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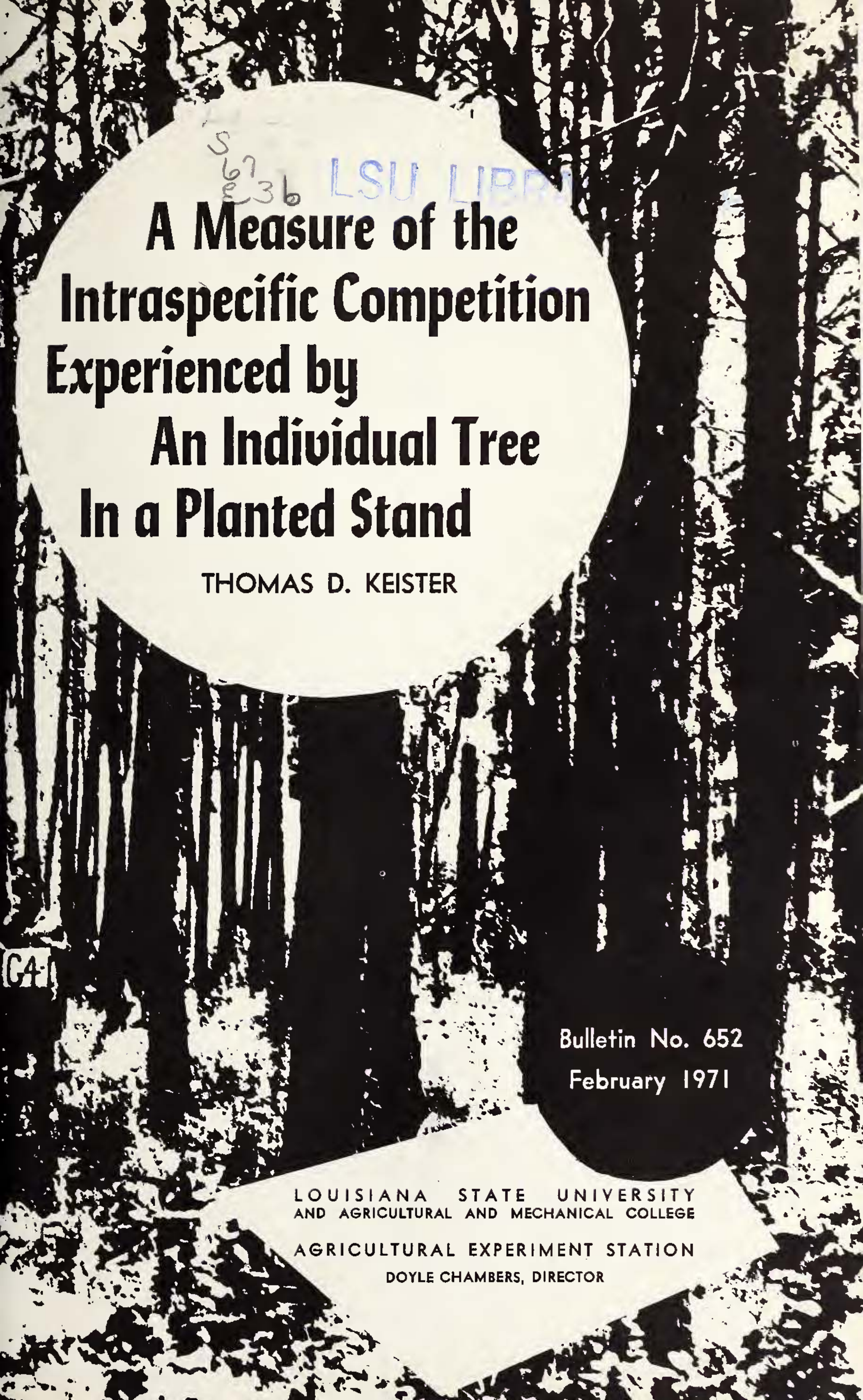

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A Measure of the Intraspecific Competition Experienced by an Individual Tree In a Planted Stand

Thomas D. Keister[1]

Introduction

One of the greatest impediments to thinning research is the large area which must be provided for the various treatments. For this reason most thinning studies have an inadequate number of replications with which to compare treatments. Another impediment is the difficulty of defining a range of thinning regimes by mathematical functions suitable for statistical analyses (Dawkins, 1960). Osborne (1939) has suggested that the first impediment may be overcome by using individual trees rather than stands as units of study. Regression techniques may be used to compare the development of individual trees that have received particular amounts of release by thinning. If individual tree measurements are used rather than stand measurements, much more information can be learned with less involvement of stands and land area. Thinning studies are usually more concerned with differences in degree of thinning rather than in kind of thinning, and individual tree measurements lend themselves to this type of study (Smith, 1959).

Probably the main reason that thinning studies have more often been concerned with stands than with single trees is the difficulty, already mentioned, of defining the degree of thinning. Wicht (1948) felt that thinning degree could be expressed in terms of stems per acre. Hummel replied in this same article that experience in Great Britain has shown that the number of stems per acre is a suitable variable for experiments designed to find the most suitable height or age at which to start thinning. However, in experiments where thinning is started on all plots at the same age and differs only in severity, such a measure is not as good as an index of stand density which considers mean basal area and height as well as the number of stems. Worthington *et al.* (1962) tried to measure thinning intensity with a specified stand-density index but found this was not satisfactory since cutting was not uniformly distributed over the entire range of tree diameters. Johnston and Waters (1961) stated that it is impossible to give a definition of a thinning grade which can be widely applied both qualitatively and quantitatively. Wicht (1936) and Vezina (1962) have both mentioned the need for research to find a measure of stand density.

This study was concerned with finding some measure of stand density, or of thinning intensity, that could be objectively applied to individual trees within a stand. It was felt that if the competition an individual

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tree was receiving from surrounding trees could be objectively measured, then the degree of thinning could be measured by determining the reduction in this competition following the thinning. Such a measure of competition would be a measure of stand density if it could describe the degree of crowding of individual trees within the portion of the area actually stocked with trees (Smith and Bailey, 1964).

The space available to a tree has been used by many workers as a measure of competition. Krajicek and Brinkman (1957) developed a "crown-competition factor" which is based on the area in the stand utilized by each tree crown. Brown (1965) computed the area potentially available to each tree by determining the smallest polygon that could be obtained by erecting horizontal bisectors perpendicular to the horizontal lines joining the center of the subject tree to the centers of the neighboring trees.

Jack (1967) developed a competition factor by comparing the sum of the heights of all of the effective neighbor trees (as defined by Brown, 1965), weighted by the proportion they contribute to the area of the polygon surrounding the sample tree, to the height of the sample tree.

One of the first to study individual tree competition was Staebler (1951), who assumed that the growing space occupied by an individual tree was circular and that the radius of the area was related to the diameter of the tree. Zones of competition occurred wherever two of these circular areas overlapped. He believed that the competition exerted upon an individual tree was directly proportional to the amount of overlap of its circle.

Newnham (1966) and Gerrard (1969) both used Staebler's basic ideas but were able to make further advances in the approach. Both men tried relating the radii of the competition circles to tree diameter, and Newnham also tried relating this radius to crown width. However, none of the resulting measures of competition contributed significantly to growth-prediction equations when combined with diameter and other tree and stand parameters. Gerrard was working in natural oak-hickory stands in Michigan and he believed that better results would have been found if the work had been done in single-species stands, preferably plantations, where the number of factors controlling the performance of individual trees is less.

Opie (1968) expressed the relative area of overlapping circles in terms of basal area per acre. He noted that a circular zone of the influence existed around each tree. The radius of this circle varied both with site and with tree size. Opie developed a method for measuring the basal-area density of a given tree by determining the area of overlap of a subject tree's zone of influence by adjacent trees, combined with the number of trees involved in this overlap. An angle gauge was used to sample for overlap throughout the zone of the subject trees.

This paper presents a method for measuring the intraspecific competition that an individual tree is experiencing in an even-aged, single-species forest stand.

Development of a Competition Index Equation

Basic Theory

The method presented in this paper is similar to those developed by Newnham, Gerrard, and Opie in that overlapping circles are also used. The basic premise is that growth made by an individual tree varies inversely with the ratio of the size of the individual to the size of the competing tree and varies directly with the horizontal distance between the individual tree and the competing tree.

Each tree interacts with all of the environmental variables in a certain area that surrounds it. For example, its crown shades a certain area and its roots occupy a certain area from which nutrients and water are taken. The combined area of interaction by a tree can be called the "circle of influence" (Zinke, 1962), and it seems reasonable to assume that this area approximates a circle (both roots and limbs, if not impeded, tend to grow away from the tree at nearly an even rate in all directions). The radius of this circle of influence will vary in size according to the species, character of soil, genetic potential, and the overall size of the tree. A zone of competition exists wherever these areas overlap, and the effect of this competition on either of the trees at the center of the influence circles is theoretically proportional to the ratio of the area of the competition zone to the area of either circle of influence.

The amount of competition received by any one tree from a single neighbor depends on the size of the individual (which determines the size of its circle of influence) and on the portion of this circle that is overlapped by the neighbor's circle of influence. The competition received by one tree (hereafter called a sample tree) from one other tree, then may be defined as:

$$I_{ik} = C_{ik}/\pi K_k^2 \qquad (1)$$

where: I_{ik} = competition received from the i th competing tree by the k th sample tree,
C_{ik} = the area in the zone of competition, and
K_k = the radius of the influence circle of the tree receiving the competition (Figure 1).

When a tree has its circle of influence overlapped by the circles of several other trees, then the amount of competition it receives will be equal to the sum of the ratios of the areas of all the competition zones to the area of the circle of influence of that individual tree. This total competition or competition index for the k th sample tree may be defined as:

$$\sum_{i=1}^{n} I_{ik} = (1/\pi K_k^2) \sum_{i=1}^{n} C_{ik} \qquad (2)$$

The area of C_{ik} may be calculated as:

$$C_{ik} = K_k^2 \arctan \left[U/(X_{ik}^2 + B)\right] + R_i^2 \arctan \left[U/(X_{ik}^2 - B)\right] - U/2$$

where: R_i = the radius of the influence circle of the i th competing tree,

X_{ik} = the horizontal distance between the k th sample tree and the i th competing tree,

$$B = K_k^2 - R_i^2$$

$$U = \left[X_{ik}^2(2A - X_{ik}^2) - B^2\right]^{1/2}$$

$$A = K_k^2 + R_i^2$$

i = 1, 2, 3, . . . , n competing trees, and

k = the k th tree of m sample trees (Fig. 1).

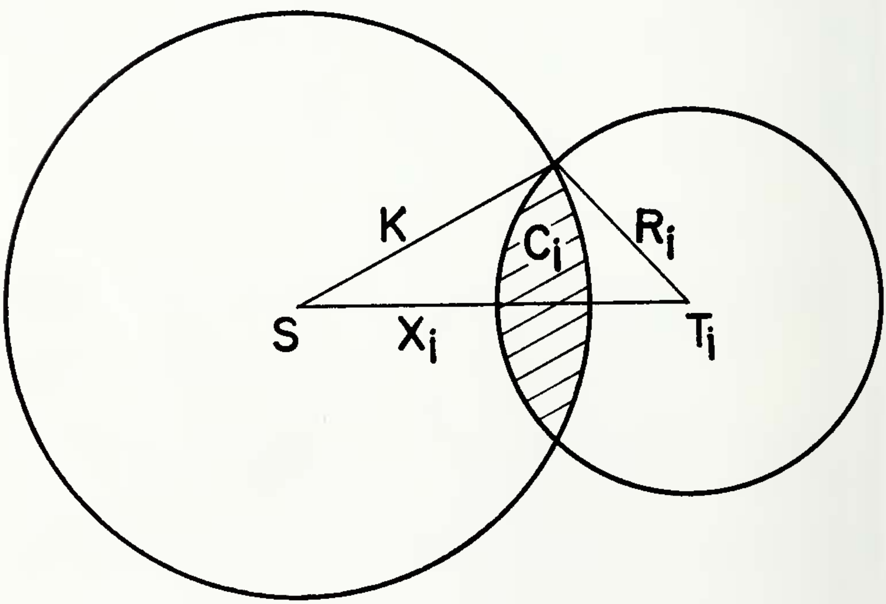

Figure 1.—Zone of competition between two trees. S = sample tree; K = radius of circle around tree S; X_i = distance between trees S and T; T_i = competing tree; R_i = radius of circle around T_i; C_i = zone of competition (diagonal lines).

The value for the competition index decreases with increasing distance between trees and as the ratio of the sum of the areas of overlap to the sample tree's circle area decreases.

The radius of a tree's circle of influence (K_k or R_i) is related to the size of the tree. If this radius is large, it is likely that the number of overlapping trees (n) will also be large, since a large circle is likely to overlap with more circles than is a small circle. However, it is possible that the k th sample tree and the k+1 th sample tree might have equal index values even though $n_k < n_{k+1}$. The k th sample tree will have a few competing trees, each contributing a large part of I_k, while the k+1 th tree will have many competing trees, each contributing a small part of I_{k+1}. It was therefore decided that the variable $(I/n)_k$ should also be considered in an equation for predicting growth.

Diameter growth is usually well correlated with the tree's diameter at the start of the growth period. That is, large trees generally make more diameter growth than small trees of the same age. Any measure of the effects of competition on growth should also consider this factor. Therefore initial diameter was included in the equation with the competition variables.

The growth equation selected for testing with field data was:

$$G_a = b_0 + b_1 I + b_2 n + b_3 d + b_4 (I/n) \quad (3)$$

where: G_a is the sample tree diameter growth for a years,

I is defined by equation 2 and equals $\sum_{i=1}^{n} I_{ik}$,

n is the number of competing trees,

d is the diameter of the sample tree at the start of the growth period, and the

b_i's are partial regression coefficients.

It was believed that some combination of these variables would account for a considerable portion of the variation in growth.

Determining the Radius of Influence

The major problem still to be solved, before the method could be field-tested, was how to determine the proper radius of a tree's influence circle. Both Newnham (1966) and Bella (1969) set this radius equal to a function of the crown radius. However, crown radius is only one parameter of tree size and it may not truly indicate the overall size of the tree. Newnham (1966), and also Gerrard (1969), used a function of tree diameter to determine the radius of the influence circle. Diameter, however, like crown width, is only one of the parameters of tree size.

In most even-aged stands there is a relationship between the stem diameter and the total height (Curtin, 1964; Czarnowski, 1961), but this relationship is modified by stand density and also by thinning treatment. Trees of the same age growing on similar sites should differ in their relationship of height to diameter according to differences in competition the individual trees have experienced in the past. A similar relationship also exists between diameter and crown radius. That is, larger trees will tend to have wider crowns. Height, diameter, and crown radius have all been used as expressions of tree size. It seemed that a combination of these measures would be a better reflection of tree size than any single measure.

It is very difficult to measure accurately the height and crown radius of every tree. However, because of the relationship between these factors and diameter, it was theorized that curves of mean height and mean crown radius as functions of diameter could be used to define the size of a tree of given diameter. The problem then was to find how best to use these variables as a meaningful expression for the radius of the influence circle. Two approaches were used.

The first approach was to assume that the radius would be proportional to the total height of a tree. That is, the radius for any tree could be defined as $T = Zh$, when Z is a proportionality value that would be constant for a given species, site, and age group, and h is the total height and is related to diameter. If the tree with radius T is selected as a sample tree, $T = K_k$; otherwise $T = R_i$.

The second approach was to assume that the size of a tree's live crown could be used to express tree vigor. It was felt that if two trees are equal in diameter and height the one that has the larger crown will be the most vigorous and should have the larger influence circle. In order to determine the radius by this approach it was necessary to consider diameter, total height, crown radius, and length of live crown.

An attempt was made to correlate the dead-limb length (i.e., height to lowest live limb) to diameter, as was done with total height and crown radius. On the plots used in this study, at least, no such relationship was found. Instead the dead-limb length was nearly constant for a given plantation, although there were differences between plantations. This meant that the tallest trees in a given stand have the longest crowns and would seem to favor the first approach, where circle radius was set proportional to tree height.

Others have noted that dead-limb length shows little relationship to tree diameter in even-aged pine stands. Stiell (1966) found dead-limb length in red pine (*Pinus resinosa* Ait.) plantations increased with age and was strongly correlated with total volume per acre and also with the ratio of average total height to the cube root of average spacing. Monterey pine (*P. radiata* D. Don.) has also shown no relation between diameter and dead-limb length (Laar, 1963). Toma (1940) made studies of Scotch pine (*P. sylvestris* L.) and reported that the crown began at about the same height on all trees in a stand, and that this height increased with increasing age. From these results it seems that dead-limb length should be rather constant in an even-aged stand and is related to the age of the stand, and perhaps also to site. Like the results reported by Stiell, the dead-limb length in this study showed a strong correlation with the ratio of average total tree height to the cube root of average spacing ($r = 0.842$).

Approach 2 called for setting the radius of the influence circle equal to some measure of the crown. It was finally decided to set the radius of a tree's influence circle equal to the distance between the tip of the tree and the intersection of a line from the base of the tree through the outer edge of the crown base and a line from the tip perpendicular to the trunk of the tree (Figure 2). Thus, if a tree of diameter d has a total height h and crown radius c, and is growing in a stand with average dead-limb length m, then the radius of the influence circle for this tree (T) can be defined as $T = (hc)/m$. If the relationships of height (h) and crown radius (c) to diameter (d) are known, and if the average dead-limb length for the stand is known, then T can be determined for any tree in the stand simply by measuring its diameter. Tall trees and trees with wide crowns will have longer circle radii than short or narrow-crowned trees.

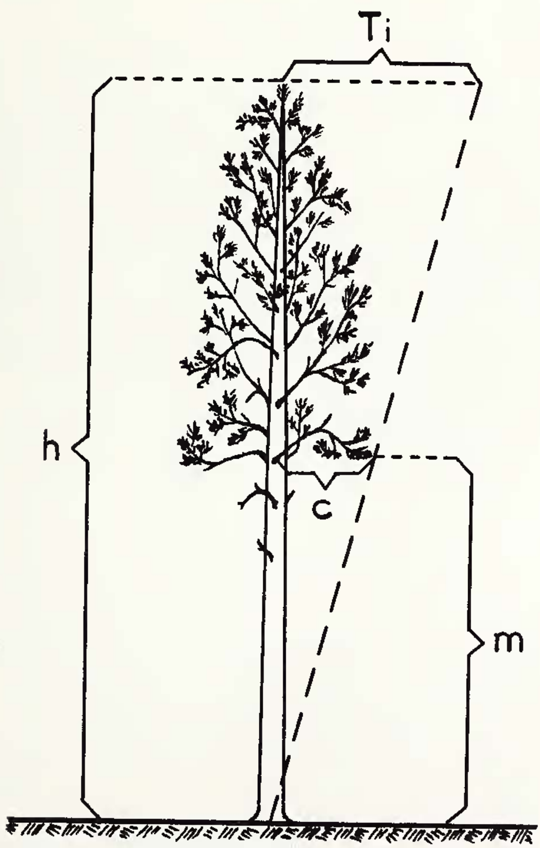

Figure 2.—Procedure for determining the radius of a tree's influence circle (T_i), as used in approach 2, where $T_i = hc/m$; h = total tree height; c = crown radius; m = dead-limb length; T_i = radius for the i th tree's circle of influence.

Field Test of the Competition Index Hypothesis

Method

A field test of the utility of this competition index for predicting growth of individual trees was begun in October 1966 by the Louisiana State University School of Forestry and Wildlife Management in cooperation with the Agricultural Experiment Station. Three ¼-acre circular plots were located in each of seven pine plantations. Three of these plantations (G1, G2, and G3) were slash pine (*Pinus elliottii* Engelm.) that had been planted in January 1952 with 1-0 planting stock. One plantation (G7) had been planted with 1-0 loblolly pine (*P. taeda* L.) seedlings in January 1956. One plantation (G5) was a mixed slash- and loblolly-pine plantation planted with 1-0 stock in December 1953. The other two plantations were both slash pine, one (G4) planted in December 1952 and the other (G6) planted in December 1953. Initial spacing was to have been 6 feet x 8 feet, but actual spacing was sometimes quite different from that intended.

The plantations were all located in Livingston Parish, Louisiana. The plots in plantations G1, G2, and G3 were established in the winter of 1966 when the trees had completed 15 growing seasons in the field. Plots in plantations G4, G5, G6, and G7 were established during the winter of 1967 when trees on G4 had completed 15 seasons, G5 and G6 had completed 14 seasons, and G7 had completed 11 growing seasons. All plots, with the exception of those in G7, were planted by hand and have been frequently burned so that survival is quite spotty. Several plots have some volunteer trees growing in them, and all have suffered some damage from recent hurricanes, so spacing is not very regular. Most of the plantations are on average to poor sites for this area. Using 25 as a base age, site indices range from a low of 64 (G6) to a high of 88 (G7); the overall average site index is 72.4.

Plantation G7 is exceptional in several ways. It is the only plantation studied that was machine planted; hence the trees are growing in rather straight rows. There are no trees growing there that were not planted. There was a minimum amount of storm damage. The most unique fact about this plantation, however, was the unusual early growth made by some of the trees. This area was cleared and all vegetation piled and burned in 1955. Seedlings that were planted in the resulting ashes made exceptional height growth over the next three years. The average annual height growth of trees growing for three years in ashes was 3.25 feet as compared with 1.63 for trees not growing in ashes. Apparently this difference resulted from the fact that the trees planted in ashes found much more available calcium, potassium, phosphorus, and magnesium than did trees planted in ordinary soil (Applequist, 1960). From the present appearance of this plantation it seems likely that these early effects are still influencing the size of many of the trees. At least the height growth on these plots has been especially good.

A summary of conditions that existed on each plot within each plantation when the plots were established is shown in Table 1. A

Table 1.—Summary of plot conditions at the beginning of the first growing season after plot establishment (per acre basis)

Plot No.	Trees	Basal area	Mean dbh	Top height[2]	Date plots established
	Number	*Sq.ft.*	*Inch*	*Ft.*	
		Slash Pine Plantation G1 planted 1/52			
1[1]	184	49	6.70	45	8/66
2	380	88	6.08	46	8/66
3	252	74	7.00	46	8/66
Average	272	70	6.54	45.7	
		Slash Pine Plantation G2 planted 1/52			
1	968	104	4.19	44	8/66
2	308	47	4.58	43	9/66
3	260	56	6.06	44	9/66
Average	512	69	4.58	43.9	
		Slash Pine Plantation G3 planted 1/52			
1	496	93	5.61	44	9/66
2[1]	264	61	6.33	44	9/66
3	564	99	5.47	42	10/66
Average	441	84	5.63	43.6	
		Slash Pine Plantation G4 planted 12/52			
1	580	103	5.24	48	8/67
2	520	76	4.71	43	8/67
3	272	57	5.96	44	8/67
Average	457	79	5.18	44.1	
		Slash & Loblolly Pine Plantation G5 planted 12/53			
1	400	71	5.39	47	8/67
2	436	86	5.70	46	9/67
3	376	72	5.53	47	9/67
Average	404	76	5.54	46.9	
		Slash Pine Plantation G6 planted 12/53			
1	376	67	5.36	39	9/67
2	260	64	6.56	38	9/67
3	252	55	6.10	37	10/67
Average	264	62	5.92	38.2	
		Loblolly Pine Plantation G7 planted 1/56			
1	520	99	5.62	44	10/67
2	588	112	5.65	40	10/67
3	516	118	6.24	43	10/67
Average	541	110	5.83	42.8	

[1]After thinning plot.

[2]Average height of dominant and codominant trees.

summary of the changes in plot stocking over the 2- and 3-year growth periods is shown in Table 2. There were many differences in stocking, both among plots within a plantation and among plantations. Differences in site, as expressed by top height, are not as pronounced, although again, there are differences. These differences were no accident, since plots were selected to give as wide a range of competition as possible.

All trees on each plot and all trees within 130 feet of the plot center were numbered and tagged. The diameter (dbh) of each tagged tree was measured to the nearest .01 inch. In addition, the total height,

Table 2.—Summary of cut and cumulative mortality

Plot	Initial		Cut		Mortality since plot establishment[1]		Present condition	
	Trees	Basal area	Trees	Basal area	Trees	Basal area	Trees	Basal area
	Number	*Sq.ft.*	*Number*	*Sq.ft.*	*Number*	*Sq.ft.*	*Number*	*Sq.ft.*
				Plantation G1				
1	272	72	88	24	16	1	168	60
2	380	88	0	0	84	5	296	92
3	252	74	0	0	32	7	220	80
				Plantation G2				
1	968	104	0	0	156	7	812	120
2	308	47	0	0	8	1	300	68
3	260	56	0	0	4	<1	256	72
				Plantation G3				
1	496	93	0	0	20	2	476	116
2	404	84	140	21	12	1	252	78
3	564	99	0	0	44	3	520	116
				Plantation G4				
1	580	103	0	0	16	1	564	125
2	520	76	0	0	12	1	508	90
3	272	57	0	0	0	0	272	76
				Plantation G5				
1	400	71	0	0	20	1	380	88
2	436	86	0	0	28	3	408	102
3	376	72	0	0	32	1	344	82
				Plantation G6				
1	376	67	0	0	12	2	364	83
2	260	64	0	0	4	<1	256	78
3	252	55	0	0	0	0	252	71
				Plantation G7				
1	520	99	0	0	24	1	496	117
2	588	112	0	0	0	0	588	134
3	516	118	0	0	20	1	496	137

[1]Mortality figures are the totals lost during a 3-year period on plantations G1, G2, and G3 and during a 2-year period on all other plantations.

dead-limb length, and crown radius were measured on each tree within a plot boundary. All plot-tree diameter measurements have been repeated annually since plot establishment. The point of the initial diameter measurement was marked with small nails on opposite sides of the tree as a guide for remeasurement. The position of each tagged tree was carefully mapped.

Equations for predicting total tree height (h) and crown radius (c) from diameter were prepared for each plantation. These equations were in the forms:

$$h = a_0 + a_1 \log_{10} d \quad (4)$$

and

$$c = b_0 + b_1 d \quad (5)$$

where the a_i and b_i are constants for a given plantation and d is tree diameter. The average dead-limb length was also calculated for each plantation (Table 3).

Table 3.—Plantation initial average dead-limb lengths, and equations for predicting total height and crown radius from diameter

Plantation	Dead-limb length		Regression coefficients for equations[1]			
	Mean	Std. error	$h = a_0 + a_1 \log_{10} d$		$c = b_0 + b_1 d$	
			a_0	a_1	b_0	b_1
	Feet	*Feet*				
G1	18.77	.3479	6.39815	44.46339	1.45561	0.75400
G2	20.60	.3114	9.85674	42.84909	0.25184	0.95116
G3	20.50	.2199	6.47566	44.34206	0.26112	0.91195
G4	20.90	.2379	6.88504	46.67679	-0.45849	1.09744
G5	20.43	.2636	6.77684	48.00886	-0.71622	1.07419
G6	14.93	.2702	7.71892	37.35445	0.21222	1.12779
G7	19.75	.2423	8.86521	40.55955	0.52423	0.99679

[1] h = total ht; c = crown radius; d = initial dbh; and a_0, a_1, b_0 b_1 = regression coefficients.

Thirty trees, which were to be used as sample trees, were selected from each plot. These were used to determine if their future diameter growth could be predicted from the initial competition index. Sample trees were selected to cover a wide range of sizes and competition indices.

One of the aims of this study was to see if the competition index could be used to measure the effects of thinning on growth. Therefore, plot 1 of plantation G1 and plot 2 of plantation G3 were thinned immediately after all trees were measured, and after the before-thinning index values were computed (Table 4).

After-thinning index values were also computed; it was then decided to thin no more plots until the effectiveness of the index as a growth predictor could be determined.

Table 4.—Before-and after-thinning conditions and average competition index values (per acre basis)

Plot No.	Before thinning: Total trees	Before thinning: Basal area[3]	Before thinning: Average index	After thinning: Total trees	After thinning: Basal area[3]	After thinning: Average index	Sample tree basis
	Number	*Sq.ft.*		*Number*	*Sq.ft.*		*Number*
Plantation G1							
1	272	72	5.2950	184	48	3.4784	30
2 & 3[1]	316	76	5.8019	316	76	5.8019	60
Average[2]	300	76	5.6329	272	68	5.0274	90
Plantation G2							
Average[2]	512	68	4.4822	512	68	4.4822	90
Plantation G3							
2	404	84	4.1761	264	60	3.2846	30
1 & 3[1]	528	96	4.5071	528	86	4.5071	60
Average[2]	488	92	4.3968	440	84	4.0996	90
Plantation G4							
Average[2]	456	80	6.2049	456	80	6.2049	90
Plantation G5							
Average[2]	404	76	5.3413	404	76	5.3413	90
Plantation G6							
Average[2]	264	60	8.0498	264	60	8.0498	90
Plantation G7							
Average[2]	540	108	7.3053	540	108	7.3053	90

[1]Unthinned plots are combined and averaged.
[2]Combined averages for 3 plots in each plantation.
[3]To nearest square foot.

Results of Field Test

Approach 1

In this approach the radius of a tree's influence was set equal to Zh, where h was the tree's total height and Z is a constant. The problem was to find the value of Z. Many different values were tried, ranging from 0.1 to 3.7 in 0.1 intervals. The resulting index values were used with the sample-tree growth for two and three years in a multiple regression analysis which dropped the least significant variable after each run of the data. The initial equation was of the form presented earlier (equation 3).

In every case diameter was the only significant variable. However, if diameter was not included, the terms I and I/n became significant. Coefficients of determination (R^2) were used to determine which equation was best for predicting growth. Some equations were able to account for 60 percent of the variation in growth. However, different values for Z gave best results on different plantations. For example, Z of 1.9 gave best results on plantations G1, G2, and G3, while a Z of 1.5 worked best in plantation G4. In fact, each plantation had its own best value for Z, and there seemed to be no way to decide which value was best before trying them all. In order for this measure of competition to be useful it is first necessary to know the value for Z. Since the only way found for determining this value was empirical, the method of approach 1 was abandoned in favor of approach 2.

Approach 2

As stated earlier, in this approach the radius of a tree's influence circle was set equal to hc/m, where h and c are total height and crown radius as defined by equations 4 and 5, respectively. The term m was a constant for trees on a particular plantation, and was set equal to the average dead-limb length. Determining the radius in this way seemed preferable to the method of approach 1, since all three of the terms h, c, and m were obtained from actual tree measures, and a combination of tree-size parameters was used.

Again, the index values for 30 trees on each plot were computed and tested against 2-year growth, using equation 3 as the initial equation. Sample trees from all plots within a plantation were combined for this test. Three-year growth data were available for trees in plantations G1, G2, G3, so this was also used with equation 3.

Results of this approach are summarized in Tables 5 and 6. As in approach 1, the initial tree diameter was usually the best single variable for predicting future diameter growth. On most plantations the initial diameter accounted for over 50 percent of the variation in 2-year diameter growth, and even a larger percentage of the variation in the 3-year diameter growth.

A statistically significant improvement in 2-year growth predictability was obtained when the index value (I) was retained in the equation. However, this improvement was not great, especially for those plantations which showed a very high correlation between growth and initial diameter.

The number of competing trees (n) was statistically significant on only plantation G3, and even there it was the least significant of the variables tested, while the fourth term, I/n, was significant only for plantations G2, G3, and G7. It was not surprising that I/n was not often significant when the simple correlations among the variables were studied. Coefficients for the correlation between diameter and I/n were all greater than .78. It was apparent from this strong relationship that diameter and I/n should probably not be combined in the same regression. It was decided to remove the term d from equation 3 and try again.

Other modifications were also considered. It seems possible that the effect of I/n on growth might be curvilinear. That is, in very open stands the effect of the competition will be very slight. In such

Table 5.—Coefficients for predicting 2-year diameter growth and the corresponding coefficients of determination (R^2)

	Independent Variables						
Constant	Initial dbh	Competition index	Competing trees	I/n	ln(I/n)	R^2	Basic equation number
	d	*I*	*n*				
			Plantation G1 (after thinning)				
0.2066	0.0691**	-0.0569**				0.5618	3
-.1153					-0.3802**	.4349	6
-.1388	.0777**					.4359	3
			Plantation G2				
.1227	.1278**	-.1041**		0.6899**		.5724	3
.6962	.0669**	-.1088**				.4955	3
1.1303		-.1311**				.3489	3
.1035	.0879**					.2709	3
			Plantation G3 (after thinning)				
-.1298	.0982**	-.0714**	0.0108*	.3851*		.6237	3
-.0214	.1020**	-.0309				.5992	3
-.1734	.1067**					.5819	3
			Plantation G4				
.1897	.1584**	.0693**				.6790	3
-.1111					-.6893**	.6332	6
-.2741	.1645**					.6010	3
			Plantation G5				
.1336	.1296**	-.0662**				6410	3
-.1273					-.5466**	.6443	6
-.3092	.1448**					.5979	3
			Plantation G6				
.3080	.1284**	-.0468**				.6113	3
-.0414					-.5964**	.6165	6
-.1317	.1392**					.5385	3
			Plantation G7				
.6238	.0709*	-.0447**		-.7448*		.5882	3
.2535	.1199**	-.0627**				.5696	3
-.2223					-.5455**	.5767	6
-.1521	.1109**					.4716	3

**Significant at .01 probability level.
*Significant at .05 probability level.

stands trees grow independently from other trees. In such open stands the factor I/n will be small even though I and n are rather large. Growth will vary according to the vigor, site, and genetic make-up of the tree. As competition increases, the I/n factor should also increase. Growth should slow in response to the increase in competition and approach zero. It is unlikely that all trees will stop growing at the

Table 6.—Coefficients for predicting 3-year diameter growth and the corresponding coefficients of determination (R^2)

	Independent Variables						
Constant	Initial dbh	Competition index	Competing trees	I/n	ln(I/n)	R^2	Basic equation number
	d	*I*	*n*				
			Plantation G1 (after thinning)				
0.23401	0.13106**	-0.09309**				0.6192	3
-.25801					-0.68599**	.4760	6
-.33144	.14530**					.5069	3
			Plantation G2				
.27232	.17245**	-.14495**		0.78646**		.5438	3
.92609	.10297**	-.15035**				.4961	3
1.59442		-.18467**				.3303	3
.10866	.13170**					.2866	3
			Plantation G3 (after thinning)				
-.18696	.14667**	-.12333**	.02148**	.62075**		.7148	3
-.07586	.16792**	-.04722*				.6807	3
-.30665	.17461**					.6633	3

**Significant at .01 probability level.
*Significant at .05 probability level.

same degree of competition since their vigor depends on a number of factors other than competition. Some trees will die quickly while others might live quite a long time under very severe competition. In other words, the effect of increasing competition on open-grown trees should be quite great, while this effect on trees already experiencing extreme competition might be very slight. The equation finally selected for trial was:

$$G_a = b_0 + b_1 I + b_2 n + b_3 \ln I/n \qquad (6)$$

where: G_a is the diameter growth over a period of $\underline{a}$ years,
I is the competition index,
n is the number of competing trees,
ln I/n is the natural log of I/n, and the
b_i's are the partial regression coefficients.

Diameter was not used because of its strong correlation with I/n. The term n was included because it was thought that I/n would then be more meaningful. That is, even if I/n is rather large, the effect on growth might not be great unless n is also quite large. The term I was included for about the same reasons as the term n. Even though I is very large the competition might not be great unless I/n is also rather large. Correlations between these three terms were poor.

The term ln I/n proved to be the best single variable for predicting 2-year diameter growth on four of the seven plantations (G4, G5, G6, and G7) and was nearly as good as initial diameter on plantation G1. On plantation G3 the initial diameter was a much better variable than ln I/n, while neither variable was very good on plantation G2.

Plantations G2 and G3 were both quite open with very low values for I and n. Since competition, as it was measured here, was slight, it could hardly be expected to show a significant effect on growth. Mean values of I, n, d, and G for the 90 samples trees from each plantation are presented in Table 7, while the results of the tests of equation 6 are shown in Tables 5 and 6.

Table 7.—Plantation mean values for the competition index (I), number of competing trees (n), initial dbh (d), and 2-and 3-year diameter growth (basis 90 trees)

Plantation	Before thinning			After thinning		Diameter growth	
	d	I	n	I	n	2 years	3 years
	Inch		*Number*		*Number*	*Inch*	*Inch*
G1	6.85	5.633	22.5	5.027	20.1	.39	.66
Plot 1[1]	6.79	5.295	20.8	3.478	13.6	.49	.85
Plot 2&3[2]	6.87	5.802	23.4			.34	.57
G2	5.00	4.482	16.2			.54	.77
G3	5.46	4.397	16.8	4.100	15.2	.41	.64
Plot 2[1]	5.81	4.176	16.7	3.285	12.0	.49	.79
Plot 1&3[2]	5.28	4.507	16.8			.37	.59
G4	5.56	6.205	20.7			.64	
G5	5.86	5.341	20.2			.54	
G6	5.85	8.050	28.5			.68	
G7	5.87	7.305	29.2			.50	

[1]Thinned plot basis 30 trees.

[2]Unthinned plots of thinned plantation basis 60 trees.

These results suggest that if mean index values are high ($I > 5$), and especially if the number of competing trees is high, then the best predictor for diameter growth is simply the natural log of I/n, although the equations using both variables I and d are also good. At any rate, it appears that the index value, I, does measure some of the effect of competition on diameter growth of individual trees. It also seems that the method used in approach 2 for determining the radius of the influence circle is reasonable, or at least it gives an approximate measure of the competition around individual trees.

Growth measurements have been continued for three years on three of the plantations (G1, G2, and G3), so equations 3 and 6 were also tested using this data. Results of this test are presented in Table 6. There was a general improvement in R^2 values when the growth for three years was used. This was not unexpected since individual year-to-year variation should be reduced. Other than this improvement, the results are much the same as for the 2-year growth equations for these plantations. Initial diameter is the best single predictor, and a slight but significant improvement in R^2 is made by adding the index value. Plantation G3 had the lowest average index value and average number of competing trees, and on this plantation significant improvement was obtained by also including the terms n and I/n.

Plantation G2 warrants some special discussion. First, there is a wide variability in number of trees and total basal area among the three plots. Plot 1 is very dense, while the other two are as open as the thinned plots on plantations G1 and G3. The average diameter is also quite different among the three plots. The most unique thing about this plantation is that neither d nor ln I/n was as good as I for predicting growth. In fact, no single variable was really good for predicting growth for this plantation. However, when d and I are both considered, it is possible to account for 15 percent more of the variation in 2-year diameter growth than is possible with I alone, and if I/n is also included an additional 8 percent of this variation can be accounted for.

As a further check the dense plot (plot 1) was analyzed separately from the other two. The trees on this plot were rather small, and so the average index for the 30 sample trees was only 5.588. Diameter was the best single variable on this plot for predicting growth, although the variables I and n were nearly as good for predicting 3-year growth.

It is not clear why the I variable was not significant when used with d to predict growth on this plot. One reason might be that most of these trees are rather small and, as a result, have small influence circles. The maximum circle radius for a sample tree on this plot was 15.6 feet. This tree's circle overlapped the circles of 39 competing trees, but the average competing tree contributed only 0.147 to the index value of 5.736. This sample tree was much larger than the average plot tree and was considerably larger than any of the other sample trees. With so many of the trees being small, it is quite possible that competition between trees had not yet become as important a factor as one might expect.

Another reason that the combination of d and I was not a good predictor of growth might be the condition of the site. The trees on this plot were growing very slowly. The area was heavily grazed by cattle and the soil was very compact. Some of the larger trees were growing quite well, but most of the small trees were hardly growing at all, regardless of their competition index. Of the 30 sample trees in the plot, eight have grown less than 0.1 inch in three years. On the entire plot 60 percent of the trees were less than 4.6 inches at dbh and averaged less than .4 inch in diameter growth in three years. With so many small trees all growing so slowly, it is not surprising that there was no competition apparent. These small trees made so little growth that there was little room for variation, and most of the variation measured was accounted for by diameter alone. In other words, this plot was nearly stagnated, and many of the trees were barely alive. A few large trees were growing well and had been doing so for some time. That is, they had dominated the other trees for several years, and so it was difficult to distinguish the difference between lack of competition and large size. Very few of the dominant trees were in direct competition with each other.

The other two plots in this plantation presented quite a different appearance. They both suffered considerable mortality due to fire and storm. The average index for the 60 sample trees on these plots was only 3.929. However, there was much more variability in diameter and in competition. The correlation between diameter and growth was very poor. Some of the smaller trees were growing well, and it is apparently in such stands that competition was having its most apparent effect.

The best equation for predicting either 2- or 3-year growth on these two plots used both I and n, although I and d were nearly as good. In either case, the variables were highly significant, although at best only 41 percent of the growth variability was accounted for. In such open stands many trees were growing nearly free of competition, and any measure of competition certainly can not account for a large part of the growth variation.

As already noted, when these three plots were combined the factors d, I, and I/n all had a highly significant effect on growth, with I being the strongest single variable. These plots represent extremes at both ends of a density scale (i.e., from very open to very dense), and the fact that the index is a useful tool here would indicate that it should also be useful in more average stands.

One of the objectives of this study was to find some measure of stand density or degree of competition that could be objectively applied to individual trees within a stand. To a degree it appears to me that the competition index I is such a measure. It has been tested with two species at three different ages and on a number of sites and, in most cases, the present index, combined with present diameter, accounted for at least 56 percent of the variation in future growth. In the one case, where only 50 percent of this variation was accounted for, the addition of the index value to the equation of growth over diameter improved the coefficient of determination by some 21 percent.

This index, of course, is still rather crude and certainly does not measure all the factors of competition precisely. In this study, at least, total height and crown radius were estimated by diameter, so that in a given plantation, trees of the same diameter were said to have the same circle radius. Exact measures of every tree, including all competing trees, might result in slightly improved estimates of growth. Exact knowledge of the root systems would also improve the reliability of growth estimates. However, the method described here does offer a method for expressing density and competition for an individual tree.

As noted, the effect of competition in this study does not appear to be very great. However the competition, as measured, was not great either. One would expect competition to be neither as great nor as variable in planted stands as in natural stands where spacing is much less regular. I feel that this measure of competition would prove much more effective in natural stands in which trees tend to be in clumps rather than in regular rows. Certainly the method should be tested in such stands. It is expected that as the value of I increases, the effects of competition will be more apparent.

The Index as a Measure of Thinning

A second objective of this study was to develop a measure of competition that can also be used as an objective measure of thinning intensity. That is, if the competition an individual tree is experiencing could be objectively measured, then the degree of thinning could be measured by determining the reduction in this competition following the thinning. It was with this idea in mind that two plots (plot 1 on plantation G1 and plot 2 on plantation G3) were thinned immediately after they were established. The plot conditions before and after thinning are presented in Tables 4 and 7. It was decided to thin no more plots until the method for measuring competition had been tested.

Since only two plots were thinned, the second objective has not been met. However, it is possible to note changes in index values for the thinned plots. Neither plantation was especially dense, even before thinning. The average index value for the 30 sample trees of plantation G1, plot 1, was reduced from 5.295 to 3.478, while the average number of competing trees was reduced from 21 to 14 as a result of thinning (Table 7). The average index value for the sample trees of plantation G3, plot 2, was reduced from 4.176 to 3.285, while the number of competing trees was reduced from 17 to 12. Competition does not seem to be an important factor affecting diameter growth unless index values are greater than 5.0, so it seems likely that thinning did little more than release trees that needed no release.

In order to note any change in growth pattern after release, it is necessary to know something about the growth pattern of similar unreleased trees growing on similar sites, or at least the growth pattern of those same trees over a previous time period. The two thinned plots were cut at the beginning of the study, so it is not possible to compare their released growth pattern against the previous growth pattern. The thinned plots had been quite similar to the unthinned plots in their respective plantations prior to thinning, so comparisons were made between the growth equation of the single thinned plot and the average growth equation of the two unthinned plots in each of plantations G1 and G3 (Table 8).

Plantation G1

In this plantation the average index value for the 60 sample trees on the unthinned plots (plots 2 and 3) was 5.802, while the average number of competing trees was 23 (Table 7). Thus, while competition was not great on these plots, it was greater than that on plot 1 even before plot 1 was thinned. Thinning reduced the average index on plot 1 considerably below the level where competition becomes a significant factor modifying 2-year growth. Hence, initial diameter showed a

Table 8.—Equations for predicting 2-and 3-year diameter growth on thinned and unthinned plots of plantations G1 and G3

Treatment	Constant	d	I_B[2]	I_A[1]	n_A	I_B-I_A	n_B-n_A	R^2
				Plantation G1				
				2-year growth				
Thinned	0.5366			-0.0686		-0.1195*	0.0580**	0.5151
Thinned	.5868		-.0925*				.0582**	.4972
Thinned	-.0426	0.0797**						.4323
Not thinned	.1088	.0702**		-.0432*				.5690
Not thinned	-.1952	.0780**						.5254
				3-year growth				
Thinned	1.0065			-.1362*		-.2511**	.1078**	.6132
Thinned	1.1197		-.1902**				.1029**	.5844
Thinned	-.2278	.1591**						.5446
Not thinned	-.0680	.1300**		-.0457				.6252
Not thinned	-.3885	.1380**						.6072
				Plantation G3				
				2-year growth				
Thinned	.0649	.0989**		-.0464				.5438
Thinned	.3866			-.0980*	0.035**			.5475
Thinned	-.1094	.1026**						.5188
Not thinned	.1729			-.0432*	.0232**			.6033
Not thinned	-.1251	.1040**		-.0120				.6123
Not thinned	-.1869	.1054**						.6100
				3-year growth				
Thinned	.2072	.1491**		-.0934				.6470
Thinned	-.1434	.1567**						.5971
Not thinned	.2182			-.0630*	.0389**			.6941
Not thinned	-.2647	.1721**		-.0118				.6886
Not thinned	-.3252	.1735**						.6877

**Significant at .01 probability level.
*Significant at .05 probability level.
[1]Subscript A means after thinning.
[2]Subscript B means before thinning.

stronger relationship to growth than any other single variable. However, the before-thinning index plus the change in the number of competing trees due to thinning gave a better equation for predicting growth. These variables were significant factors for predicting both 2- and 3-year growth if initial diameter was not used. On the unthinned plots the combination of the variables d and I gave the best equation for predicting 2-year growth.

All three plots of plantation G1 were burned by wildfire near the end of the second year of the 2-year growth period. Mortality was quite extensive as a result of these fires, and competition was further reduced (Table 2). This was especially true on plot 2, which lost the equivalent of 84 trees per acre or 5 ft² in basal area. Plot 3 lost the equivalent of 32 trees per acre or 7 ft² in basal area. The thinned plot lost very few trees (16 per acre or 1 ft^2 basal area) as a result of these fires.

As a result of these fires competition on plots 2 and 3 was reduced considerably, while it was hardly affected on plot 1. This is reflected in the 3-year growth equations (Table 8). The initial index value was no longer a factor in the diameter growth of the unthinned plots. On the other hand the after-thinning index, the change in the index due to thinning, and the reduction in number of competing trees all were statistically significant in the 3-year diameter growth equation for the thinned plot.

From these results it would appear that the fire reduced competition to a level where it was no longer a significant factor. On the other hand, as trees on the thinned plot continued to grow the competition level increased. It is important to realize that competition is dynamic, increasing or decreasing as trees grow or die. In order to illustrate this change the index values were recalculated, based on the diameter of the surviving trees at the end of the second growing season. The average index for all three plots increased from 5.027 (after thinning) to 5.438. Nearly all of this increase was on the thinned plot, which changed from 3.478 to 4.013 while the index on the unthinned plots only changed from 5.802 to 6.002.

When all three plots are combined, the index value is a highly significant factor of both 2-year and 3-year diameter growth. For this analysis the values after thinning were used. A wide range of sample tree values was available when the three plots were combined. Index values ranged from 1.39 to 9.05, diameter ranged from 2.6 to 12.7 inches, and competing trees ranged from 7 to 61 per sample tree. Growth per sample tree also covered a wide range. The 3-year growth, for example, ranged from 0.01 to 1.79 inches; yet some 62 percent of this variation could be explained as variations in initial diameter and in competition.

Plantation G3

This plantation did not appear to be as open as plantation G1. The average basal area (92 ft^2 per acre) was rather high. However, the trees were well spaced and there were openings, due to hurricanes, scattered throughout. As a result, the average index for the sample trees on these plots was only 4.397 (ranged from 1.22 to 7.88) even before plot 2 was thinned. The average competition for these trees was lower, even before thinning, than the average competition for any other plantation. The variance for the index was also low on this plantation.

Thinning reduced the average index of the thinned plot from 4.176 to 3.285, and the overall average for the plantation to 4.100. The two unthinned plots had an index average of 4.507. Competition does not appear to be a great factor in the growth on this plantation, and was certainly not a significant variable in the 2-year growth equation, unless it was included with diameter, number of competing trees, and the average index per competing tree (I/n). The best single variable for predicting 2-year growth was the initial diameter, which alone accounted for some 58 percent of the growth variation. When the variables I, n, and I/n were also included, only 62 percent was accounted for (Table 5).

Competition was not a significant factor affecting either 2-year or 3-year diameter growth on the thinned plot. Neither was it significant on the unthinned plot when included with diameter. On these plots the number of competing trees combined with the index gave a good estimate of both 2- and 3-year growth. However, diameter alone was just as good. It appears from these results that there was little gain in individual tree diameter growth on this plantation as a result of thinning.

The best 3-year growth equation, when thinned and unthinned plots were combined, was the one that considered the four variables, d, I, n, and I/n, just as for the 2-year growth equation. However, the I variable was significant when combined with d alone. Competition is apparently becoming a factor in this plantation. Average competition index values increased on both the thinned and unthinned plots, so that by the end of the second year of the growth period the overall average index increased from 4.100 to 5.018.

Discussion

The purpose of this study was to measure intraspecific competition and to study the effects of this competition on the diameter growth of a tree. Such diameter growth can be affected by a large number of factors other than competition. An attempt was made to control as many of these other factors as possible. Variations in diameter growth due to species, climate, and soil variation were controlled to some extent by limiting the number of species studied to two, by locating the entire study within a relatively small area (130 sq. miles), and by comparing only those differences among trees within a single plantation.

Some factors could not be controlled. For example, the genetic composition of these trees was not known. Variations due to micro-site differences within a single plot were not controlled, except as these differences had affected past growth (i.e., variations in initial diameter are probably the result of differences in genetic composition, micro-site, and past competition).

It is generally believed that much of the variation in diameter growth among trees within an even-aged stand is the result of competition. But competition comes from many sources. Other trees of the same or different species, brush, vines, grass and all other vegetation are possible sources of competition. The purpose of this study was to study and measure only the single source, intraspecific competition. Plantations were selected rather than natural stands in order to eliminate variation due to differences in age, but also to eliminate other species of trees as sources of competition. All vegetation had been removed from these plantation areas prior to planting. Frequent fires (both wild and prescribed) had kept hardwood sprouts and brush to a minimum. Grass and brush are known to be significant sources of competition to trees, especially young trees (Curtis, 1964; Larson and Schubert, 1969). On the plantations in this study, however, there is not a great deal of difference in the grass cover between plots within the same plantation. It is believed that little of the variation in current tree diameter growth results from variation in grass or brush cover.

The method used for measuring intraspecific competition involves assigning a circular area to each tree and then determining how much of this area is occupied by the areas of other trees. In theory, the more a tree's area is occupied by the areas of other trees, the less will be the diameter growth it makes. Variation in diameter growth that can not be explained in this way is, in theory, due to the variations in some of the other known factors affecting diameter growth, or else it is due to random error.

The index described above is not a precise measure of intraspecific competition. It is doubtful if every tree influences an area that is exactly circular, and it is very doubtful if the radius of such an area is exactly proportional to hc/m. However, this index does seem to give a good approximation of competition in that it is a significant variable in equations for predicting individual tree growth.

The influence circle is meant to be an expression of total space available to a tree, including its crown and its roots. It is relatively easy to determine the area occupied by a tree's crown but very difficult to determine the area of its roots. It seems likely that the roots extend some distance beyond the extent of the limbs, so that the influence circle should have a radius greater than the average radius of the tree's crown. If this is so, then it is likely that trees not adjacent to the sample tree can still be competing with the sample tree.

An early study of the effect of competition on growth of individual southern pine trees was carried out by MacKinney (1933). He noted the number and size of competing trees in 10-foot zones out to 30 feet from his sample trees and discovered that competing trees in the outer zones had more effect on basal-area growth of sample trees than those adjacent (within 10 feet) to the sample trees.

More recent studies have given new insight into the horizontal distance tree roots extend. Kaufman (1968) has reported that slash pine can, under certain conditions, extend their roots as much as 56 inches per year during the first 3 years after planting. Pritchett and Robertson (1960) noted that 5-year-old slash pine absorbed nutrients from as far away as 32 feet from the base of the trunk. Hough *et al.* (1965) introduced I-131 into the soil and detected radioactivity in trees as far as 55.1 feet from the point of the treatment. This distance was related to the age of the tree. It is clear from these and other studies (see also Curtis, 1964; Ferrill and Woods, 1966) that roots are likely to extend some distance beyond the maximum extent of the crown.

The maximum sample-tree radius in the present study was 46 feet. However, most trees had a much smaller radius than this. Judging from the results of studies concerning root extension, this maximum radius might not be too great since this was for a tree whose diameter was over 12 inches. Nevertheless, the method for determining this radius is only an approximation that requires the assumption that the total influence circle is directly related to certain measures of the above-ground portion of the tree. The only proof available that this is true is the fact that diameter growth was significantly affected by competition as measured according to these assumptions.

Only a small portion of the variability in growth was accounted for by the index if initial diameter was also included. This could be either because competition was not measured correctly or because there was little competition to measure. Young planted stands generally exhibit less evidence of competition than do natural stands. In plantations the minimum space between trees is set by planting distance and, since there is generally some mortality each year, by age 15 the average spacing is much greater than this minimum. Also, there is often less variation in diameter within planted stands. It therefore seems likely that in many of the plantations of this study there was little competition to measure. Actually, in those plantations where the average index for the sample trees was 5.3 or greater, the best variable for predicting growth was the natural log of I/n. This would seem to indicate that if competition is a strong factor, then the combination of I and n is a reasonably good measure of this competition and is a useful measure for predicting growth regardless of the tree's initial diameter.

One advantage of this method is that it can be used to express density and also changes in density due to mortality or thinning. Various tree parameters, such as diameter or crown radius, can be used to predict growth. However, these parameters show no immediate change if thinning is done. The index and the number of competing trees both change according to the degree of thinning and therefore may be used as measures of density and thinning intensity. An added advantage to this index method is that a measure of the variation in the competition index can be computed so that statistical comparisons can be made between the mean indices of several stands. Preliminary tests have indicated that the distribution of competition indices in a stand does not differ significantly from a normal distribution; therefore, standard statistical tests may be used for such comparisons (Keister, 1966).

This competition-index method considers the actual spacing of the trees rather than assuming an even or regular spacing. It also requires consideration of the relative sizes of the various individual trees. Finally, the method makes possible the use of individual trees rather than plots for thinning and growth studies.

The most serious disadvantage of this competition index is the large number of field measurements necessary for its computation. The heights, crown lengths, crown radii, and diameters of a number of trees must be measured so that curves of total height and crown radius can be computed, and so that the average dead-limb length can be determined. In addition, the diameters of all possible competing trees surrounding a particular sample tree must be measured and the horizontal distance between trees must be determined.

In general, however, the advantages of being able to use individual trees rather than plots in thinning and growth studies should offset the disadvantage of the rather cumbersome field work. I believe that the competition index described here shows promise as a useful tool in thinning research and growth studies, and may also find use in stand simulation for management purposes.

Summary

A method is presented for measuring the intraspecific competition experienced by an individual tree in a planted stand. It is theorized that each tree in the stand interacts within a circular area surrounding the tree, that the size of this area is proportional to the size of the tree, and that intraspecific competition occurs in proportion to the area within the zone where two or more of these circles overlap.

A competition index for a particular tree is expressed as the ratio of the sum of the areas of overlap within the particular tree's influence circle to the total area of the tree's influence circle. That is, if area of overlap between the k th tree and the i th tree is C_{ik} then the competition experienced by the k th tree from the i th tree is defined as:

$$I_{ik} = C_{ik}/\pi K_k^2$$

where K is the radius of the k th tree's circle. The total competition index for the k th tree is defined as:

$$\sum_{i=1}^{n} I_{ik} = (1/\pi K_k^2) \sum_{i=1}^{n} C_{ik}$$

Two approaches were tried for determining the radius of a tree's influence circle. In the first approach this radius was set equal to Zh, where h is the total height of the tree and Z is a factor that should be constant for a given species, site, and age. This approach was tested in the field and finally discarded since Z could only be determined empirically for a given stand and no method was found for predicting the proper value of Z from existing stand conditions.

The second approach was to set the radius equal to a combination of three measurable tree and stand parameters. The radius was set equal to hc/m, where h and c are total height and crown radius, respectively, and m is the dead-limb length. The height and crown radius are both related to diameter, while in the plantations used in this study the dead-limb length is quite constant and is thought to be an expression of age, site, and total stand density.

This method for measuring competition was tested in four 15-year-old

and one 14-year-old slash-pine plantation, one 11-year-old loblolly-pine plantation, and one 14-year-old mixed slash- and loblolly-pine plantation. These plantations were growing on several different sites in Livingston Parish, in southeastern Louisiana, and included a wide range of conditions.

The first objective was to see if the index could be used to predict diameter growth since diameter growth is thought to be modified by competition. Three ¼-acre plots were located in each plantation, and 30 trees were selected as sample trees on each plot. The diameter, height, crown radius, and dead-limb length of every tree on each plot were measured. The position in relation to the plot center was determined for every tree, and stand maps were prepared.

The index values for each sample tree were computed at the start of the study, and diameter growth was measured for two years in all plantations and for three years in three of the 15-year-old slash-pine plantations.

The initial tree diameter was the best single variable for predicting diameter growth in most plantations, and about 50 percent of the variation in growth could be accounted for by this variable alone. The addition of the index value to diameter accounted for a slight but statistically significant improvement in the growth equations for all but one of the seven plantations studied.

In plantations that had average index values higher than 5.1 or that had a wide range of indices, the best variable for predicting growth was the natural log of I/n, where I is the competition index value for a particular sample tree and n is the number of competing trees (i.e., trees whose circles of influence overlap the circle of the sample tree). This single variable was as good as or even better than the equation that used initial diameter and the index. Plantations that were more open (i.e., average indices <5.1) did not show this relationship, probably because most sample trees on such plots had indices that were rather low. The best equation, then, for predicting growth in open plantations was:

$$G = b_0 + b_1 d + b_2 I$$

while if the plantation was more dense the best equation was:

$$G = b_0 + b_1 \ln(I/n)$$

where G is the diameter growth over a 2- or 3-year period,
d is the dbh at the start of the growth period,
I is the competition index at the start of the growth period,
n is the number of competing trees, and the
b_i's are the partial regression coefficients.

These results indicated that this measure of competition was valid.

A second objective of this study was to see if the index could be used as an objective measure of thinning intensity. One plot from each of two of the oldest slash-pine plantations was thinned before the start of the initial growing season. No other thinning has been done at this time, so this objective has not really been met. The thinned plantations were not very dense, even before thinning, so the reduction in competition apparently had no great effect on the growth of the sample trees. One plot had an average index of 5.295 before thinning while the other had an average index of only 4.176. The after-thinning average index on these plots was, respectively 3.478 and 3.285. Competition was not a significant factor on either plot during the first two growing seasons. The 3-year growth on the plot originally having an I of 5.295 was significantly affected by competition. Over 60 percent of the variation in 3-year growth on this plot was accounted for by the equation:

$$G = 1.0065 - .1363\ I_A - .2511\ I_D + .1078\ n_D$$

where I_A is the after-thinning index, I_D is the difference in the before- and after-thinning indices, and n_D is the change in the number of competing trees due to thinning. In the other plot competition has not been a strong factor.

These results were not conclusive but do indicate that the index might be used to measure the release from competition obtained by thinning. This study is being continued.

Literature Cited

Applequist, M. B. 1960. Effects of cleared-and-burned hardwood slash on growth of planted loblolly pine in Livingston Parish, Louisiana. Jour. Forestry 58:899-900.

Bella, I. E. 1969. Competitive influence-zone overlap: a competition model for individual trees. Canada Dept. Forestry, Bi-Monthly Res. Notes 25:24-25.

Brown, G. S. 1965. Point density in stems per acre. New Zealand Forest Res. Note 38. 11 p.

Curtin, R. A. 1964. Stand density and the relationship of crown width to diameter and height in *Eucalyptus obliqua*. Australian Forestry 28:91-105.

Curtis, James D. 1964. Roots of a ponderosa pine. U. S. Forest Serv., Intermount. Forest and Range Exp. Sta. Res. Paper INT-9. 10 p.

Czarnowski, M. 1961. Dynamics of even-aged forest stands. La. State Univ. Press, Baton Rouge. 123 p.

Dawkins, H. C. 1960. The Pudden clinal plot; thinning experiments without surrounds. Empire Forestry Rev. 39:168-171.

Ferrill, Mitchell D., and Frank W. Woods. 1966. Root extension in a longleaf pine plantation. Ecology 47:97-102.

Gerrard, D. J. 1969. Competition quotient: a new measure of the competition affecting individual trees. Mich. State Univ. Agric. Exp. Sta. Res. Bull. 20. 32 p.

Hough, Walter A., Frank W. Woods, and M. L. McCormack. 1965. Root extension of individual trees in surface soils of a natural longleaf pine-turkey oak stand. Forest Sci. 14:265-274.

Jack, W. H. 1967. Single tree sampling in even-aged plantations for survey and experimentation. Proc. 14th Congr. Int. Union For. Res. Organ. Pt. 8, Sec. 25:379-403.

Johnston, D. R., and W. T. Waters. 1961. Thinning control. Forestry 34:65-74.

Kaufman, C. M. 1968. Growth of horizontal roots, height, and diameter of planted slash pine. Forest Sci. 14:265-274.

Keister, Thomas D. 1966. Thinning methods in slash pine plantations. Ph.D. Thesis, La. State Univ., Baton Rouge.

Krajicek, J. E., and K. Brinkman. 1957. Crown development: an index of stand density. U. S. Forest Serv., Cent. States Forest Exp. Sta. Res. Note 108. 2 p.

van Laar, A. 1963. The influence of stand density on crown dimensions of *Pinus radiata* D. Don. Forestry in South Africa 3:133-142.

Larson, M. M., and G. H. Schubert. 1969. Root competition between ponderosa pine seedlings and grass. U. S. Forest Serv., Rocky Mountain Forest and Range Exp. Sta. Res. Paper RM-54. 12 p.

MacKinney, A. L. 1933. Increase in growth of loblolly pine left after partial cutting. Jour. Agr. Res. 47:807-821.

Newnham, R. M. 1966. Stand structure and diameter growth of individual trees in a young red pine stand. Canada Dept. Forestry, B-Monthly Res. Notes 22:4-5.

Opie, Jack E. 1968. Predictability of individual tree growth using various definitions of competing basal area. Forest Sci. 14:314-323.

Osborne, J. G. 1939. A design for experiments in thinning forest stands. Jour. Forestry 37:296-304.

Pritchett, W. L., and W. K. Robertson. 1960. Problems relating to research in forest fertilization with southern pines. Soil Sci. Soc. Amer. Proc. 24:510-512.

Smith, J. Harry G. 1959. Comprehensive and economical designs for studies of spacing and thinning. Forest Sci. 5:237-245.

——— and Gordon R. Bailey. 1964. Influence of stocking and stand density on crown widths of Douglas-fir and lodgepole pine. Commonwealth Forestry Rev. 43:243-245.

Staebler, G. R. 1951. Growth and spacing in an even-aged stand of Douglas fir. Unpubl. M. F. thesis, Univ. Mich., Ann Arbor.

Stiell, W. M. 1966. Red pine crown development in relation to spacing. Canada Dept. Forestry Publ. 1145. 44 p.

Toma, G. T. 1940. Kronenuntersuchungen in langfristigen Kiefer durchforstungsflachen. Zeitschrift fur. Forst und Jagdwesen 1940:305-340, 379-404.

Vezina, P. E. 1962. Crown width-d.b.h. relationship for open-grown balsam fir and white spruce in Quebec. Forestry Chronicle 38:463-473.

Wicht, C. L. 1936. Thinning research techniques. U. S. Dept. Agr., Forest Serv. Trans. 224. 61 p.

———. 1948. Replicated thinning experiments—with comments by F. C. Hummel and D. J. Finney. Forestry 22:113-117.

Worthington, Norman P., Donald L. Reukema, and George R. Staebler. 1962. Some effects of thinning on increment in Douglas-fir in western Washington. Jour. Forestry 60:115-119.

Zinke, Paul J. 1962. The pattern of influence of individual forest trees on soil properties. Ecology 43:130-133.