Forest Ecology and Management, 6 (1983) 343—360
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

TESTS OF AGE-INDEPENDENT COMPETITION INDICES FOR INDIVIDUAL TREES IN NATURAL HARDWOOD STANDS

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(Accepted 27 January 1983)

ABSTRACT

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

Recent studies have demonstrated that simple indices of competition that incorporate competitor size and inter-tree distances generally perform as well in predicting individual tree growth as more complex approaches of assessing spatial pattern. A major limitation of diameter-distance indices, however, is that their numerical values decrease in a given stand over time even when the stocking level remains constant. In this paper two modifications are proposed which make the index essentially independent of age, thus necessitating only one competition-growth regression for each species on a given site and allowing comparisons between different stands. Tests of several index designs in three even-aged temperate hardwood stands indicated that the correlation between competition and growth is optimal over a wide range of competition radii and that the inclusion of inter-tree distances is of little value despite considerable small-scale variability in the stocking level around individual trees. Highest correlations were obtained when competitors were defined to be only those trees of equal or higher crown class than the subject tree. In these hardwood stands a comparison of the size of a subject tree to that of the competitors was necessary for reasonable correlations with growth. These correlations varied greatly among species even within a single stand and appear to be related to the shade tolerance of the species. For general use the index $(\Sigma D_j)/D_i$ is recommended, where D_j is the diameter of competitor j and D_i is the diameter of subject tree i. This index can be computed rapidly in the field and does not require mapping of stem positions.

INTRODUCTION

A common element among many individual-tree based growth models is the inclusion of an index designed to quantify the degree of competitive stress on individual trees in a stand. Most of the indices that take spatial pattern of individual trees into account can be grouped into the following categories: (1) indices that measure the amount of overlap of hypothetical "zones of influence" among neighboring trees (Newnham, 1964; Opie, 1968; Gerrard, 1969; Bella, 1971; Ek and Monserud, 1974); (2) growing space polygons that measure the area potentially available to each tree (Brown, 1965; Moore et al., 1973; Adlard, 1974; Alemdag, 1978); and (3) indices incorporating relative diameters and distances between subject tree and competitors (Hamilton, 1969; Lin, 1969; Hegyi, 1974; Ellis, 1979; Woods and Whittaker, 1981). Although the coefficients of determination between growth rate and competition index are often fair to good (r^2 of 0.4 to 0.8), most investigators who have made comparative tests between the indices have found little difference in predictive ability despite the substantial differences in design (Gerrard, 1969; Bella, 1971; Moore et al., 1973; Hegyi, 1974; Daniels, 1976; Alemdag, 1978). In most cases the differences in r^2 among the different indices is only on the order to 2—5%. It has also been found in row plantations that the use of a distance-dependent competition index may not always be superior to a simple non-spatial variable such as plot basal area (Martin, 1978; Meldahl, 1979).

The essentially equal predictive ability of the different indices suggests that it may be desirable to focus greater attention on the simpler diameter-distance indices. Lower computational cost was the major reason that Hegyi (1974) developed his diameter-distance index in preference to the influence-zone overlap formulas available at the time. Further advantages of this type of index is that it is the only one of the types mentioned above that can be measured easily in the field, and use of a computer, while advantageous, is not essential. Like growing space polygons, diameter-distance indices allow for asymmetrical development of crowns and root systems, but are less constrained by the geometry of patchy mosaics. In addition to their use in forest growth projection and simulation, diameter-distance indices are potentially useful for experimental purposes in biological field studies. The present study, for example, was motivated by the need for an index that could be used in comparing shade tolerance of species at similar levels of competition under field conditions. Woods and Whittaker (1981) have used a similar type of index to assess reproductive strategies in mixed species forests, and other applications are possible, such as assessing the susceptibility of individual trees to insect attack or response to fertilization treatments (Ellis, 1979).

Currently, the greatest limitation in the use of diameter-distance indices is the difficulty in interpreting the changes in the value of the index over time. If competitors are selected within a fixed radius from the subject tree, competition will appear to decrease over time as the number of stems per unit area decreases and the distances between trees increase. A similar problem is inherent in the growing space polygon approach. For diameter-distance indices this problem can be partly remedied by use of an angle guage to select competitors, but the use of a particular basal area factor is somewhat arbitrary and does not ensure that values of the index at two points in time are directly comparable in terms of competitive stress. The purpose of the present study was to modify diameter-distance indices so that the values are essentially independent of stand age and dependent only on the relative spatial pattern of trees. Systematic tests of various index designs were made in order to determine optimal design features and to gain further insight into the nature of the competitive process. Previous tests of competition indices have been done primarily in conifer plantations where spatial variability in stem pattern is low. The present tests were done in natural hardwood stands where spatial variation is much higher, in some cases augmented by experimental thinnings.

PROCEDURES

Index designs

The most widely-used diameter-distance index is a sum of the ratios of diameters of a subject tree and its competitors weighted by the distance from the subject tree (Hamilton, 1969; Hegyi, 1974; Daniels, 1976; Alemdag, 1978; Meldahl, 1979):

$$\mathrm{CI} = \sum_{j=1}^{n} \frac{D_j/D_i}{\mathrm{DIST}_{ij}} \tag{1}$$

where CI = competition index; D_j = diameter of competitor tree j; D_i = diameter of subject tree i; DIST_{ij} = distance between trees i and j; n = total number of competitors.

With this design, doubling the diameter of a competitor will double that tree's contribution to the total competition index, and doubling the distance from the subject tree will reduce its contribution by 50%. This index has no clear spatial interpretation, although the inverse of this index is proportional to the sum of the perpendicular distances to the sides of the growing space polygon of the subject tree, with the qualification that some of the competitors included in this index would be omitted in the polygon approach due to geometric constraints.

A number of variations on this index design were tested. The principal variations involved elimination or modification of the distance term, substitution of basal area for diameter, selection of competitors by crown class, and selection of the radius within which competitors are included (hereafter called the "search radius"). These indices were compared with the use of the subject tree's initial diameter as a predictor of growth rate. In all, 19 designs were compared and are designated by number from C1 to C19 (Table I). Alteration of index design was done systematically, component by component, in order to test various hypotheses on the influence of spatial patterns and forest structure on individual tree growth.

Modifications for age independence

Formula (1) was modified to make the competition index responsive only to a change in the relative spatial pattern of trees as determined by the pro-

TABLE I

Coefficients of determination (r^2) for diameter growth-competition index regressions; all regressions are highly significant ($P < 0.01$) except where noted otherwise (s5 = significant at 0.05 level; ns = not significant at 0.05 level)

Index number	Competition index	Competitor crown classes	Search radius	Nettleton, WI		Black Rock, NY[a]	Prospect Hill, MA		
				Sugar maple	Elm	Sugar maple	Red oak	Yellow birch	Red maple
C1	$\Sigma\ BA_j$	All	3.5 × mcr	0.09	0.20	0.23	0.06	0.08^{ns}	0.00^{ns}
C2	$\Sigma\ BA_j$	I, CD, D	3.5 × mcr	0.07	0.16	0.16	0.04	0.07^{ns}	0.00^{ns}
C3	$\Sigma\ BA_j$	> ST	3.5 × mcr	0.27	0.46	—	0.31	0.20	0.03
C4	$\Sigma\ \frac{BA_j}{DIST_{ij}/R}$	All	3.5 × mcr	0.17	0.04^{ns}	0.25	0.10	0.14^{s5}	0.02^{s5}
C5	$\Sigma\ \frac{BA_j}{DIST_{ij}/R}$	> ST	3.5 × mcr	0.32	0.26	0.25	0.36	0.38	0.05
C6	$\Sigma\ \frac{BA_j/BA_i}{DIST_{ij}/R}$	> ST	3.5 × mcr	0.31	0.58	0.58	0.73	0.42	0.13
C7	$\Sigma\ \frac{D_j/D_i}{DIST_{ij}/R}$	All	3.5 × mcr	0.13	0.34	0.55	0.70	0.51	0.13
C8	$\Sigma\ \frac{D_j/D_i}{DIST_{ij}/R}$	I, CD, D	3.5 × mcr	0.12	0.38	0.55	0.66	0.58	0.13
C9	$\Sigma\ \frac{D_j/D_i}{DIST_{ij}/R}$	All	3.5 × mcr (I, CD, D) 3.0m (S)	0.11	0.32	0.56	0.65	0.55	0.12

C10	$\Sigma \dfrac{D_j/D_i}{\mathrm{DIST}_{ij}/R}$	> ST	3.5 × mcr	0.30	0.58	—	0.74	0.41	0.16
C11	$\Sigma \dfrac{D_j/D_i}{\mathrm{DIST}_{ij}/R}$	All	3.5 × str	0.04^{ns}	0.03^{ns}	0.71	0.00^{ns}	0.02^{ns}	0.02
C12	$\Sigma \dfrac{D_j/D_i}{\mathrm{DIST}_{ij}/R}$	All	BAF=1.0m² /ha	0.22	0.44	0.54	0.68	0.53	0.12
C13	$\Sigma \dfrac{D_j/D_i}{\mathrm{DIST}_{ij}/R}$	All	BAF=2.0m² /ha	0.32	0.34	0.49	0.65	0.48	0.10
C14	$\Sigma \dfrac{D_j/D_i}{\sqrt{\mathrm{DIST}_{ij}/R}}$	> ST	3.5 × mcr	0.33	0.67	0.55	0.75	0.35	0.16
C15	$\Sigma \dfrac{D_j/D_i}{(\mathrm{DIST}_{ij}/R)^2}$	> ST	3.5 × mcr	0.17	0.37	0.53	0.64	0.38	0.06
C16	$D_i/\bar{D}_{oj}$	I, CD, D	3.5 × mcr	0.15	0.50	0.66	0.67	0.44	0.16
C17	$D_i/\bar{D}_{oj}$	I, CD, D	BAF=1.0m² /ha	0.10	0.46	0.62	0.65	0.27^{s5}	0.16
C18	$\Sigma\ D_j/D_i$	> ST	3.5 × mcr	0.32	0.67	0.55	0.74	0.33	0.16
C19	D_i	none	none	0.09	0.43	0.70	0.71	0.38	0.18

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[a] Crown classifications not available for Black Rock maple plantation. All index designs used on that tract include competitors of all crown classes except for indices C2, C8, C16, and C17, where competitors < 8.0 cm dbh were not included.

Abbreviations:

Competition Index: BA_j = basal area of competitor j, D_j = diameter of competitor j, D_i = diameter of subject tree i, $\bar{D}_{oj}$ = mean diameter of overstory competitors, DIST_{ij} = distance between subject tree i and competitor j, R = search radius.

Crown classes: S = suppressed, I = intermediate, CD = codominant, D = dominant, ST = subject tree crown class.

Search radius: mcr = mean crown radius of overstory trees, str = crown radius of subject tree, BAF = basal area factor.

portion of overlap of crown and root systems of adjacent trees. This can be done by two changes in the basic design. The first is to make the search radius a constant multiple of the average crown radius of the overstory trees. This keeps the search radius increasing at the same rate as the crowns, and any increase in the number of competitors over time signifies increased crowding and competition. Although making the search radius a multiple of stem diameter would be simpler and require less data, inspection of a number of crown diameter-stem diameter relationships in the literature (Krajicek et al., 1961; Newnham, 1964; 1966; Bella, 1971; Ek, 1974) revealed that crown diameters generally increase at a much slower rate than stem diameters. Thus doubling the search radius in response to a doubling of stem diameter would increase the number of competitors in situations where the stocking level has remained constant. In actual practice, all that is needed for search radius calculation are crown diameter-stem diameter measurements which can be quickly obtained in the field.

Modification of the search radius alone will not make the index independent of age since the absolute distance between trees continues to increase with age, reducing the magnitude of the index. This problem is easily solved by relativizing the distances in relation to the search radius (i.e., dividing inter-tree distances by the search radius). The modified competition index is therefore:

$$\mathrm{CI} = \sum_{j=1}^{n} \frac{D_j/D_i}{\mathrm{DIST}_{ij}/R} \quad \text{and} \quad R = b \cdot \mathrm{mcr}$$

where R = search radius; mcr = mean crown radius of overstory trees (or crown radius of subject tree); and b = a constant.

The simplified example in Fig. 1 shows a hypothetical stand that has remained at exactly the same level of stocking at two different ages. Furthermore, the crown sizes of all trees increased at the same rate during this period. The competition index of subject tree S is therefore exactly the same at both times, even though the number of competitors per unit area has decreased. In a more realistic example where trees are growing at different rates, the competition index of the subject tree will still undergo little change if the subject tree growth rate is close to the mean growth rate of its competitors. These modifications should greatly reduce or eliminate the effects of age on the index attributable solely to differences in scale caused by an increase in average tree size. Although field verification of age-independence is probably not possible, actual trials of the index in well-stocked stands ranging in age from 40 to 300 years showed similar index values for dominant-codominant trees in the various stands. The same standardization procedure can be used for selection of competitors by angle-guage methods, in which case the plot radius factor becomes a multiple of crown radius.

Since great variations often exist in understory density from stand to stand, and since the minimum diameter of trees tallied on plots is often

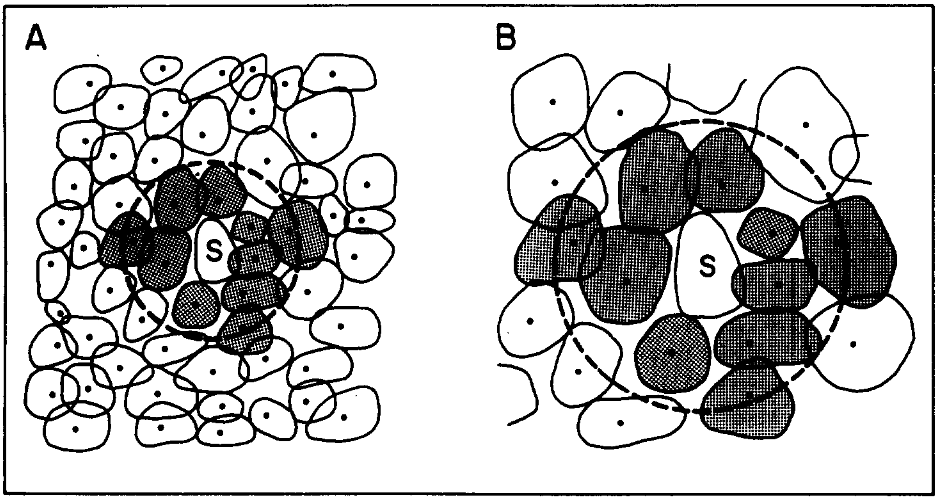

Fig. 1. Illustration of the principle of age-independence in assessing the degree of competition around individual trees. At time A, the radius of competition or 'search radius' for subject tree S is 3.5 × the mean crown radius of overstory trees, yielding ten competitors (stippled crowns) for inclusion in the competition index. At time B, 50 years later, the number of trees per unit area is much lower and average tree size greater due to natural mortality and growth. However, since the relative size and distances to competitors have remained the same, the competition index and number of competitors are also the same at a search radius equal to 3.5 × the new mean overstory crown radius. Any increase in competition index over time indicates increased crowding or stocking around the subject tree even if the number of trees per unit area has decreased.

highly variable, it appears more desirable to make the search radius a multiple of mean crown radius of overstory trees rather than of all trees in the stand.

It should be emphasized that optimal tree growth in the absence of competition (the y intercept of the growth-competition regression equation) varies with the age or initial size of the tree — that is, different-sized trees have different maximum growth potentials. Therefore whenever growth is being simulated for stands with a wide range of ages, the recommended approach is to use the competition index in an equation that will predict the reduction in growth from the optimum or include initial diameter as an additional variable in the equation (Ek and Monserud, 1974; Meldahl, 1979). The inclusion of initial diameter as an independent variable would probably also compensate for the possibility that at a given competition index value, trees in very young stands may receive more light because of the comparatively low crown density of young trees.

Evaluation procedures

The modified indices were tested in three temperate even-aged hardwood stands. The tracts selected for the evaluations all have large permanent plots on which it was possible to make tests of optimal search radius over a wide range and which have stem maps of individual trees. Study area characteristics are as follows:

(1) A 0.61 ha plot in a natural even-aged stand of sugar maple (*Acer saccharum*), American elm (*Ulmus americana*), and American basswood (*Tilia americana*) on a well-drained upland site (Nettleton research site), in the Nicolet National Forest, northeastern Wisconsin; site index 21 (m) for *Acer saccharum*; stand age 35 years at first measurement and 50 years at last measurement; with thinned and unthinned sections.

(2) A 1.1 ha plot in a natural even-aged stand of northern red oak (*Quercus rubra*), red maple (*Acer rubrum*), and yellow birch (*Betula alleghaniensis*) on a well-drained upland site (Prospect Hill) in the Harvard Forest, central Massachusetts; site index 20 (m) for *Quercus rubra*; stand age 74 years at first measurement and 80 at last measurement.

(3) A 0.19 ha plantation (not in rows) of *Acer saccharum* on a well-drained upland site in the Harvard Black Rock Forest, southern New York; site index 18 (m) for *Acer saccharum*; stand age 44 years at first measurement and 48 at last measurement; with thinned and unthinned sections.

In each stand, the point quarter sampling method (Cottam and Curtis, 1956) was used at random points to select trees for crown radius measurements. Crown widths (projected to the ground) were measured along four cardinal compass directions for 24 overstory trees (intermediate, codominant crown classes) in each stand. A crown radius-stem diameter relationship was then constructed for each stand (all species pooled) and the mean crown radius for each stand at the time of the first measurement period predicted from the regressions.

On each tract a border zone was established along the plot edge equal to the search radius, and no subject trees were selected within the border zone. The border zone was kept constant among different trials so that the same population of subject trees was used in each trial.

Regression equations used for predicting diameter increment or basal area increment as a function of competition index were selected according to trends observed in the scatter diagrams. Linear, quadratic, and negative power functions were utilized, and the equation selected for each species/site combination was the statistically significant regression having the highest coefficient of determination (Table I, Fig. 2). At any given site, generally only one equation type was used for each species (or each column in Table I) except in certain cases where some index designs yielded linear relationships and the others for the same species were clearly curvilinear.

RESULTS

Modifications of the search radius

A series of tests was carried out in all stands to determine if there is a well-defined optimal search radius for indices that utilize a fixed radius of

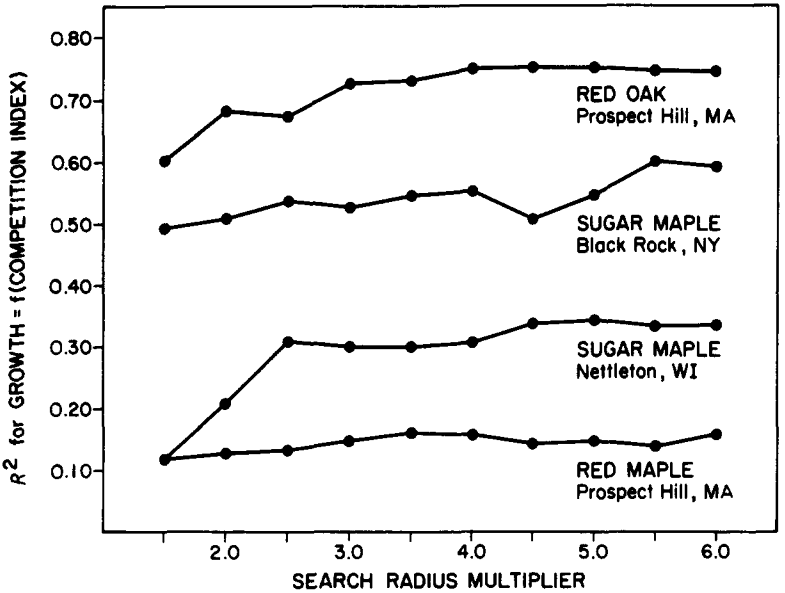

Fig. 2. Coefficient of determination (r^2) between observed mean annual diameter growth and competition index C10 for several species and locations at different relative radii of competition (search radii). The search radius multiplier is a multiplier applied to the mean overstory crown radius to obtain the actual search radius for each stand and measurement period.

competition. In each case, the search radius was varied from 1.5 to 6.0 X the mean crown radius of overstory trees in the stand, and the correlation between the competition index and observed diameter growth recorded. As shown in Fig. 2, all trials were similar in indicating that r^2 values are close to their maximum over a very broad range of search radii for the basic distance-weighted size ratio C7 or C10. It is only at the shorter distances (search radius multiplier of 1.5 to 2.0) that the correlation undergoes a sharp reduction, mainly because at a small search radius no competitors are detected for many subject trees. Between a multiplier of 2.5 and 6.0 there is only a difference of a few percentage points in the r^2 value for all species. This relative insensitivity to search radius length is not due to weighting by inter-tree distances, for similar results were obtained for index C18 that does not include distances. There is, however, a very strong correlation between index values for a given subject tree at different search radii. For example, the correlation coefficient for values of index C18 at two different search radii (3.5 X and 5.5 X mean crown radius) for sugar maple was 0.94 at Nettleton and 0.99 at Black Rock. This suggests that in most cases there is not a great deal of variability in competitor density within a moderate range of distances from an individual tree, even though there may be much variability among subject trees in different parts of the stand.

Use of an angle-guage approach to selecting competitors was also tried so that the distance within which a competitor was selected was proportional to the size of the competitor. Basal area factors of 1.0 m^2/ha and 2.0 m^2/ha were used. As can be seen by comparing the results from indices C12 and C13 with their fixed radius counterparts C7 or C10, little or no difference was observed. But use of the angle-guage approach is not recommended because it necessitates the use of a very wide border zone along the plot boundaries; otherwise large competitors will be counted less frequently for subject trees toward the plot edge. A basal area factor of 1.0 m^2/ha, for example, requires that no subject trees be selected within a border zone 30 m wide if some competitor trees 60 cm in diameter are present in the stand.

A third variation, that of including competitors within a distance of 3.5 × the crown radius of the subject tree, gave poor results when competitors of all crown classes were accepted (index C11). If only competitors of equal or higher crown class than the subject tree were accepted, the correlations with this approach were comparable to the fixed radius approach, but the correlations of competition index with observed growth were positive instead of negative. Since the largest trees had the largest search radius, they also had the largest number of competitors and the highest index. The correlation is probably spurious and may indicate only that observed growth is positively correlated with the size of the subject tree. A similar problem appears to be inherent in the influence zone overlap indices.

Selection and evaluation of competitors

In making initial comparisons among index designs, a fixed search radius was used equal to 3.5 × the mean crown radius of overstory trees in the stand. The first design tested was one that does not include any direct information on the subject tree, but merely sums the basal area of all competitors within the search radius (index C1 in Table I). Steneker and Jarvis (1963) reported relatively high r^2 values (0.56—0.66) when they used this approach in spruce-aspen stands, but in the present study almost no correlation at all was found between this index and observed diameter growth. The r^2 was close to 0 and not statistically significant in several cases (Table I). When the basal area of each competitor was weighted by its distance from the subject tree only a very small increase in the correlation occurred (index C4). However, when the basal area or diameter of the subject tree was included in the index as a ratio with that of its competitors, the correlation was greatly improved (index C7 vs. C4). For red oak on the Prospect Hill tract, this alteration in design increased the r^2 from 0.10 to 0.70.

Correlations between growth and competition index were little affected by whether or not suppressed trees were included in the index (index C8 vs. C7). The procedure of counting suppressed trees as competitors only within 3.0 m of the subject tree also had little effect (index C9). Although there was considerable variability in the density of suppressed trees around individual subject trees (e.g., a coefficient of variation of 31.5% at Nettleton), index values with and without suppressed trees were so highly correlated with each other (e.g., $r = 0.91$ at Nettleton) that the overall effect of variations in suppressed tree density on the index appears to be minor.

In many cases, however, a differential selection among potential competitors based on their crown class had a major effect on the strength of the correlation between competition index and growth. If competitors were defined to be only those trees of crown class equal to or higher than that of the subject tree (dominant and codominant trees counted as a single class), a substantial increase occurred for the index that sums the basal area of all competitors around the subject tree (index C3 vs. C1). When this criterion of competitor selection was applied to the distance-weighted size ratio C7, an increase in r^2 was found for most species that ranged from 24 percentage points to 3 percentage points (index C10 vs. C7). Since an increase in the correlation was observed for all species except for yellow birch at Prospect Hill, this criterion of competitor selection was used in making most of the comparisons among index designs shown in Table I.

Modification of the distance term

In most previous tests with diameter-distance indices, the contribution of a competitor tree to the total index has been inversely weighted by the distance to the subject tree (e.g., index C7). The influence of a competitor of a given size thus drops off at a curvilinear rate with increasing distance from the subject tree. Two variations of index design were tested in which the competitor is weighted by the square of the distance, which causes the influence to drop off at a faster rate, and the square root of distance, which causes the influence to drop off at a slower rate. Squaring the distance caused a substantial decrease in the correlation of up to 21 percentage points in the r^2 (index C15 vs. C10). Similar results were noted by Steneker and Jarvis (1963), Daniels (1976), and Meldahl (1979). Weighting by square root of the distance did not affect the r^2 when compared with the unmodified distance term (index C14 vs. C10). The most interesting modification, however, was elimination of the distance term altogether, which resulted in virtually no change in all species except two (index C18). The correlation for Americam elm on the Nettleton site actually increased (r^2 change from 0.58 to 0.67) whereas yellow birch at Prospect Hill showed a moderate decline (r^2 change from 0.41 to 0.33). Thus in these natural even-aged hardwood stands, a consideration of inter-tree distances is virtually of no value in most cases for predicting the growth of individual trees. This is despite the fact that parts of some stands have been thinned and the variability in stocking around individual trees is high. For example, on the Prospect Hill tract the density of competitors around individual subject trees and within the standard search radius ranged from 370 to 1482 per ha. At the Black Rock maple plantation, density of competitors around individual subject trees ranged from 1235 to 3581 per ha.

Species differences

The strength of the correlation between any particular competition index and observed growth appeared to be heavily dependent upon the species, for there were great differences in r^2 among species even in the same stand of trees. At Prospect Hill, for example, the r^2 for index C10 was 0.74 for red oak, 0.41 for yellow birch, and 0.16 for red maple. The strength of the correlations appear to be related in a general way to apparent shade tolerance of the species. Thus the species with the highest correlations (red oak and American elm) would generally be regarded as the least tolerant species in the group (Baker, 1949; Spurr and Barnes, 1980) and neither species has successful seedling establishment beneath the canopy of the stands reported here. The species with the lowest correlations (sugar maple and red maple) are regarded as shade-tolerant species and both have large numbers of seedlings and saplings in the stands where they occur as overstory species.

DISCUSSION

The inclusion of subject tree characteristics

It has been noted by other investigators that competition indices, regardless of the type, often do not show a much higher correlation with observed growth than could be obtained by using initial diameter of the subject tree as the independent variable (Gerrard, 1969; Bella, 1971; Alemdag, 1978). In the present study, this was found to be true in half the cases, including one case in which competition index has a lower correlation than initial diameter. In three cases, however, the competition index predicted growth substantially better than initial diameter (r^2 of 0.67 vs. 0.43, 0.51 vs. 0.38, 0.30 vs. 0.09). Moreover, current diameter is a valid predictor of future growth only in the absence of silvicultural treatments or other disturbances that alter the average stocking level of the stand. This restriction, of course, is unacceptable for most modelling efforts.

A more important consideration is whether the success of a competition index is due to the inclusion of initial diameter in the index. In the present study, none of the indices that exclude the initial size of the subject tree showed good correlations with observed growth. This does not, however, necessarily indicate that the predictive value of a competition index is dependent upon a spurious correlation with initial diameter, so that the index merely predicts that "big trees grow fast." The high correlation between diameter growth and initial diameter in even-aged stands is at least in part a secondary effect of the results of competition. The slow growth of small trees in even-aged stands is due as much to the fact that most of them are suppressed as to an inherently low growth potential of small trees, a point easily demonstrated by the response to release from suppression induced by cutting the surrounding trees. In forests managed under the selection system, the correlation between diameter growth and initial diameter may be weaker because small trees are not necessarily suppressed and may be growing in gaps. Crow et al. (1981) reported little difference in diameter growth in selection stands among trees ranging from 15 to 46 cm in diameter, but the level of stocking (i.e. competition) had substantial effects on individual tree growth. Thus initial diameter is in itself a kind of competition index, especially in even-aged stands.

Further investigations also suggest that inclusion of some indication of the size of the subject tree in relation to its competitors is necessary because otherwise the crown position and crown competition of the subject tree cannot be adequately determined. The tests reported in Table I indicate that knowledge solely of the size and spatial pattern of competitors around the subject tree gives a poor basis for predicting growth (indices C1—C5). Fig. 3. suggests why this is the case. In Fig. 3A, frequency distributions of the index C5, which weights competitor basal area by distance without reference to the size of the subject tree, are presented separately for each crown class. The distributions of dominant/codominant and intermediate trees overlap almost completely, and the range of competition index values for intermediate trees is as great as that of suppressed trees. This type of competition index, therefore, gives a poor indication of crown competition. But when basal area of the subject tree is included (index C6), reasonably good separation of crown classes is obtained (Fig. 3B). Thus 66% of the dominant/codominant trees are in the lowest competition index class (0—50), compared to only 17% of the intermediate trees and 1% of the suppressed trees. Likewise, 66% of the intermediate trees have index values between 50 and 150, compared to 28% of the dominant/codominant trees and 17% of the suppressed trees. All of the trees with an index > 350 are suppressed.

Inspection of plot maps showed that even when a large dominant competitor was located close to a subject tree, crown class of the subject tree could not be accurately predicted and could vary from dominant to suppressed. The ability of hardwoods to avoid competition by developing highly asymmetric crowns allows several dominant trees to coexist in close proximity. This asymmetry can also cause trees to become suppressed even when the density of stems around the subject tree is relatively low. Therefore growth cannot adequately be predicted from stem spatial pattern alone and requires some indication of the crown class or competitive status of the subject tree. An obvious example would be a tree growing in a moderate gap in the forest canopy, in which case the amount of sunlight intercepted by the crown is dependent upon the height of the tree in relation to that of the surrounding canopy. A comparison of stem diameter of a subject tree with those of its competitors, however, will not always accurately indicate the relative crown position of a subject tree, which is probably one reason why differential selection of competitors based on crown class improves the growth-competition index correlation (index C10 vs. C7). That is, if competitors are defined to be only those trees of equal or higher crown

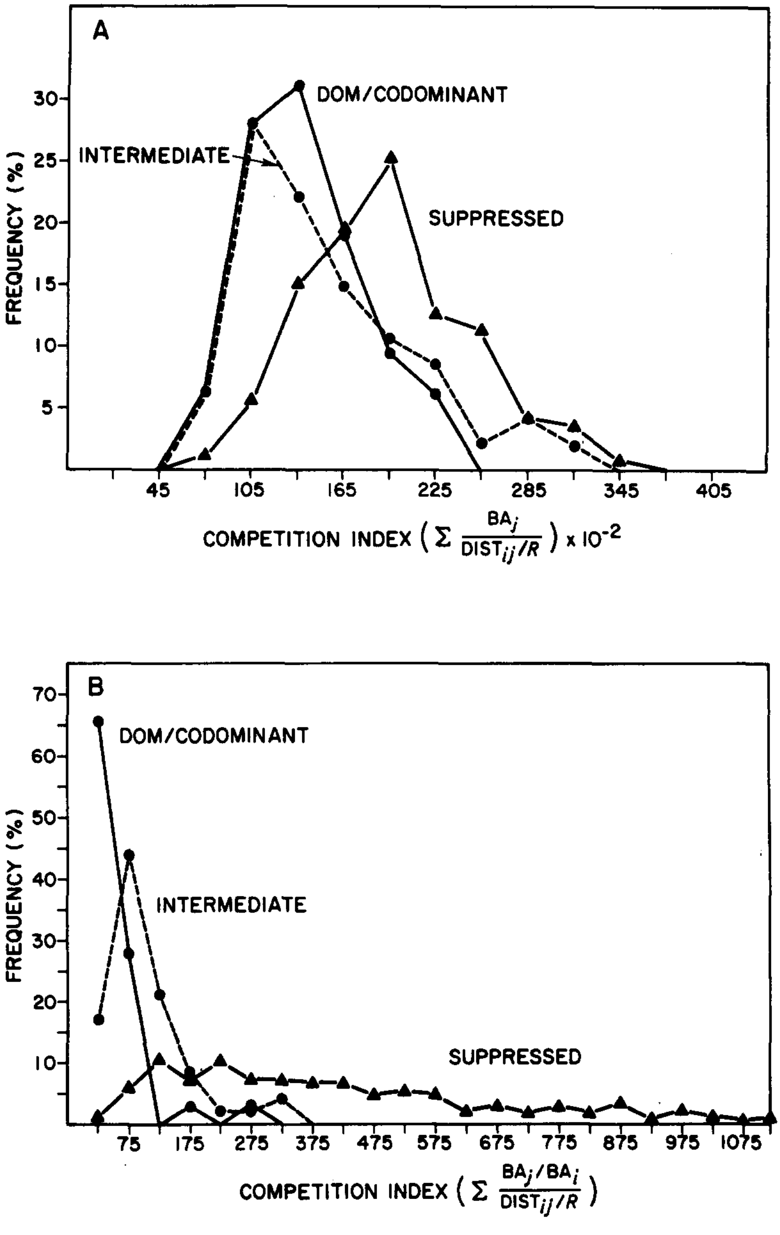

Fig. 3. Histograms of two competition indices for each crown class of red maple on the Prospect Hill tract. The competition index used in part B includes the basal area of the subject tree whereas the index in part A does not. Although there is some overlap in competition index among different crown classes in both cases, the index in part B gives a much better assessment of crown competition. Similar results were obtained for other species and sites.

class than the subject tree, some additional information on the crown class of the subject tree is indirectly incorporated into the index.

Selection of search radius

Since moderate variation in search radius length has little effect on the growth-competition index correlation, the actual search radius to be used is a matter of personal choice on the part of the investigator. However, a standard search radius would be helpful in comparing results among different studies, inasmuch as the actual magnitude of the index is greatly affected by the search radius used. A search radius of 3.5 × the mean crown radius of overstory trees is recommended for most applications. This distance appears to be long enough to assess important variations in local stocking near the subject tree, and the correlation of the index with growth is close to the observed maximum, yet it is a short enough distance that in many stands it could be used on small plots 810 m^2 or less in size without 'losing' too many trees to the border zone.

Use of non-spatial indices

The results obtained in these natural hardwood stands support Alemdag's (1978) conclusion in reference to conifer row plantations that "the extra time and expense involved in measuring coordinates. . .may not be easy to justify." The lack of importance of inter-tree distances is understandable in row plantations since there is so little variability in spacing. Yet even in natural hardwood stands with highly variable spacing, an indication of the relative size of the subject tree in conjunction with some indication of the local density of stocking appears to be all that is necessary to predict individual tree growth. The plasticity of hardwood crowns may be a contributing factor in this phenomenon. An additional factor may be the lack of a strong correlation between the amount of light and moisture available to an individual tree and the variety of stem or crown spatial patterns found at any given stocking level in many forests. Several investigators have noted that the location of saplings in relation to the border or center of small openings ($<$50 m in diameter) has a surprisingly small or insignificant effect on height growth (Tryon and Trimble, 1969; Smith, 1977; Metzger, 1980). In fully stocked stands or uniformly thinned stands, the effect of stem location would be expected to be even less. It is possible that inter-tree distances may be beneficial in predicting tree growth in some stands where large gaps occur in the canopy at irregular intervals, as after group selection or crop-tree release cutting, but this point needs testing.

In nearly all cases in the present study, a ratio of the diameter of the subject tree to mean diameter of the surrounding overstory trees gives almost as high a correlation with observed growth as competition index (cf. index C16, Table I). However, this type of index would only be responsive to changes caused by silvicultural treatments if included along with stocking level in a multiple regression. Basal area would probably not be a suitable indicator of stocking level in such cases; use of percent canopy cover or a stocking chart (e.g., Gingrich, 1967) would be preferred.

Another useful and versatile non-spatial index is:

$$\sum_{j=1}^{n} D_j/D_i$$

listed as index C18 in Table I. This index takes into account both the relative size of subject tree to competitors as well as the stocking level, since the index increases as the number of competitors per unit area increases. The search radius can be set to a constant multiple of mean crown radius to ensure age-independence. In the present study, this index was consistently among the top performers listed in Table I. The index is easily calculated without a computer. For field use an equivalent version of the index that can be rapidly computed is:

$$(\sum_{j=1}^{n} D_j)/D_i$$

A disadvantage of this index is that if each subject tree is to have a circular zone of competition with constant search radius, only one subject tree can be located at the center of each plot unless stem positions are mapped. However, if it can be assumed that the zone of competition around each subject tree need not be perfectly circular, then several subject trees could be included near the center of each plot, greatly increasing its efficiency and eliminating the need for stem mapping.

ACKNOWLEDGEMENTS

Wisconsin permanent plot data were kindly made available by Thomas Crow of the U.S. Forest Service, and data in Massachusetts and New York by the Harvard Forest staff. I also thank James Guldin for computer programming assistance and George Martin for comments and suggestions. Research supported by the College of Agricultural and Life Sciences, School of Natural Resources, University of Wisconsin, Madison.

REFERENCES

Adlard, P.G., 1974. Development of an empirical competition model for individual trees within a stand. In: J. Fries (Editor), Growth Models for Tree and Stand Simulation. Royal College of Forestry, Stockholm, Sweden, pp. 22—37.

Alemdag, I.S., 1978. Evaluation of some competition indexes for the predictions of diameter increment in planted white spruce. Inf. Rep. FMR-X-108, Canadian Forestry Management Institute, Ottawa, Ont., 39 pp.

Baker, F.S., 1949. A revised tolerance table. J. For., 47: 179—181.

Bella, I.E., 1971. A new competition model for individual trees. For. Sci., 17: 364—372.

Brown, G.S., 1965. Point density in stems per acre. N.Z. For. Res. Notes 38, 11 pp.

Cottam, G., and Curtis, J.T., 1956. The use of distance measures in phytosociological sampling. Ecology, 37: 451—460.

Crow, T.R., Jacobs, R.D., Oberg, R.R. and Tubbs, C.H., 1981. Stocking and structure for maximum growth in sugar maple selection stands. U.S. For. Serv. Res. Pap., NC-199, 16 pp.

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

Ek, A.R., 1974. Dimensional relationships of forest and open grown trees in Wisconsin. Res. Note 131, Department of Forestry, University of Wisconsin, Madison, WI, 7 pp.

Ek, A.R. and Monserud, R.A., 1974. FOREST: a computer model for simulating the growth and reproduction of mixed species forest stands. Research Report R2635, University of Wisconsin-Madison School of Natural Resources, Madison, WI, 13 pp. + Appendix.

Ellis, R.C., 1979. Response of crop trees of sugar maple, white ash, and black cherry to release and fertilization. Can. J. For. Res., 9: 179—188.

Gerrard, D.G., 1969. Competition quotient: a new measure of the competition affecting individual forest trees. Agric. Exp. Stn. Res. Bull. 20, Michigan State University, East Lansing, MI, 32 pp.

Gingrich, S.F., 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the central states. For. Sci., 13: 38—53.

Hamilton, G.J., 1969. The dependence of volume increment of individual trees on dominance, crown dimensions, and competition. Forestry, 42: 133—144.

Hegyi, F., 1974. A simulation model for managing jack-pine stands. In: J. Fries (Editor), Growth Models for Tree and Stand Simulation. Royal College of Forestry, Stockholm, Sweden, pp. 74—90.

Krajicek, J.E., Brinkman, K.A. and Gingrich, S.F., 1961. Crown competition-a measure of density. For. Sci., 7: 35—42.

Lin, J.Y., 1969. Growing space index and stand simulation of young western hemlock in Oregon. Ph.D. Thesis, Duke University, Durham, NC, 182 pp.

Martin, G.L., 1978. A dynamic network analysis of silvicultural alternatives for red pine. Ph.D. Thesis, University of Wisconsin, Madison, WI, 189 pp.

Meldahl, R.S., 1979. Yield projection methodology and analysis of hybrid poplars based on multispaced plots. Ph.D. Thesis, University of Wisconsin, Madison, WI, 228 pp.

Metzger, F.T., 1980. Strip clearcutting to regenerate northern hardwoods. U.S. For. Serv. Res. Pap. NC-186, 14 pp.

Moore, J.A., Budelsky, C.A. and Schlesinger, R.C., 1973. A new index representing individual tree competitive status. Can. J. For. Res., 3: 495—500.

Newnham, R.M., 1964. The development of a stand model for Douglas fir. Ph.D. Thesis, University of British Columbia Faculty of Forestry, Vancouver, B.C., 201 pp.

Newnham, R.M., 1966. Stand structure and diameter growth of individual trees in a young red pine stand. Can. Dep. For. Rural Dev. Int. Rep. FMR-1, 19 pp.

Opie, J.E., 1968. Predictability of individual tree growth using various definitions of competing basal area. For. Sci., 14: 314—323.

Smith, H.C., 1977. Height of tallest saplings in 10-year-old Appalachian hardwood clearcuts. U.S. For. Serv. Res. Pap., NE-381, 6 pp.

Spurr, S.H. and Barnes, B.V., 1980. Forest Ecology (3rd Edition). Wiley, New York, NY, 687 pp.

Steneker, G.A. and Jarvis, J.M., 1963. A preliminary study to assess competition in a white spruce-trembling aspen stand. For. Chron., 39: 334—336.

Tryon, E.H. and G.R. Trimble, 1969. Effect of distance from stand border on height of hardwood reproduction in openings. Proc. W.Va. Acad. Sci., 41: 125—133.

Woods, K.D. and Whittaker, R.H., 1981. Canopy-understory interaction and the internal dynamics of mature hardwood and hemlock-hardwood forests. In: D.C. West, H.H. Shugart and D.B. Botkin (Editors), Forest Succession: Concepts and Application. Springer Verlag, New York, NY, pp. 305—323.