A REVIEW OF THE PRESENT METHODS OF MEASURING STAND DENSITY AND A PRESENTATION OF NEW RESEARCH ON THE APPLICATION OF CROWN COMPETITION FACTOR TO DOUGLAS-FIR

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A REVIEW OF THE PRESENT METHODS OF MEASURING STAND DENSITY AND A PRESENTATION OF NEW RESEARCH ON THE APPLICATION OF CROWN COMPETITION FACTOR TO DOUGLAS-FIR

INTRODUCTION

As intensive management of forest land within the Douglas-fir subregion increases, the need for a functional measure of density is becoming more adamant. According to Spurr (13:275), the "ideal" measure of density should be simple, objective, measure the degree of utilization of an area by trees, and be unrelated to age and site. The reason that a density measure should be independent of age and site is explained by Curtis (5:4)

> Density may be regarded as a causal factor, subject to manipulation in the managed forest. If interpretation is in terms of the effect of density on growth or if interest is in the relation of growth to age or site, then it is highly desirable that the density term be independent of age and site and hence, clearly distinguishable from them.

At the present time there is no "ideal" measure of density. Basal area, which is dependent upon age and site, is presently used as the standard measure.

In 1961 Krajicek, Brinkman, and Gingrich of the Central Forest Experiment Station, published an article entitled "Crown Competition--A Measure of Density," which describes a new measure of density called crown competition factor, or CCF (9:35). According to the authors, preliminary research indicated that CCF might meet the criteria for the "ideal" measure of density. It is the purpose of this paper to explore the possible application of this relatively new method to second-growth Douglas-fir stands.

CURRENTLY USED MEASURES OF DENSITY

Definition

In the past, there has been some confusion over the exact definition of the term stand density. Krajicek et al. (9:35) explains it thus.

> Density, as foresters commonly use the term, is the relation between the number of trees or some volumetric or areal unit to a specific area, usually one acre. In effect, then, a a density measure is intended to help determine the relation of the average tree in the stand to the maximum growing space it could utilize on one hand, and the minimum growing space necessary to live on the other. It is within this range that the forester wishes to maintain density to fully utilize the site for maximum production of desired usable volume.

The term density is often confused with the term stocking which is a relative term used to describe the degree of adequacy of a given stand condition to meet the management objective. Thus, a stand with a density of 70 square feet of basal area per acre may be classified as overstocked or understocked, depending upon what density is considered desirable (3:104).

There are three main measures of density that are currently being used: basal area, tree-area ratio, and stand density index.

Basal Area

Basal area, the most popular measure of stand density, is the cross-sectional area of a stand measured at breast height. Two advantages are that it is simply and objectively obtained, especially with the use of the wedge prism. Another advantage is that after an initial rapid rise in young stands it tapers off to a nearly constant level for mature stands for a given site. Because of these advantages it is commonly used as a standard against which other measures of density are compared (13: 276).

However, there are several inherit disadvantages in using basal area. Robert O. Curtis (5:4) points out.

> Although basal area has the advantages of clear and objective definition and determination, it is partially dependent on both site and age. Hence, in a regression equation predicting growth as a function of age, site index, and basal area, the coefficient of basal area is not necessarily interpretable as a measure of the effect of density on growth. "Significance" of basal area may mean simply that the expressions in age and site index are inadequate; basal area may also express effects of site and age.

Samuel F. Gingrich (8:41) points out another disadvantage in using basal area:

> A comparison of tree-area requirements with basal area reveals the basic weakness of basal area as a measure of stand density. Over a period of time trees increase in diameter, but if stands are continually cut to maintain a constant basal area, the stocking condition, density, or degree of competition, actually decreases. Doubling the diameter of a tree increases its basal area four times, but increases the tree-area requirements only about three times. Thus, as tree diameter increases the basal area of a stand must also increase if the percent stocking is to remain the same.

Tree-area Ratio

A measure of density called tree-area ratio was developed by Chrisman and Schumacher (8:39). It is a fairly simple and objective measure of density that is relatively independent of age and site. "The tree-area ratio is based on the premise that the growing space used by a tree depends on the size of the tree and is related to stem diameter by a second-degree parabola."

Therefore, since density is determined by the sum total of the growing spaces of the individual trees, the percent space utilized on a per-acre basis can be expressed by the formula:

$$\text{Tree-area ratio} = aN + b\Sigma D + c\Sigma D^2$$

where N = the number of trees per acre

ΣD = the sum of the individual diameters (13:283).

According to Spurr (13:285), there are several advantages and disadvantages to the tree-area ratio method. The main advantages are that it provides a measure of density readily usable for unevenaged and open-grown stands, and that it is relatively independent of site and age. However, there are three main objections to the measure. One, because the relationship must be determined empirically from plot data, the character of the plots used will affect the constants in the formula. It follows then that the measure is not necessarily valid when applied to samples varying widely in density or composition from the original data. Second, because diameter is an expression of growing space over the entire life of the tree, it is not necessarily an expression of present growing space. Third, from a theoretical standpoint, the relationship between growing space and D. B. H should be S-shaped and not a second-degree parabola.

Stand-Density Index

Stand-density index was developed by Reineke in 1933 (12:627). He found that when the log of the number of trees per acre of fully stocked stands were plotted over the log of the diameter of the average tree weighted by basal area of the same stands, a straight-line relationship generally resulted. He also found that the slope, termed the reference curve, could be used to define the limits of maximum stocking. This reference curve is expressed by the formula:

$$\log N = -1.605 \log D + K$$

where N = number of trees per acre,

D = the diameter of the tree of average basal area

K = constant varying with species (13:277).

"Stand-density index," as defined by Reineke, is the number of trees of 10-inch diameter as determined by the point where the reference curve intersects the point where D = 10. Its value is determined by the value of K. For instance, if K = 4.605, and D = 10, the reference equation becomes:

$$\log N = -1.605(1.000) + 4.605$$

or

$$\log N = 3.00$$

The number of trees of 10-inch diameter represented by the reference curve, then, is 1,000, this being the stand-density index for this particular curve.

The stand-density index of any stand may be determined from this reference curve. For instance, for a stand containing 120 trees per acre with an average diameter of 15 inches, K is determined by substituting in the equation:

$$\log 120 = -1.605 \log 15 + K$$

$$2.079 = -1.605 \times 1.176 + K$$

$$K = 3.066$$

The stand-density index is found by substituting 10 for D and the new value for K in the original equation. It is 230 (13:277). These two steps can be combined into the formula:

$$\log SDI = \log N + 1.605 \log D - 1.605$$

The advantages and disadvantages of SDI are much the same as those for tree-area ratio. Stand-density index varies slightly with age, and possibly with site, but not to the extent that basal area does.

However, it is much more complex than basal area and is not a finite value but an approximation of average stand relationships that may or may not apply to a given stand (13:281).

CROWN COMPETITION FACTOR: CONCEPT AND DEVELOPMENT

Crown competition factor was first introduced as a measure of density in 1961 (9:35). It is based on the same theory as tree-area ratio. That is, it is based on the premise that the growing space used by a tree depends on the size of the tree and is related to stem diameter. However, unlike tree-area ratio, CCF is based on the relationship of crown area to the DBH of open-grown trees, not trees competing in a stand.

In order to establish a relationship between crown width, CW, and DBH for open-grown trees, Krajicek et al. (9) measured 88 white oaks, 60 red and black oaks, 35 hickories and 157 Norway spruce. They found that the crown width and DBH for the hardwoods were highly correlated with a correlation coefficient of approximately 0.98. The crown width and DBH for Norway spruce were also highly correlated with $r = 0.983$.

> Since such a close relationship exists between the crown diameter and DBH of open-grown trees, and this relationship is nearly constant within a species, it may be inferred that the crown of a tree of given DBH cannot occupy more than a certain area even with unlimited growing space (9:37).

Using the least squares solution they derived a formula for predicting CW from DBH. From the regression analysis of their combined oak-hickory data:

$$CW = 1.829 DBH + 3.12$$

The percentage of an acre occupied by a vertical projection of the crown can be computed by dividing the square feet of crown area by 435.6. Since this is the maximum percentage theoretically possible for a tree of a specified DBH, it is called "maximum crown area," or MCA. The MCA value of a tree with a crown diameter of CW is:

$$MCA = \frac{\frac{\pi CW^2}{4}}{435.6}$$

or $$MCA = 0.0018 (CW)^2$$

Therefore since $CW = 1.829 DBH + 3.12$

$$MCA = 0.006 DBH^2 + 0.0205 DBH + 0.0175$$

"If a tree has DBH of 16 inches and a MCA of 1.22 then 82 open-grown trees of that size would cover an acre completely ($82 \times 1.22 = 100$ percent, or the sum of MCA values equals 100)" (9:38).

Maximum crown area, which is the expression used to express the area used by a "single open-grown tree," is not to be confused with "crown competition factor" or CCF.

"CCF is defined as the sum of the MCA values for all trees in the stand, divided by the area in acres. It is used as an expression of stand density" (9:39). The CCF formula for oak-hickory stands is:

$$CCF = 1/A\ 0.0060(DBH_i^2 N_i) + 0.0205(DBH_i N_i) + 0.0175(N_i)$$

where DBH_i = individual DBH or DBH class

N_i = number of trees in DBH class

A = area in acres.

In the previously mentioned example the sum of the MCA values, or the CCF, for 82 trees 16 inches in diameter is 100. The CCF value of 164 trees 16 inches in diameter would then be 200. This would mean that each tree in the latter stand would occupy one-half of the available growing space as those trees in the former stand. This shows that CCF is not a measure of crown closure, as both stands would have a completely closed canopy, but instead a measure of area available to the average tree in the stand in relation to the maximum area it could use if it were open grow, or in other words, the degree of crowding.

When Krajicek _et al._ (9) applied the CCF formula for Norway spruce to the stand table data for even-aged Sitka spruce and western hemlock, he found that except for the poor sites and young age classes, the CCF values were fairly constant. From these results it was hypothesized that CCF is relatively independent of site and age.

Vezina (15), working with the balsam fir and white spruce, established a correlation coefficient of r = 0.945 between CW and DBH for white spruce, and a correlation coefficient of r = 0.93

between CW and DBH for open-grown balsam fir. After plotting scatter diagrams showing the dependence of CCF on site index and stand age, he concluded that there was no strong relationship evident between CCF and site index, but that there was a slight decrease of CCF with the increase of age.

PREVIOUS STUDIES OF CCF FOR DOUGLAS-FIR

Little research has been done to evaluate the use of CCF as a measure of density for Douglas-fir. The only research on this subject has been conducted by Elwood L. Miller (11) and Stephen J. Titus (14).

Review of Paper by Elwood Miller

The objectives of Miller's study were as follows:

1. To determine the correlation between crown diameter and DBH for Douglas-fir.
2. To investigate the possibility of using another variable or the interaction of two variables to predict crown width with greater accuracy than by using DBH alone.
3. To develop, if possible, a method to alleviate the discrepancy in CCF values evident in the low age and site classes.
4. To determine if CCF values are dependent on site and age; and if so, try to show any trends that exist (11:22-23).

Miller used data from two different sources. He used the measurements of DBH, total height, and crown width taken on 60 open-grown Douglas-fir trees for a tree-space study by Barnes (8). These trees were located in the vicinity of Corvallis, Oregon. The trees were located mainly in open fields and were considered to have been free from competition throughout their entire life. Then, to increase his sample size, Miller (11) measured 45 additional trees.

> Diameter breast height, total tree height, and crown width, (measured in two directions at right angles to each other and averaged) were measured for each selected tree. The

selection of the tree to be measured was based on the following specifications:

a. Free from all present competition with no signs of past competition
b. Crown extending to the ground or nearly so
c. Lowest branches the longest
d. No evidence of any damaging agent, human or otherwise.

When he plotted the field data, he found that the relationship between CW and DBH was not linear, as were the relationships investigated by Krajicek _et al._ (9) and Vezina (16). When Miller applied a straight line regression analysis to his data, the resultant intercept was CW = 9.75 feet when DBH = 0., which is much too high. "It was also noted that his correlation coefficient (r = 0.917) was somewhat lower than those reported by Krajicek _et al._ and Vezina" (11:24). Miller then tried various other variables and combinations of variables, with the combination of variables, with the combination [(DBH^2 × total height) + DBH] having the highest correlation of R = 0.929 (9:26).

Miller rejected the multiple variable solution because it was too complicated and decided to split the data into two groups: one having DBH values from 0 to 5.0 inches and the other having values from 5.1 inches and up.

A straight line regression analysis was used for each group to relate DBH and CW. The equations for crown width were as follows:

CW = 4.354 + 2.198 DBH
r^2 = .814
Number of trees sampled = 15
Standard error = ±1.79 feet or 17.3 percent

For the 5.1 inch and higher group:

$CW = 11.675 + 1.097DBH$
$r^2 = .779$
Number of trees sampled = 90
Standard error = ±6.52 feet or 18.4 percent (11:29).

It is important to note that although the intercept of the first equation is low enough to be realistic, r^2 is only 0.814 for the small trees and 0.779 for the larger trees. These values are very low in relation to those reported by Krajicek et al. (9) and Vezina (15). This is partly due to splitting the data and reducing the range of the "X" variable.

Using two different CCF formulas derived from these regression equations, Miller computed the CCF values for the Douglas-fir stand tables presented in the USDA Technical Bulletin 201 (10:47-48). Since the stand table from which the data were taken does not give stand information for poor site and young age classes, Miller was unable to test whether the method of splitting the data and calculating two formulas was effective in reducing high CCF values for young ages and poor sites. However, from the higher CCF values obtained for age 40, site IV; and age 60, site V; it is indicative that it did not. See Table 1.

Since, according to Spurr (13), a measure of density should be relatively independent of site and age, Miller attempted to establish a dependence of CCF on site and age.

> The average CCF value for each site was computed and compared with each CCF value for every age within a given site. The deviation from the mean for each age was expressed in a percent and graphed. A definite downward trend was evident between age class 40 and age class 160 (11:32).

Table 1. CCF values based on Douglas-fir stand table in Tech. Bull. 201 (Using two equations)

Age class	Site index I	II	III	IV	V
20	233.7	249.3			
40	254.0	283.7	326.6	345.7	
60	224.2	280.5	313.9	329.3	332.6
80	233.9	263.8	295.5	316.8	370.4
100	229.6	258.1	282.2	293.6	301.6
120	229.6	253.0	278.6	291.5	288.0
140	234.4	251.6	272.6	285.5	272.9
160		255.8	272.9	283.0	279.9

"To check the apparent dependence of CCF values on site, average CCF values for each age were computed and compared with CCF values for each site within the given age. Once again, the deviation from the mean was expressed as a percent and graphed." A definite increase in value was noted for each increase in site. Although these deviations from the mean were computed and graphed, Miller did not compute a correlation coefficient between CCF and age and site, so no definite conclusions can be drawn from his results (11:32).

Review of Paper by Steve Titus

In his paper of CCF Titus (14) used the same data as that used by Miller (11). However, he did not have Miller's original data and therefore had to interpret the values from a graph. He interpreted crown width to the nearest foot and DBH to the nearest inch. He also deleted three trees from Miller's data and one tree from Barnes' data because the values were so erratic as to indicate an error in measurement. Since the specification for Barnes' data are unknown, and because Miller's data had to be interpreted off a graph, the tests and evaluation made in Titus' study were only to be taken as tentative until a more vigorous study could be undertaken (14:43).

Titus applied a stepwise regression program to the data using an IBM 1410 computer. Crown diameter was the dependent variable, and the first three powers of DBH were independent variables. He reasoned that the simple curvilinear model would fit the curvature of the plotted data better than a linear model, and would lower the intercept, which was unrealistically high in Miller's equation (11, 14). Titus calculated both linear and a simple curvilinear formulae for the combined data of 101 trees. The results were:

$$Y = 8.372 + 1.267DBH \quad \text{with} \quad r^2 = 0.886$$

and $$Y = 6.609 \pm 1.463DBH - 0.0013DBH^3 \quad \text{with} \quad R^2 = 0.937$$

The intercept is lower for the simple curvilinear model than for the linear one, but it is still a little too high.

> In accordance with the practice followed in earlier studies, CCF values for fully stocked stands of various sites and ages were calculated using data from USDA Bulletin 201 (10)....As stated previously, the tendency of these values to be fairly consistent indicates that the normal yield tables are based on density criteria similar to those of the CCF because, by definition, stands with the same CCF values

have the same density, regardless of site or age. Any attempt to evaluate the variation among these values is unnecessary (14:49).

See Table 2 and 3.

Table 2. CCF values based on Douglas-fir stand table in USDA Technical Bull. 201 (linear model of CW over DBH)

Age class	Site index I	II	III	IV	V
40	238	270	304	357	450
60	242	271	293	296	329
80	249	268	288	295	340
100	251	270	289	288	276
120	255	270	287	284	273
140	264	273	285	285	271
160	256	281	289	286	268

Table 3. CCF values based on Douglas-fir stand table in USDA Technical Bull. 201 (curvilinear model of CW over DBH)

Age class	Site index I	II	III	IV	V
40	244	256	288	320	398
60	254	282	297	294	300
80	259	282	300	299	333
100	254	283	304	297	273
120	250	280	301	296	275
140	250	270	299	299	277
160	250	281	301	301	277

The previous statement made by Titus is in error. He states that, "...the tendency of these values to be fairly consistent indicates that the normal yield tables are based on density criteria similar to those of the CCF..." (14:49). Close examination of the CCF values of the yield tables reveals that the values are not fairly consistent between the low site, young age classes and the average site, middle age group. This would lead one to believe that the criteria for the measures of density are not the same, and that this warrants further investigation. Titus did not calculate the CCF values for the 20 year age class; it is within this age class that Miller had the largest variation from the mean CCF value (11).

Titus also states that the values are consistent "...because, by definition, stands with the same CCF value have the same density, regardless of site or age" (14:49). This statement is unjustified because it has not been shown that CCF is independent of site and age. In fact, one of the main purposes in calculating the CCF values of the normal yield table is to determine whether or not there was an obvious trend with either age or site. Since Miller found obvious dependency of CCF on both site and age, and by observation it appears as though these trends are present in the values calculated by Titus, it seems feasible that these trends should be investigated further.

PRESENT STUDY OF CCF FOR DOUGLAS-FIR

The original purpose of this study was to further examine the relationship between crown width and DBH for Douglas-fir under 20 inches DBH. In past work with Douglas-fir (11, 14), CCF values calculated from the yield tables of Tech. Bull. No. 201 (10), have been much higher for the young age classes and poor sites than values calculated for higher sites and ages (Table 1, 2, and 3). Also, there has been a problem in finding a realistic intercept for the relationship between crown width and DBH. Miller (11), using a linear equation had an intercept of 9.75 which indicates a crown width is 9.75 feet for a tree with a zero DBH. This value was much too high to be realistic, so he used two linear equations to lower the intercept to 4.35 feet which was more realistic. Titus, using curvilinear analysis, had an intercept of 6.61, which is also too high. Therefore, in order to study this problem further, the original data collected for this study were limited to trees with a DBH less than 20 inches. Also, by limiting the DBH to less than 20 inches, it was possible to determine the ages of the trees. This was necessary in order to study the effect of age and site on the CW-DBH relationship.

However, the scope of the study was later expanded to include trees larger than 20 inches DBH, and to test the relationship between crown area (CA) and basal area (BA). It was hypothesized that since there was a high correlation between CW and DBH, there should also be a high correlation between crown area and basal area. If this is true, then the data needed to compute CCF could be taken by point sampling methods, and the need for a complete tree count by DBH class would be eliminated.

Methods

The trees measured for this study had to meet the same specifications used by Miller (11:32). These specifications were:

1. Free from all present competition with no signs of past competition
2. Crown extending to the ground or nearly so
3. Lowest branches the longest
4. No evidence of any damaging agents, human or otherwise

Diameter breast height, total tree height, crown width, and age were measured for each tree. Crown width was measured at right angles and averaged. If the limbs were curved upward, they were pulled down to the horizontal. The original data collected consisted of 49 trees with a DBH less than 20 inches.

In order to increase the sample size, the data collected by Miller (11), and Barnes (2), were examined. Since the criteria by which Barnes' data were collected were unknown, it was decided that any trees on which the crown width at right angles varied by more than two feet would be eliminated. This was based on the assumption that theoretically an open-grown tree would have a circular crown. The fact that the majority of trees measured had circular crowns lends support to this assumption. This criteria was also applied to the author's data, so seven trees were disqualified. Twenty-nine trees were originally used from Barnes' data.

The original values of Miller's data were unavailable, so the values had to be interpreted from a graph. Crown width was interpreted to the nearest foot, and DBH to the nearest inch. When the data from the three sources were plotted (Figure 1), it became obvious that Miller's data averaged much lower than either the author's or Barnes' data indicating either a large difference in measuring technique, or bias from interpreting the graph. For these reasons, it was decided not to include Miller's data.

Results

A stepwise regression was performed by an IBM 1620 computer. Crown width was the dependent variable and DBH, DBH^2, DBH^3, total height, and age the independent variables. The results of the regression program were:

$$CW = 3.788 + 3.03 DBH - 0.130 DBH^2 + 0.004 DBH^3$$

with $R^2 = 0.956$

Std. Err. $Y \cdot X = \pm 2.29$.

Std. Error $\overline{Y} = \pm 1.17\%$

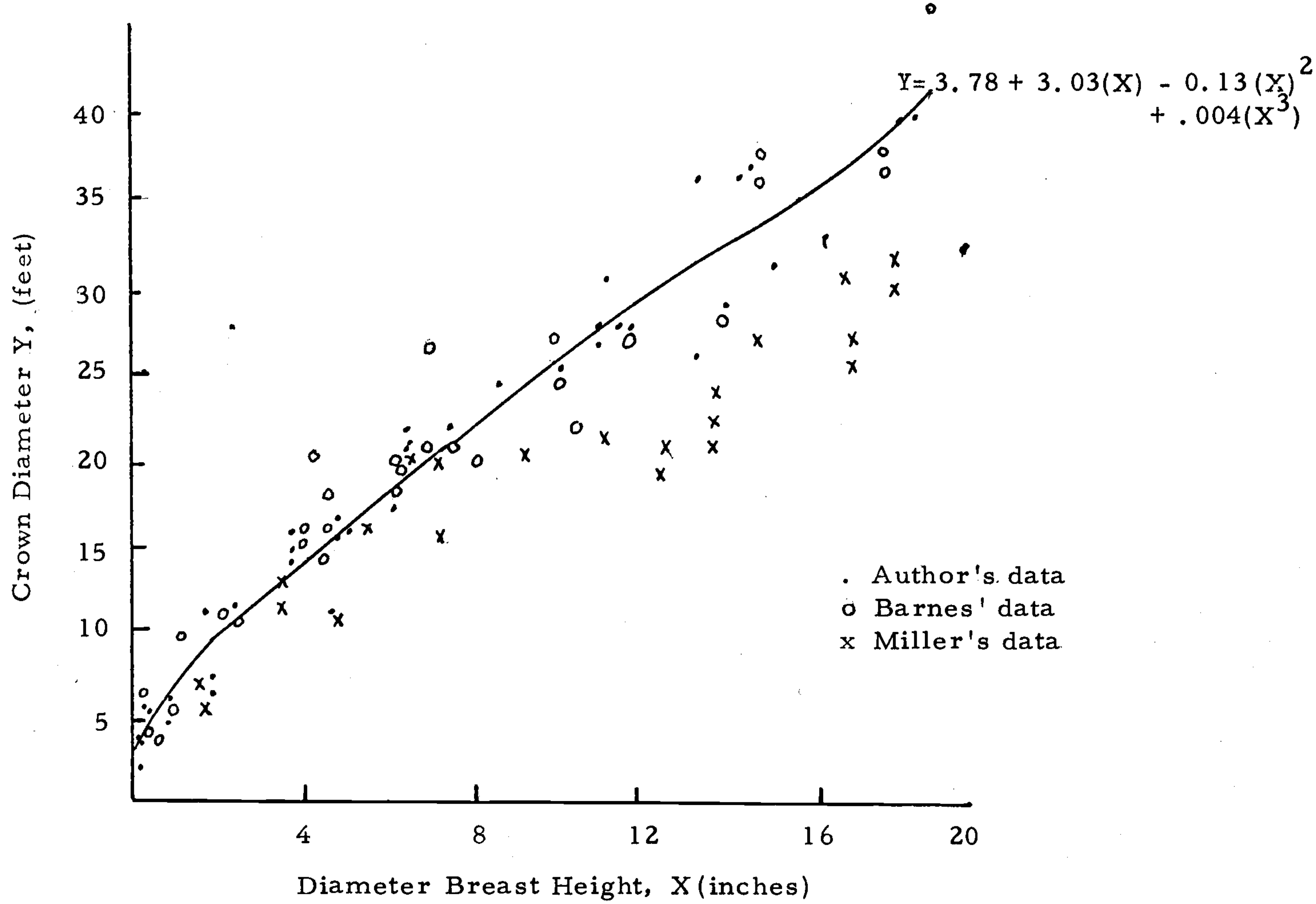

Figure 1. Graph of crown diameter prediction equation for combined author's and Barnes' data for trees under 20" DBH.

It should be noted that age, and total height, the two components of site, were nonsignificant at the 95 percent level. However, the data were collected from a narrow range of sites, and therefore it is possible that a larger sample taken from a wider range of sites might produce different results. The R^2 for the equation is 0.956 which is higher than the results obtained by either Titus (14), R^2 = 0.94, or Miller (11), $r^2 = 0.81$ and $r^2 = .78$. The probable reasons for the higher correlation are one, the crowns had to be circular, a criteria not used by either Miller or Barnes, and two, Miller's data were not used because of its questionable accuracy. The intercept of 3.79 feet is considered realistic, because the average crown width of the three smallest trees measured, 0.1 inches DBH, was 4.3 feet.

Increase of Maximum DBH

After it was determined that age was not a significant independent variable, it was decided to increase the sample to include trees up to 40 inches DBH. Age was not determined for the larger trees. Also, with the data including trees up to 40 inches DBH it would be possible to calculate the CCF values of the stand tables in USDA Tech. Bull. 201 without extrapolating the equation beyond the data. More open-grown trees were measured, and the trees over 20 inches DBH were added from Barnes' data. Due to the large size of these crowns, trees were not eliminated unless the crown widths varied more than three feet between maximum and minimum diameters (Figure 2).

A stepwise regression was performed on the data by a CDC 3300 computer. There were 88 observations. The stepwise regression used crown width as the dependent variable and DBH, DBH^2, and DBH^3 as the independent variables. The results of the regression program were:

$$CW = 4.93 + 2.20\,DBH - 0.02\,DBH^2$$

with $R^2 = 0.969$

Std. Err. $Y \cdot X = \pm 2.80$

Std. Err. $\overline{Y} = \pm 1.43\%$

The R^2 of 0.969 is the highest yet obtained for the CW-DBH relationship using Douglas-fir, and the intercept of 4.9 feet is realistic. In contrast to both the equation computed from the first group of data, and the equation computed by Titus (14), the DBH^3 variable was not selected at the 5 percent probability level. The regression line is plotted in Figure 2.

The formula for crown competition factor is derived from the regression equation as follows:

$$CW = 4.93 + 2.20\,DBH - 0.02\,DBH^2$$

$$MCA = 0.0018(CW^2)$$

$$CCF = MCA \text{ per area/acres}$$

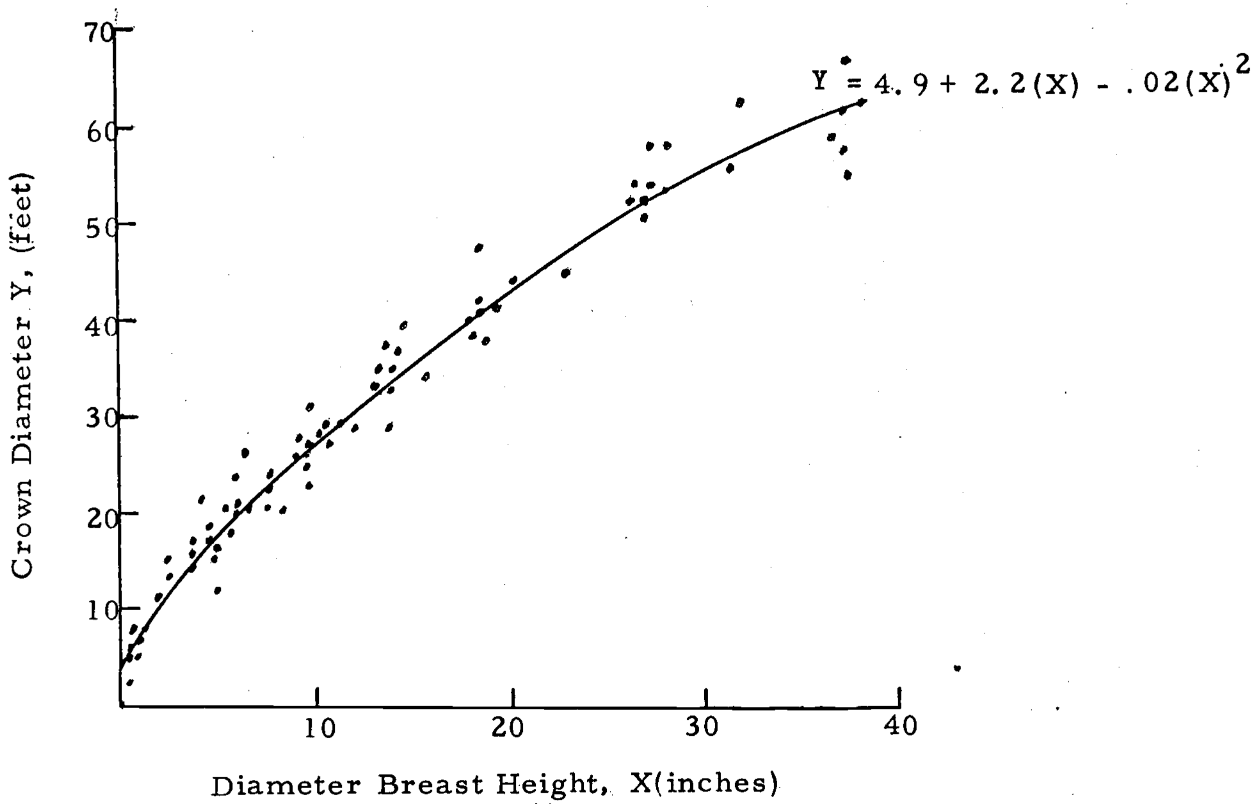

Figure 2. Graph of crown diameter prediction equation for combined author's and Barnes' data for trees up to 40" DBH.

therefore:

$$CCF = 1/A[.044(Ni) + .039(DiNi) + .008(Di^2Ni) - .0002(Di^3Ni) + .0000008(Di^4Ni)]$$

where CCF = crown competition factor

Di = DBH class

Ni = number of trees in that DBH class

Discussion

In order to help determine if CCF is a practical measure of density the formula was applied to the Douglas-fir stand table in USDA Tech. Bull. No. 201 (10). This would help determine if the measure was consistent for a certain accepted level of density at various ages and sites. In this case the normal stand is used as the standard. The results of the calculations are shown in Table 4.

The CCF values range from a low of 255 at age 20, site index I to a high of 447 at age 80, site index V. The standard deviation of the population is 46., and the coefficient of variation is 12.6 percent. Thefefore, the values are fairly consistnet about a mean of 364.

Table 4. CCF values for Douglas-fir stand table in Tech. Bull. No. 201 (Author's CW over DBH curvilinear model)

Age class	Site index I	II	III	IV	V	Average
20	255	283	---	---	---	269
40	334	345	376	391	---	361
60	338	385	406	392	377	379
80	327	375	409	408	447*	379
100	272	365	408	407	369	364
120	276	350	397	403	376	360
140	271	340	386	403	379	355
160	---	332	383	400	379	373
Ave.	296	346	395	400	376	364

* Not included in the averages

To further study the CCF values calculated from the yield table, they were plotted over age by site class (Figure 3), and over site class by age (Figure 4). It is interesting to note that if CCF was not plotted by site class, the data would look scattered with no obvious trends (Figure 5). If Vezina (15:41) had stratified his data by age and site class when he plotted his scatter diagram, it is possible that he would have noticed a more obvious trend between CCF and age or site.

When CCF is plotted over age by site class as in Figure 3, there seems to be some slight trend. The values first increase with age, then level off, and finally decrease slightly at higher ages. The CCF value for site V, age 80 is 447. This is much higher than the

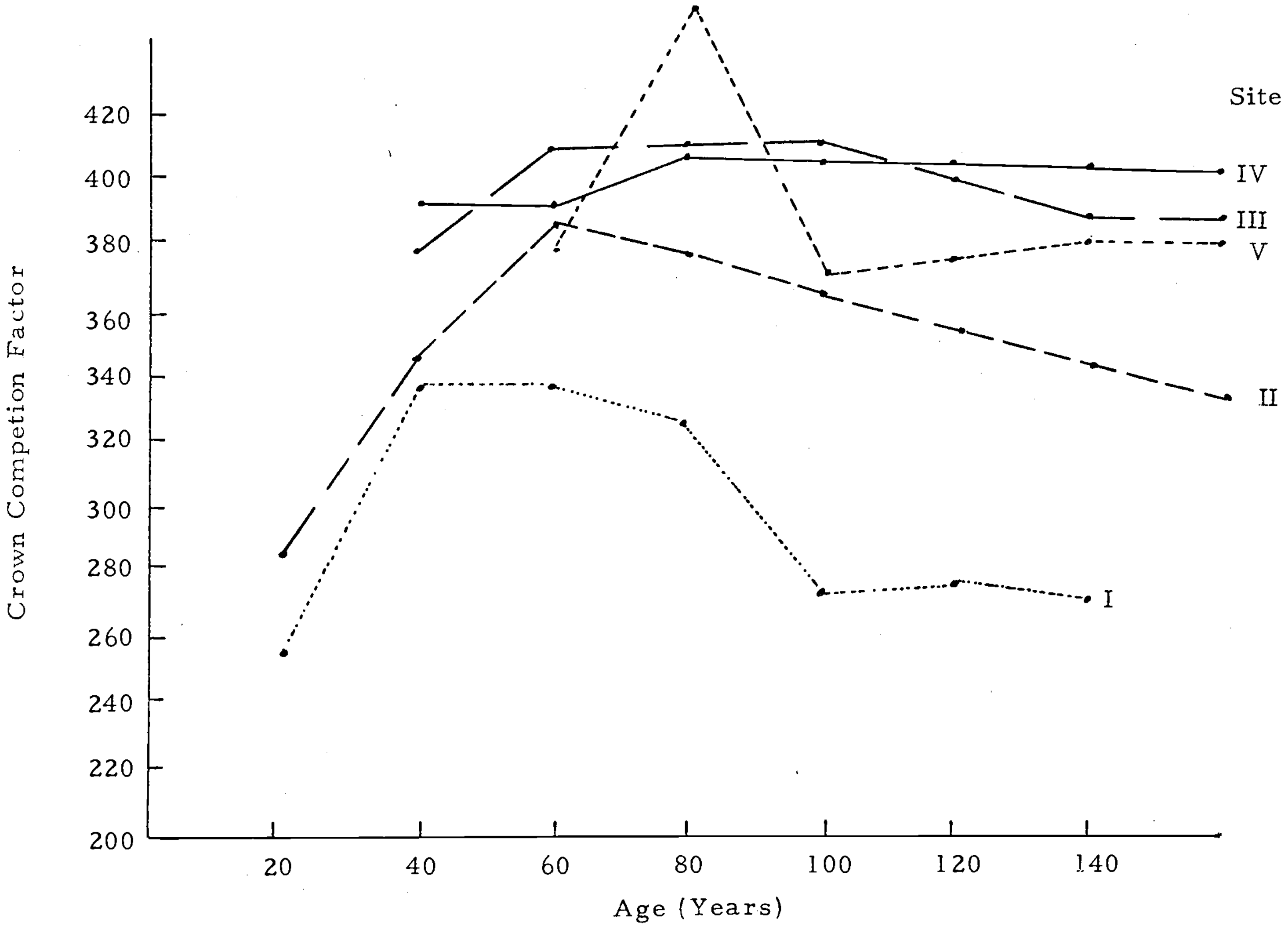

Figure 3. Graph of relationship between CCF values and age by site class for USDA Tech. Bull. 201 (using prediction equation for crown diameter)

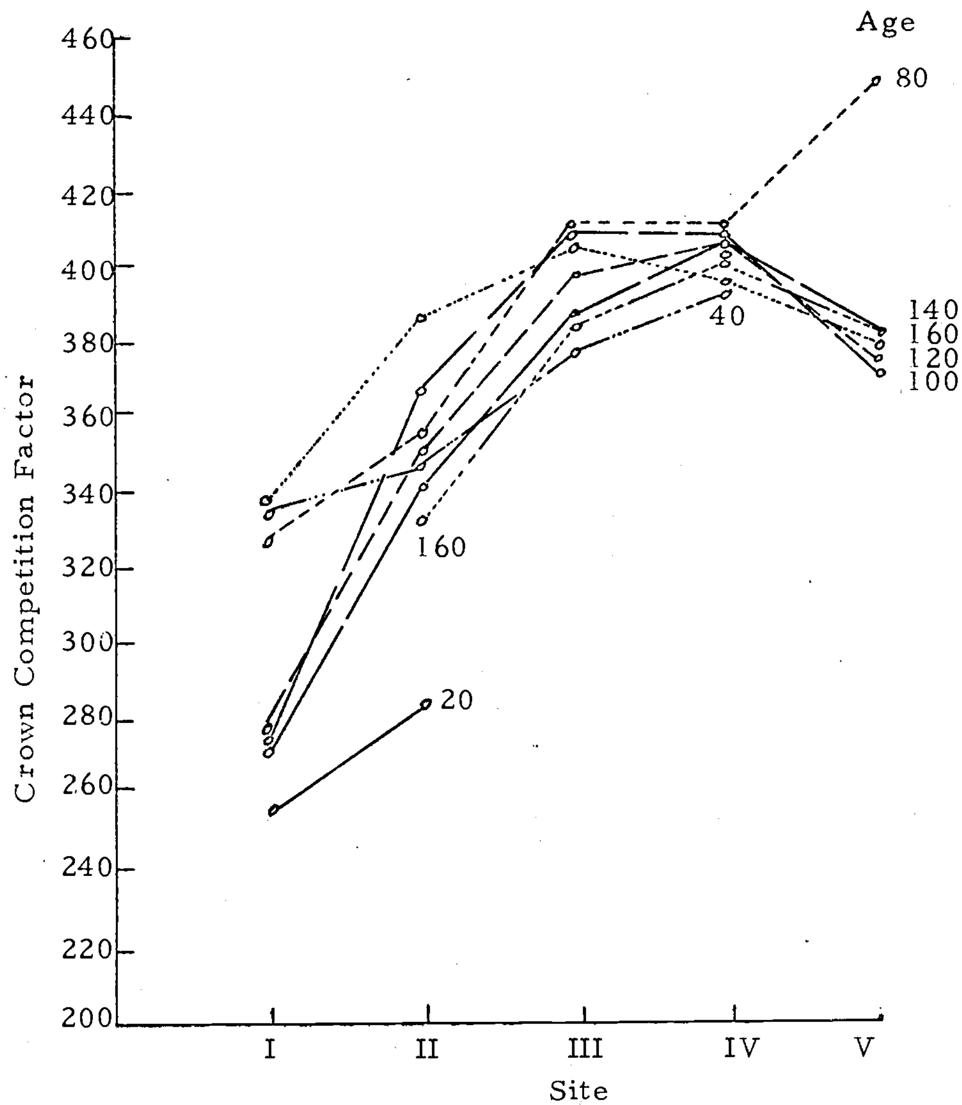

Figure 4. Graph of relationship between CCF values and site class by age for USDA Tech. Bull. 201 (using prediction equation for crown diameter)

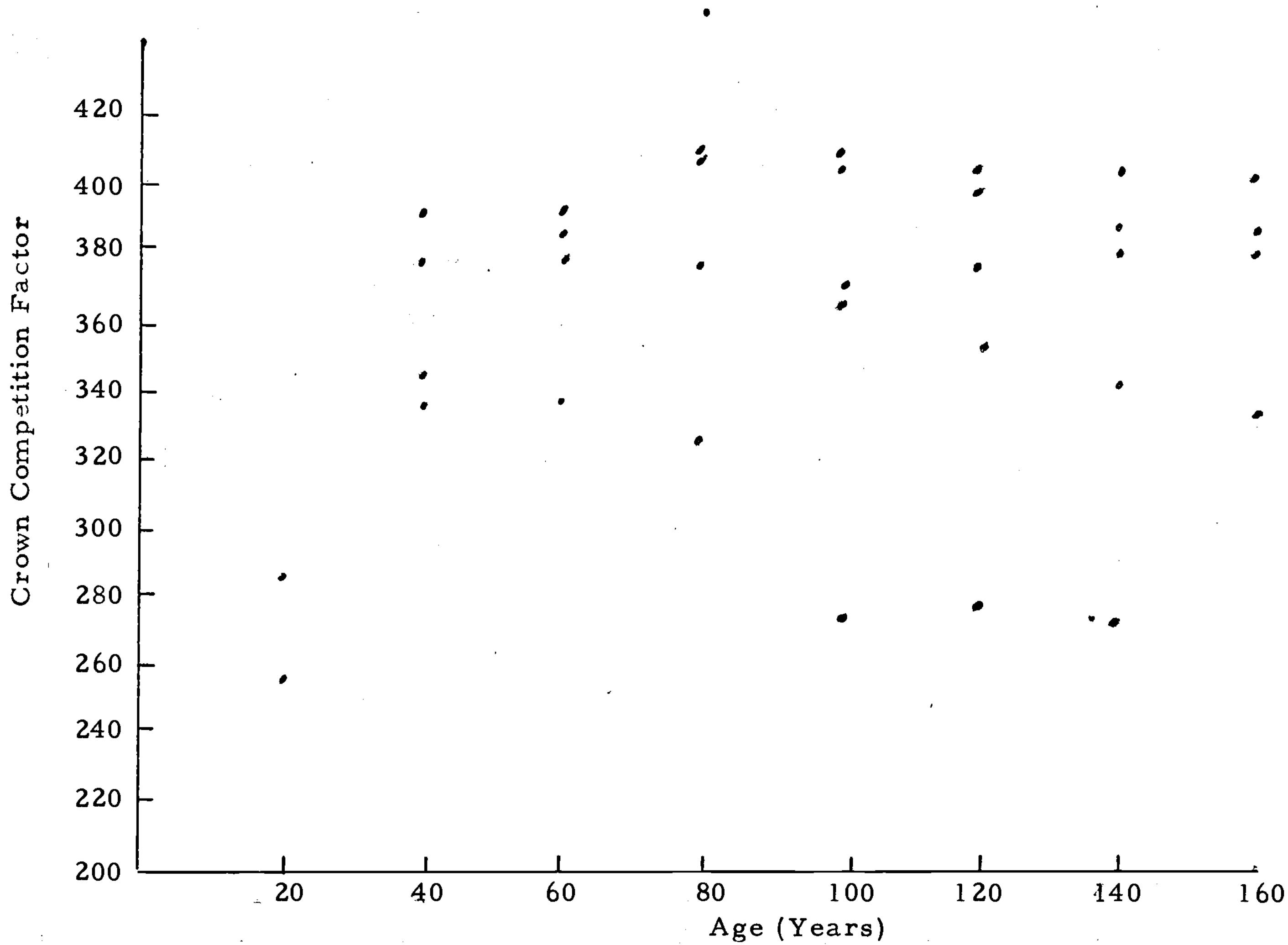

Figure 5. Graph of relationship between CCF values and age for USDA Tech. Bull. 201 (using prediction equation for crown diameter)

mean, and it deviates widely from the pattern of the other values. It is possible that this may be due to an error in the original stand table.

A definite trend is illustrated in Figure 4 where CCF is plotted over site index by age. As site decreases from site I to site IV, CCF generally increases, however, as site continues to decrease from site IV to site V, CCF also decreases. The only exception is the same one mentioned for Figure 3, the CCF for site V, age 80.

From observation it appears that there is very little, if any, correlation between CCF and age, but there is a definite correlation between CCF and site. These conclusions are the same as those drawn by Miller, for he states that:

> Secondly, there appears to be very definite trends established, especially with changes in site. It is easily seen that as the site index moves from I to V, the CCF values also increase. Although it is less easily seen, there does appear to be a downward trend in CCF values as the age increases from site III to site V. Finally, the values appear to show some consistency, except for the much higher value of the 80 year old stand on site V (11:31).

However, two things should be pointed out: first, the measured trees were all from a similar site. All the data were collected within a short radius of Corvallis, Oregon. The site probably ranged from a middle site IV to a low site II. If the data had been collected from a wider range of sites and geographic locations, then it is quite possible that the equation predicting crown width from DBH would be different, and that one might get different results when applying the new CCF equation to the yield tables. Secondly, it is highly possible that the trends shown by CCF at different sites are not so much a function of the dependence of CCF on site, but a reflection of the variability of the criteria by which the yield tables were first constructed.

CCF PREDICTED FROM BASAL AREA

One apparent disadvantage to CCF is the difficulty of collecting data in the field. A complete stem count by diameter class is needed for accurate results. This is most practical using a fixed radius plot method of cruising, but the recent trend in cruising has been away from this method and towards the variable plot method. In an attempt to make CCF practical for variable plot curising, the relationship between crown area and basal area was established. It was hypothesized that if there was a high correlation between crown width and DBH, then there must also be a high correlation between crown area and basal area.

Results

A stepwise regression was performed by a CDC 3300 computer using crown area as the dependent variable and basal area (BA), BA^2, and BA^3 as the independent variables. The data were the same as that used previously. The probability level used to enter the variables was five percent. The equation derived by the computer was: $CA = 101.68 + 616.42 BA - 39.07 BA^2$. The coefficient of determination, R^2 was 0.949 which is higher than that found in the literature (6, 9, 11, 15), but is lower than the correlation between CW and DBH.

It is also interesting to note that the intercept of 101.68 is much too high. The crown width of a tree with a crown area of 101.68 sq. feet is 11^+ feet. The range of CW's for trees 4.5 feet tall is between 3.5 feet and 6 feet, averaging about 4.3 feet. However, the reason the intercept is so high is quite obvious. The scatter diagram in Figure 6 shows that the crown width of a tree increases very rapidly as a tree grown from 0.0 to 0.04 square feet in basal area. Since the curve is steep here, it takes only a slight change in the curve to bring about a large change in the intercept. A possible solution to this problem might be to use either weighted regression or logarithmic transformations to satisfy the assumption of equal variance along the X-axis. This has not been done by the author and may be a possibility for future research.

The CCF formula was derived and used to calculate the CCF values for the Douglas-fir stand tables in USDA Tech. Bull. 201 as before (10:14). The derivation of the CCF formula is:

$$CA = 101.68 + 616.42\,BA - 39.07\,BA^2$$

$$CA = \frac{\pi (CW)^2}{4}$$

$$MCA = \frac{\frac{\pi (CW)^2}{4}}{435.6}$$

$$MCA = \frac{CA}{435.6}$$

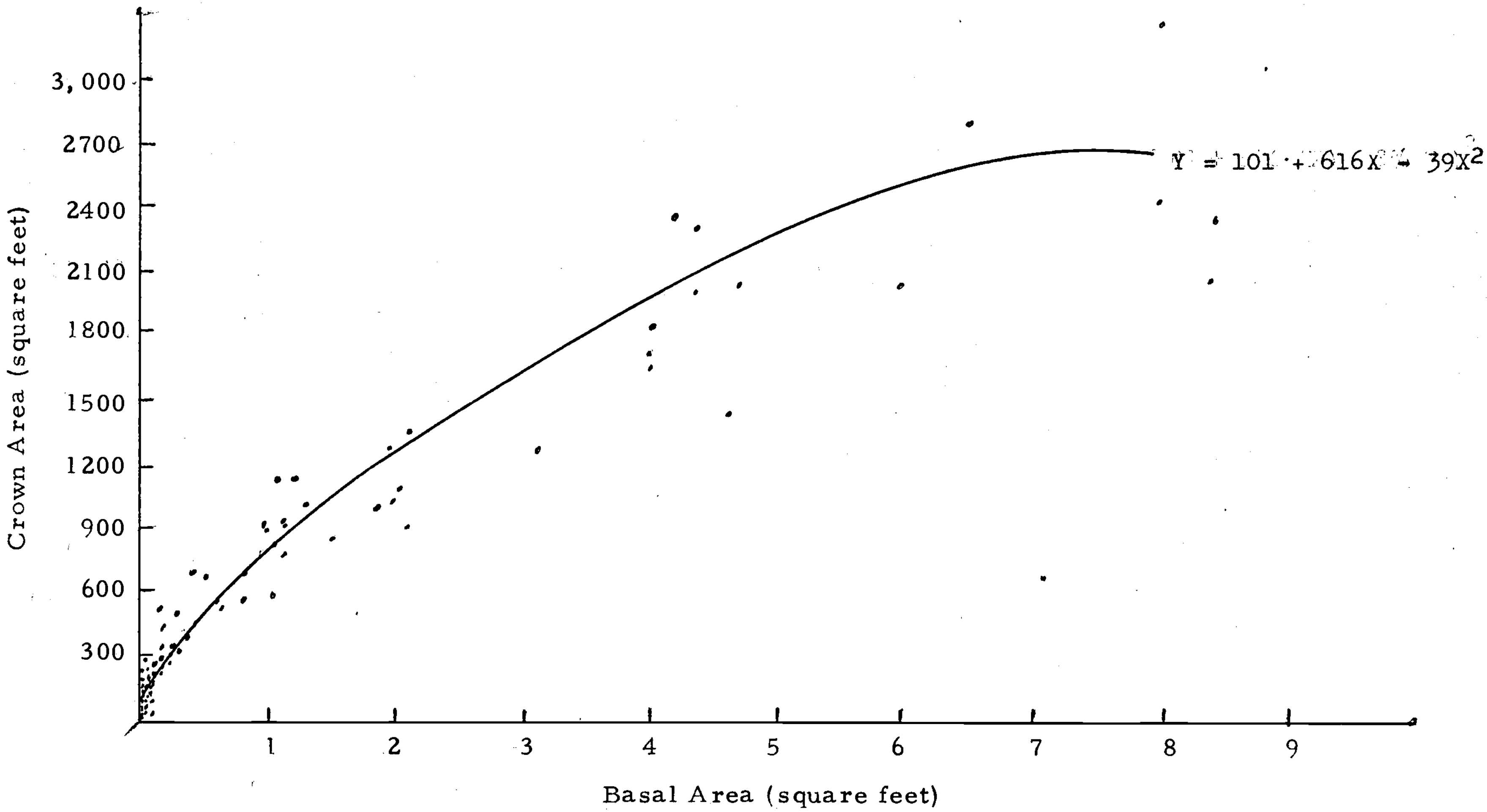

Figure 6. Graph of crown area prediction equation for combined author's and Barnes' data for trees up to 40" DBH.

$$MCA = \frac{101.68 + 616.42\,BA - 39.07\,BA^2}{435.6}$$

$$CCF = MCA$$

therefore: $CCF = [\Sigma \cdot 233N + 1.415\,BA(N) - 0.089\,BA^2(N)]$

The results of the calculations are shown in Table 5.

Table 5. CCF values based on Douglas-fir stand table in Technical Bull. 201 (Author's CA over BA curvilinear model)

Age class	Site index I	II	III	IV	V	Ave.
20	277	343	470*	830*	1705*	310
40	317	349	382	431	526*	370
60	343	385	385	385	397	379
80	350	384	395	385	368	376
100	344	390	404	391	359	377
120	328	390	408	395	357	375
140	306	384	408	401	360	371
160	283	374	412	404	361	366
Ave.	318	374	399	398	367	371

* Not included in calculations of averages

Discussion

Except for the values for the young age class and poor sites, which are marked by an asterisk, the CCF values are fairly consistent about a mean of 371. In comparison with the CCF values obtained using the equation derived from the CW-DBH regression, hereafter referred to as (a), it is interesting to note several things about the CCF values in Table 5, hereafter referred to as (b):

1. The means of the two sets of values are very similar; 364 for (a) and 371 for (b)

2. The range of the values is greater for (a) than (b); 192 vs. 154

3. The coefficient of variation is less for (b) than for (a); 9.4 percent vs. 12.6 percent

4. The same general trends for CCF plotted over age and site are apparent for both (a) Fig. 3, and (b) Fig. 7

5. The values for the low site and young age classes are much higher than the mean for (b). One possible explanation is that since the intercept for the basic equation was high, the formula calculates a much higher value for total crown area than what is realistic for small trees.

6. The S.E. $\bar{Y}$ for (a) is lower than the S.E. $\bar{Y}$ for (b); 1.17 percent vs. 1.43 percent

In order to further evaluate the value of CCF as a measure of density, a correlation analysis was performed by an IBM 1620 computer between all combinations of the following variables: site index, age class, average DBH, total basal area, and CCF. The data used were from the stand table in USDA Tech. Bull. 201 (10:14), and Table 5. The results are shown in Table 6:

Table 6. Correlation coefficients and significance for combinations of pertinent variables

Variables	Corr. Coef.	% Sig.
BA vs. Age	.772	99.9
BA vs. SI	.387	95.0
CCF vs. Age	.031	NS
CCF vs. BA	-.065	NS
CCF vs. SI	-.555	99.9

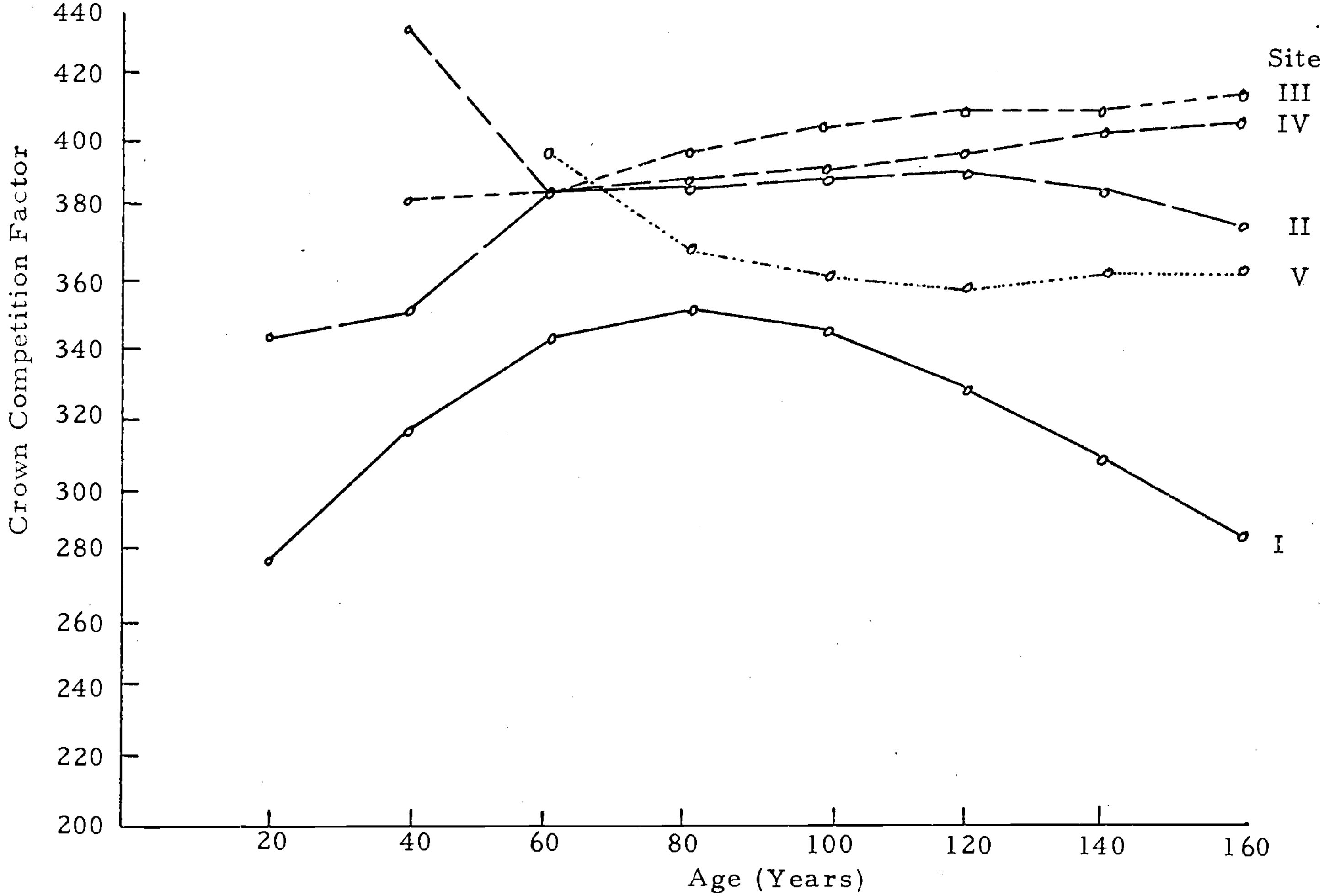

Figure 7. Graph of relationship between CCF values and age by site class for USDA Tech. Bull. 201 (using prediction equation for crown area)

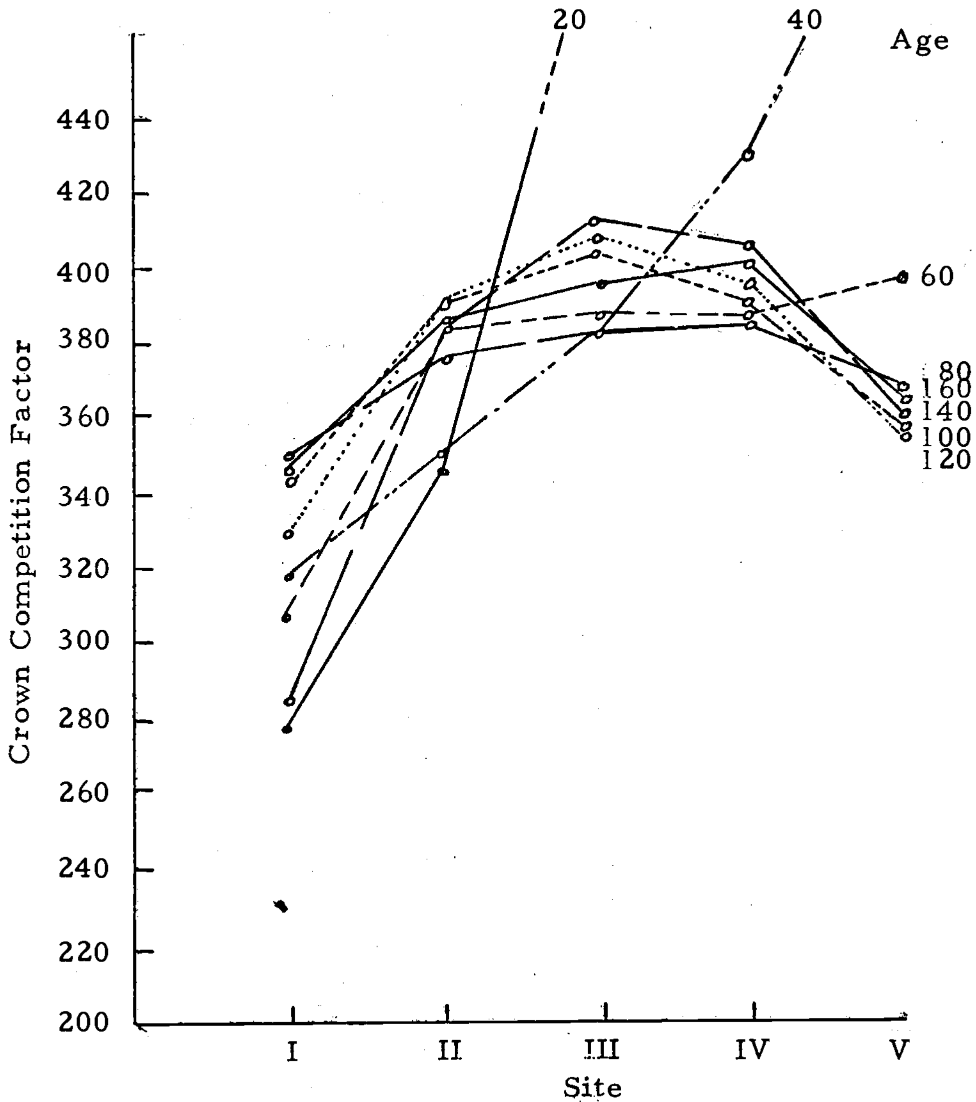

Figure 8. Graph of relationship between CCF values and site by age for USDA Tech. Bull. 201 (using prediction equation for crown area)

The results of the correlation analysis support the previous observation that CCF is dependent upon site, at least for the stand table in USDA Tech. Bull. 201 (10). Surprisingly it shows that CCF is more dependent upon site than is BA. However, it also shows that CCF is not dependent upon age, whereas basal area is. Also the fact that the correlation between CCF and BA is non-significant indicates that CCF and BA measure density in an entirely different way.

EVALUATION AND CONCLUSION

The results of this study show that CCF is a possible functional measure of density. According to Spurr, the ideal measure of density should be simple, objective, measure the degree of utilization of an area by trees, and be unrelated to age and site (13:275). As discussed earlier, no present measure can be called the "ideal" measure.

CCF appears to meet most of the criteria set forth by Spurr. Although the concept appears complicated, the actual computation is simple (16:7). Once the relationship between crown width and DBH is established, and the CCF formulat derived, the only data needed to determine the density of a stand is the number of trees by DBH class. This can be obtained from either fixed or variable radius plots.

Crown competition factor is objective. It is a measure of area available to the average tree in the stand in relation to the maximum area it could use if it were open grown, or the degree of growing.

As shown in Figures 3, 4, and 5, CCF appears to be almost completely independent of age and slightly dependent upon site. However, due to the fact that age or site could not be obtained for all the data, and because all the data were collected within a narrow range of site, these statements are not absolutely conclusive. It is interesting to note that the literature (6, 15) shows results just the opposite. Both studies showed no relationship between CCF and site, but a slight negative relationship between CCF and age.

The most important question concerning CCF is what is its relationship to the biological and economical growth of the forest stand? Some other questions that should be studied in the future are:

1. What is the maximum CCF value?

2. What is the optimum CCF value?

3. Is there a constant CCF value for optimum biological or economical stand growth, or does it change according to different variables?

4. What are the effects of clustering on CCF?

5. Can CCF be used for mixed stands?

These are just a few of the more important questions that must be answered before CCF can be accepted as a practical measure of density.

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