria that is closer to the actual competitive relationships of trees in the forest than fixed-radius plots or horizontal angle gauge sweeps (Biging and Dobbertin, 1992). Selection of the angle, Θ, is still somewhat arbitrary. An angle of 55 degrees from the horizontal was selected for this study after a preliminary analysis indicated that this value yielded the highest simple correlation with basal area growth.

The competitive stress index (Arney, 1973) can be viewed as a distance-dependent variant of the crown competition factor index. Any competitor whose potential open-grown crown radius overlaps the open-grown crown radius of the subject tree is assumed to be competing for growing space. The competitive stress index was calculated as:

$$\mathrm{CSI} = 100 \cdot \left(\sum_{j=1}^{n} \mathrm{AO}_{ij} + \mathrm{CA}_j \right) / \mathrm{CA}_j \qquad (3)$$

where AO_{ij} is the overlap area of the open-grown crowns of subject i and competitor j, and CA_j is the open-grown crown area of competitor j.

The open-crown radius was calculated as a function of DBH, using equations from Arney (1973) and Farr et al. (1989). A variant of this index, CSIL, imposed the additional constraint that only competitors with a basal area larger than the subject tree would be included as neighbors. This index modeled local competition as a one-sided process and is conceptually similar to the size-distribution variants of the relative size indices.

Competition indices derived from a tessellation of the point pattern of trees in a stand are commonly referred to as area potentially available (APA) indices. These indices are determined by first computing the Dirichlet tessellation for the entire stand. This involves subdividing the horizontal area of the stand so that there is a unique polygon associated with each tree. The area of this polygon can be construed as the horizontal growing space available to the tree. APA was originally proposed as an index of point density by Brown (1965). Variations have also been developed which weight APA based on DBH or some other measure of tree size (Moore et al., 1973, Pelz, 1978, Nance et al., 1987).

Two forms of the APA index were used. The first was APA, standard area potentially available based on the tessellation of all trees in the stand. An additional layered variant, APAL, was developed for this study. It computed the tessellation separately for each of three crown classes (dominant and codominant combined into one class, intermediate and suppressed). The tessellation for each of these classes was based on all trees of equal or higher crown class. For example, the APAL values for the suppressed trees were based on a tessellation of all trees in each plot. APAL values for the intermediate trees were based on a tessellation of the intermediate and dominant–codominant trees in each plot. APAL values for the dominant–codominant trees were based on a tessellation of only the dominant–codominant trees in each plot.

The idea for this variation came from direct observation of crown interactions in the Jordan River stand. The lateral expansion of the crowns of dominant and codominant trees appeared to be constrained only by the crowns of other dominant–codominants, while the crowns of smaller trees appeared to be constrained by all trees of equal or greater crown class. The layered tessellation variant thus produced a one-sided model of competition in which the available growing space of a given tree was only restricted by trees of equal or larger size.

4.3. Thinning indices

Basal area growth following thinning should be correlated with the amount of new growing space made available by the treatment. This new growing space can be measured in terms of the change in the competitive status of the residual trees (Smith and Bell, 1983). For each of the spatial and non-spatial indices discussed previously, a thinning index was calculated that measured thinning in terms of the change in the competition index following the thinning treatment. For competition indices that exhibit a positive correlation with competitive stress (all except APA, APAL and the relative size indices) the corresponding thinning index was computed as:

$$\Delta \mathrm{CI} = 1 - \mathrm{CI}_a/\mathrm{CI}_b \qquad (4)$$

where ΔCI is a thinning index based on competition index CI, CI_a is the competition index measured immediately following thinning and CI_b is the competition index measured before thinning.

For competition indices that exhibit a negative correlation with competitive stress (APA, APAL and the relative size indices), the thinning index was computed as:

$$\Delta \mathrm{CI} = \mathrm{CI}_a/\mathrm{CI}_b - 1 \qquad (5)$$

Both forms of this index equal zero when no thinning treatment is applied and they increase with the amount of removal.

4.4. Edge effects

Edge effects present a difficulty when calculating distance-dependent competition indices for trees within a mapped plot. A combination of two methods was used to deal with this problem. Any trees whose APA or APAL overlapped the plot boundary were excluded from consideration as subject trees in both the distance-independent and distance-dependent models. This had the effect of widening the established buffer zone around each plot. All independent variables used in the models were calculated using this subset of the data, with edge trees eliminated. Trees that were excluded from consideration as subject trees when computing the APA and APAL indices were still used as potential competitors when calculating the other competition indices. Linear expansion factors (Martin et al., 1977, Martin, 1982) were used to correct the size-ratio and area overlap indices for any potential competitors lying outside the plot boundary. This method produces an unbiased estimate of the competition index for an edge tree based on the sizes and location of competitors within the plot.

4.5. Model building

Exploratory analysis of the data revealed a strong linear relationship between the square root of basal area growth and DBH measured at the beginning of each measurement period. The slope of this relationship varied with both the severity of the thinning treatment and the crown class of the individual tree. No significant response to the fertilization was detected. For a tree of a given size at a given thinning level, the square root of basal area growth decreased linearly with stand age. The following equation was therefore used to model basal area growth of trees in the Jordan River stand:

$$\sqrt{\mathrm{BAI}} = b_0 + \mathrm{DBH}(b_1 + b_2\Delta\mathrm{CI} + b_3\mathrm{CC}) + b_4\mathrm{AGE} + \sum_{i=5}^{p} b_i\mathrm{CI}_i$$

(6)where BAI is 3-year basal area increment (cm^2), DBH is diameter at breast height (cm), ΔCI is a thinning index, CC is an indicator variable for crown class ($1 =$ intermediate or suppressed, $0 =$ dominant or codominant), AGE is stand age (years), b_i is an estimate of the ith parameter and $\Sigma_{i=5}^{p} b_i\mathrm{CI}_i$ is a linear combination of one or more competition indices and their associated parameters.

Two separate models were fit for each species, i.e., distance-independent and distance-dependent. The distance-independent models were fit using only non-spatial thinning and competition indices in the pool of initial variables. The distance-dependent models were fit from an initial pool that included both spatial and non-spatial indices. The result was the development of four separate basal area growth models.

- Douglas-fir, distance-independent (DFDI)
- Douglas-fir, distance-dependent (DFDD)
- Western hemlock, distance-independent (WHDI)
- Western hemlock, distance-dependent (WHDD)

An all-subsets algorithm was utilized to test various combinations of the thinning and competition indices in order to find the combination that maximized the adjusted R^2 value (R^2_{adj}). Since the growth periods had different lengths (four three-year periods and one six-year period), each observation was weighted by the inverse of the length of its measurement period to correct for increased variance in the longer measurement period (Martin and Ek, 1984).

The assumption of uncorrelated errors is required to make standard statistical hypothesis tests about the parameters of a linear regression model (Neter et al., 1989). Autocorrelation does not affect the parameter estimates, but may cause an unknown bias in estimates of the residual variance and the variance of the parameter estimates (Ford and Sorrenson, 1992). Time plots of the residuals from the fitted models (Neter et al., 1989) did not indicate any temporal autocorrelation. Attempts to test for spatially autocorrelated errors within the plots, using correlograms, were hampered by the low number of subjects trees in many of the plots. Because of uncertainty about the influence of spatial autocorrelation, randomization tests were used as a final check to ensure that all parameters in the model were statistically significant. Randomization testing is a nonparametric method that does not require the assumption of independent error terms (Mitchell-Olds, 1987, Manley, 1991).

A randomization test is justified in this instance because, if basal area growth is independent of a variable, x_i, when the other variables are already in the model, the processes generating the data should make any x_i equally likely to occur with any set of observations (Manley, 1991). The test statistic used was the residual sum of squares from the final model. To test the statistical significance of an independent variable, the vector of values for that variable was randomly permutated 999 times with respect to the remaining independent variables and the dependent variable. The residual sum of squares was calculated for each of these 999 permutations, and the test statistic was compared to the distribution of residual sums of squares obtained under randomization. If the test statistic was among the lowest 50 residual sums of squares generated under randomization (corresponding with a one-sided test at the 0.05 level of the null hypothesis that $B_i = 0$), the independent variable was considered to explain a significant amount of the variation in the dependent variable.

5. Results

The following equations were found to maximize the R^2_{adj} for the models described above:

Models *DFDI* and *WHDI*:

$$\sqrt{\mathrm{BAI}} = b_0 + \mathrm{DBH}(b_1 + b_2 \Delta\mathrm{BAH} + b_3\mathrm{CC}) + b_4\mathrm{AGE} + b_5\mathrm{BAL}^2 \quad (7)$$

Models *DFDD* and *WHDD*:

$$\sqrt{\mathrm{BAI}} = b_0 + \mathrm{DBH}(b_1 + b_2 \Delta\mathrm{BAH} + b_3\mathrm{CC}) + b_4\mathrm{AGE} + b_5\mathrm{BAL}^2 + b_6\log(\mathrm{APAL}) \quad (8)$$

where ΔBAH is the decrease in basal area per hectare following thinning and other variables are as defined previously.

The final models fit the data well, accounting for between 83.1 and 85.3% of the total variation (Table 1). Randomization tests indicated that all independent variables were significant at the $p < 0.05$ level. The signs of the coefficients all indicated that they were behaving as would be expected in the growth models (Tables 2 and 3). Basal area growth increased with increasing tree size (DBH) and neighborhood size (APAL). Basal area growth decreased with increasing competition (BAL) and age. Increased basal area removal (ΔBAH) and higher crown class (CC) both increased the slope of the

Table 1
Summary information for basal area growth models

Model	Equation	n	p	MSE	Adjusted R^2
DFDI	Eq. (7)	802	6	3.60	0.8496
DFDD	Eq. (8)	802	7	2.014	0.8525
WHDI	Eq. (7)	2134	6	2.166	0.8308
WHDD	Eq. (8)	2134	7	2.198	0.8378

n, number of observations used to fit the model.
p, number of parameters in the model.
MSE, mean squared error.

Table 2
Parameter information for Douglas-fir basal area growth models

Model	Coefficient	Variable	Value	VIF	Partial r^2
DFDI	b_0	Intercept	10.38	N/A	N/A
	b_1	DBH	0.1809	2.768	0.4198
	b_2	DBH·ΔBAH	0.07576	1.378	0.1138
	b_3	DBH·CC	−0.05133	1.488	0.0331
	b_4	AGE	−0.1472	1.202	0.1092
	b_5	BAL^2	-7.87×10^{-7}	2.809	0.1607
DFDD	b_0	Intercept	8.772	N/A	N/A
	b_1	DBH	0.1741	2.919	0.3930
	b_2	DBH·ΔBAH	0.06087	1.737	0.0628
	b_3	DBH·CC	−0.04490	1.530	0.0252
	b_4	AGE	−0.1469	1.202	0.1107
	b_5	BAL^2	-7.919×10^{-7}	2.810	0.1650
	b_6	log(APAL)	0.6793	1.886	0.0190

VIF, variance inflation factor; DBH, diameter at breast height (cm); ΔBAH, percentage basal area removed; CC, indicator variable for crown class (1 = intermediate or suppressed, 0 = dominant or codominant); AGE, stand age (years); BAL, total basal area of trees with basal area larger than the subject tree (cm^2); APAL, layered area potentially available (m^2).

Table 3
Parameter information for western hemlock basal area growth models

Model	Coefficient	Variable	Value	VIF	Partial r^2
WHDI	b_0	Intercept	7.1705	N/A	N/A
	b_1	DBH	0.1889	3.002	0.3656
	b_2	DBH·ΔBAH	0.1285	1.651	0.1435
	b_3	DBH·CC	−0.07713	1.802	0.1170
	b_4	AGE	−0.1144	1.345	0.0748
	b_5	BAL^2	-1.942×10^{-7}	3.028	0.0246
WHDD	b_0	Intercept	5.8938	N/A	N/A
	b_1	DBH	0.1802	3.090	0.3473
	b_2	DBH·ΔBAH	0.1039	1.892	0.0907
	b_3	DBH·CC	−0.07197	1.828	0.1062
	b_4	AGE	−0.1244	1.365	0.0896
	b_5	BAL^2	-1.654×10^{-7}	3.068	0.0185
	b_6	log(APAL)	0.7902	1.947	0.0420

VIF, variance inflation factor; DBH, diameter at breast height (cm); ΔBAH, percentage basal area removed; CC, indicator variable for crown class (1 = intermediate or suppressed, 0 = dominant or codominant); AGE, stand age (years); BAL, total basal area of trees with basal area larger than the subject tree (cm^2); APAL, layered area potentially available (m^2).

basal area increment–DBH relationship. Variance inflation factors for individual variables were all lower than 3.1, well below the threshold level of 10 generally considered to indicate that an individual parameter value may be excessively influenced by multicollinearity (Neter et al., 1989, Chatterjee and Price, 1991).

Partial coefficients of determination (r^2_{par}) for the individual variables in each model measured the marginal contribution of each variable with the remaining variables already in the model (Tables 2 and 3). They provided an indicator of the amount of unique variation in the dependent variable accounted for by each independent variable. DBH had the highest r^2_{par} in all of the models. BAL had second-highest in both of the Douglas-fir models, but had the lowest in both of the western hemlock models. The contribution of the distance-dependent competition measure (APAL) was small for both species, although its contribution to the model was larger than the distance-independent competition variable (BAL) in the western hemlock model.

6. Discussion

The APAL index made the highest contribution to R^2_{adj} of all of the spatial competition indices, when included in the models along with variables for size, thinning, crown class, age and a non-spatial competition index. Daniels et al. (1986) also found that a weighted APA index yielded the highest partial correlation when included in multiple regression models of basal area growth. The strength of APA indices lies in the fact that they contain unique information about the spatial pattern of a given tree with respect to its nearest neighbors, which cannot be captured by the non-spatial indices. In addition, tessellation-based indices are the only spatial indices that capture the influence of interactions between competitors on the subject tree. (Kenkel, 1991).

Although the contribution of APAL to the distance-dependent models was statistically significant and larger than that of the other neighborhood competition indices, the addition of APAL resulted in only a small improvement in the fit of these models. For both species, this increase in the R^2_{adj} resulting from the addition of APAL was less than 0.01. Studies carried out in a variety of other forest types have also concluded that spatial competition indices do not greatly improve the fit of basal area and diameter growth models (Biging and Dobbertin, 1995, Tome and Burkhart, 1989, Corona and Ferrara, 1989, Daniels et al., 1986, Martin and Ek, 1984, Lorimer, 1983).

There are three probable reasons for the low contribution of APAL in this study: The regular pattern of residual trees created by thinning, a strong relationship between individual tree size and competitive status and the possibility of large zones of competitive influence within the stand.

The spatial pattern of trees in all of the plots varied from random to regular. The thinned plots in particular had a highly regular spatial distribution of trees, implying that growing space was equally distributed among trees in the thinned plots. Therefore, competition indices taking the number and distance of competitors into account were less likely to make a significant contribution to a model already containing measurements of tree size and non-spatial competition indices. This may also have been why ΔBAH, a plot-level thinning index, was more effective than indices measuring thinning at the level of the individual tree.

Lorimer (1983) noted that diameter at breast height is in itself a type of neighborhood competition index, since variation in DBH provides information about the developmental history of a tree. Trees in an even-aged stand having a large DBH have experienced little competitive stress in the process of stand development, relative to trees with smaller DBH that have been suppressed by greater competitive stress. Barring a radical alteration of stand structure, the competitive environment for a tree of a given size will remain similar in the near future. Thus, DBH can be as effective as more complex indices at predicting future growth rates. The relationship between size and competitive status is illustrated by the fact that DBH had significant correlation with BAL and APAL for both Douglas-fir ($r = -0.73$ for BAL, $r = 0.56$ for APAL) and western hemlock ($r = -0.71$ for BAL, $r = 0.60$ for APAL).

Competition for light in this stand may have occurred at a scale as large as, or larger than, the mapped study plots. Most trees on the site were taller

(32 m average height of dominant and codominant trees at a stand age of 53) than the plots were wide (26.5 m on one side). Only a minor portion of the light striking the crowns of trees in a stand comes directly from above. Most of the light that reaches intermediate and suppressed crowns, as well as the mid-to-lower portions of dominant crowns, has to penetrate the forest canopy diagonally (Oliver and Larson, 1990). The height of the trees in the Jordan River stand, combined with the low incident angle of solar radiation at high latitudes (Canham et al., 1990), very likely caused light availability for a given tree to be influenced by competitors a long distance away. The areas defined by the boundaries of the sample plots were therefore as effective a measure of competitive neighborhood as the more detailed neighbor selection methods.

The fact that both BAL, which measured competition at the plot level, and APAL, which measured competition at the nearest-neighbor level, were significant in the distance-dependent models suggested that competition in the Jordan River stand occurred at more than one scale. At the plot level, one-sided competition for light depended on a tree's vertical position in the stand, which was reflected by both BAL and DBH. The thinning variable, ΔBAH, captured plot-level variation in the light environment caused by removal of competitors. Competition on a local scale was reflected by APAL in terms of horizontal crown area available to a given tree, as constrained by its nearest neighbors of equal or greater crown class. These local processes included crown abrasion and physical limitations to crown expansion caused by the presence of the neighboring trees.

7. Conclusion

The results of this study indicate that the additional effort and expense required to obtain spatially referenced stand data are not justified in instances where the objective is to develop empirical models of forest growth in mature stands that have been thinned from below to a regular spatial distribution. Although the new APAL index performed better than the other spatial competition indices, its contribution to the overall model was only marginal. A non-spatial thinning index proved more effective than the spatial thinning indices. Spatial indices may still prove useful, however, when modeling basal area growth under certain other stand conditions:

(1) Uneven-aged management or crown thinnings can create residual stands in which some small trees remain suppressed, while other small trees are released by the removal of the overstory. In these situations, the correlation between individual tree size and competitive status may be weak.

(2) Thinnings or green-tree retention cuts with an aggregated distribution of residual trees are being proposed as a way to enhance habitat for some wildlife species (Carey and Johnson, 1995). Residual trees located at the edges of these clumps, or in the open areas between clumps, will exist in a very different growing environment than that of trees of similar size in the interior of clumps.

(3) In dense unstratified stands, a tree's growth may be more sensitive to local crowding than to its vertical position in the stand.

Finally, it should be noted that thinning treatments alter the morphological development of residual trees as well as their growth rate. Changes in crown morphology may be particularly important in determining the long-term growth patterns of trees released by thinning. Competition indices based on crown measurements have shown promise in some studies (Biging and Dobbertin, 1992, Cole and Lorimer, 1994, Biging and Dobbertin, 1995). In order to develop generalized models of stand development that can reflect the effects of a wide range of thinning treatments, it will be necessary for these models to describe the effects of thinning on individual tree crowns and the overall stand environment, as well as the combined effects of crown morphology and stand environment on the basal area growth of individual trees.

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