USE OF COMPETITION INDICES IN THE
SELECTION OF WESTERN HEMLOCK PLUS TREES

by

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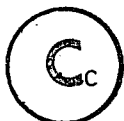THE REQUIREMENTS FOR THE DEGREE OF

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ABSTRACT

Use of Competition Indices in the Selection of Western Hemlock Plus Trees

Western hemlock's primary role in an integrated forestry operation
is in high density stands which produce a large cubic volume in relatively
short rotations. This implies an efficient use of growing space, an
important characteristic of the future tree. Selections of individual
trees for inclusion in an improvement program should reflect this species
management format.

The objective of plus tree cruising is to select trees which are
phenotypically superior for use in tree improvement breeding programs.
The possibility of obtaining a 10-15% improvement in a selection category
without waiting 20 to 40 years for results of progeny tests seems econom-
ically tempting. Unfortunately, environmental and genetic components
of variability in a given trait resist separation in field selections.
The objective of this study was to develop selection criteria which
reflect two important characteristics: a) rapid growth rate and b)
efficient utilization of space or growth under stand competition.

Permanent sample plots in coastal British Columbia were used to
investigate competition, crown characteristics and growth increment
in even-aged, second growth stands of western hemlock. Several cur-
rently available competition indices were used in five year basal area
increment regressions. A regression weighting procedure is described
which allows the selection of trees having growth residuals larger than
a prescribed confidence interval. The entire plot serves as an environ-

mental base line (for selection). A second approach utilizes low level 70 mm aerial photography of crowns. Crown efficiency regressions are developed based on current crown area and five year basal area increment. Again a confidence interval is established with which to select the plus tree candidate.

In an additional phase of the study, previously selected trees were visited with the goal of evaluating crown attributes on the basal area increment of these trees. One or more check trees were selected near each of the prior selections; these trees were compared with respect to growth, height, crown area projection, and length of crown. No statistical differences could be found between the two groups reaffirming the value of initial selection intensification.

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INTRODUCTION

Western hemlock (Tsuga heterophylla, (Rafn.) Sarq.) is one of the four major timber producing species of the Pacific Northwest. Its range extends from southwestern Alaska to north coastal California, with inland regions in the Canadian Rocky Mountains and Idaho, Montana and western Washington in the USA. The most extensive areas are found in coastal area extending from Alaska to Oregon. In early inventories of the region it was often treated as a weed species, at least partly due to its relation to eastern hemlock (Tsuga canadensis (L.) Carr.) which was known to have poor wood quality. Indeed, western hemlock has many desirable qualities for both lumber and pulp production. In British Columbia, western hemlock is currently the major pulping timber. It is preferred in dissolving grade pulps and yields quality pulp in both mechanical and chemical pulping processes (Wellwood, 1960).

To escape association with its eastern relative, western hemlock was often referred to as Alaskan pine. Still, it was not until after WW II that Leon Koerner, an immigrant from Czechoslovakia, founded Alaska Pine and Cellulose, Limited, based primarily on hemlock. His enterprise elevated the tree to commercial importance in British Columbia. In recent years, it has in some respects become the most important single species, exceeding in volume cut, the formerly dominant Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco). In 1976 it exceeded all species harvested, including spruce (Picea spp.), with about 22% of the total cut (5.3 MM cunits of a total 24.5 MM cunits) and in stumpage returned to the province of B. C., it contributed $10 million of a total

$49 million (BCFS Annual Report, 1976). In standing mature inventory, western hemlock represents a major component, totalling approximately 648 million cunits. Of this volume a total of 350 million cunits are estimated to be directly disposable by the B. C. Forest Service (BCFS, 1975). Today western hemlock's large remaining volume and its suitability for both solid wood and pulp products make it a very important contributor to the wealth and future of the people of British Columbia.

Genetic Improvement

The scientific study of western hemlock, like its utilization by industry, has lagged behind Douglas-fir. Only a few of the papers included in Walters' (1963) annotated bibliography of western hemlock relate to genetics of the tree. So, it is not surprising to to find that interest in the genetic improvement of western hemlock is very recent. At the prompting of the B. C. forest industry the Canadian Forest Service initiated a western hemlock tree improvement program in 1968. Piesch (1974) discussed the program and some of the technical difficulties associated with its establishment. Of major concern was the difficulty of initial tree selection for inclusion in an improvement program. It was noted that selection of an individual from a stand, is complicated by tendancy for the establishment period of a stand to extend over several years. Also, the capacity for western hemlock to respond to release further adds to variation in tree size and age within stands. These characteristics of the species complicate a selection system based on comparisons of individuals with neighbors growing under similar site conditions. In fact, the importance of initial selection is a crucial part of any improvement program and deserves commensurate attention.

Initial selection is still the determinant of ultimate gains in an improvement program. The selected trees determine the genetic base on which species improvement may be achieved. Increasing the amount of attention paid to the selection of individuals increases the amount of improvement in yield or in any other heritable characteristic of interest. The genetic constraints in a selection program are the heritability and the variance of the selected character. If the simplest formula for potential gain is examined, one finds that the intensity of the selection is the only variable which foresters may influence at the initial selection.

$$G = h^2 * \sqrt{v} * i \qquad (1)$$

Where G = the gain, h^2 = the heritability, v = the phenotypic variance for the population, and i is the intensity of selection.

There is a trade-off between genetic gain and cost of selection. The more stringent the wild stand selection scheme, the higher the costs. Porterfield (1975) performed an economic analysis of the yields and costs of improvement in southern U. S. forests using a marginal cost analysis approach. Figure (1) represents the increase in cost due to increasing selection intensity in that program. A 6% discounting rate was used. Increased selection intensity must be based on firm grounds.

Classical, phenotypic, plus tree selection methods used in the late 1950's and early 1960's in coastal B. C. for Douglas-fir, expression--are the cumulative product of its genetic potential and environmental influences. Since the underlying objective of plus tree cruising is the selection of phenotypes which have the greatest probability of being superior genotypes, special care must be taken to account for the modifying environmental factors. Indeed, the purpose of check or
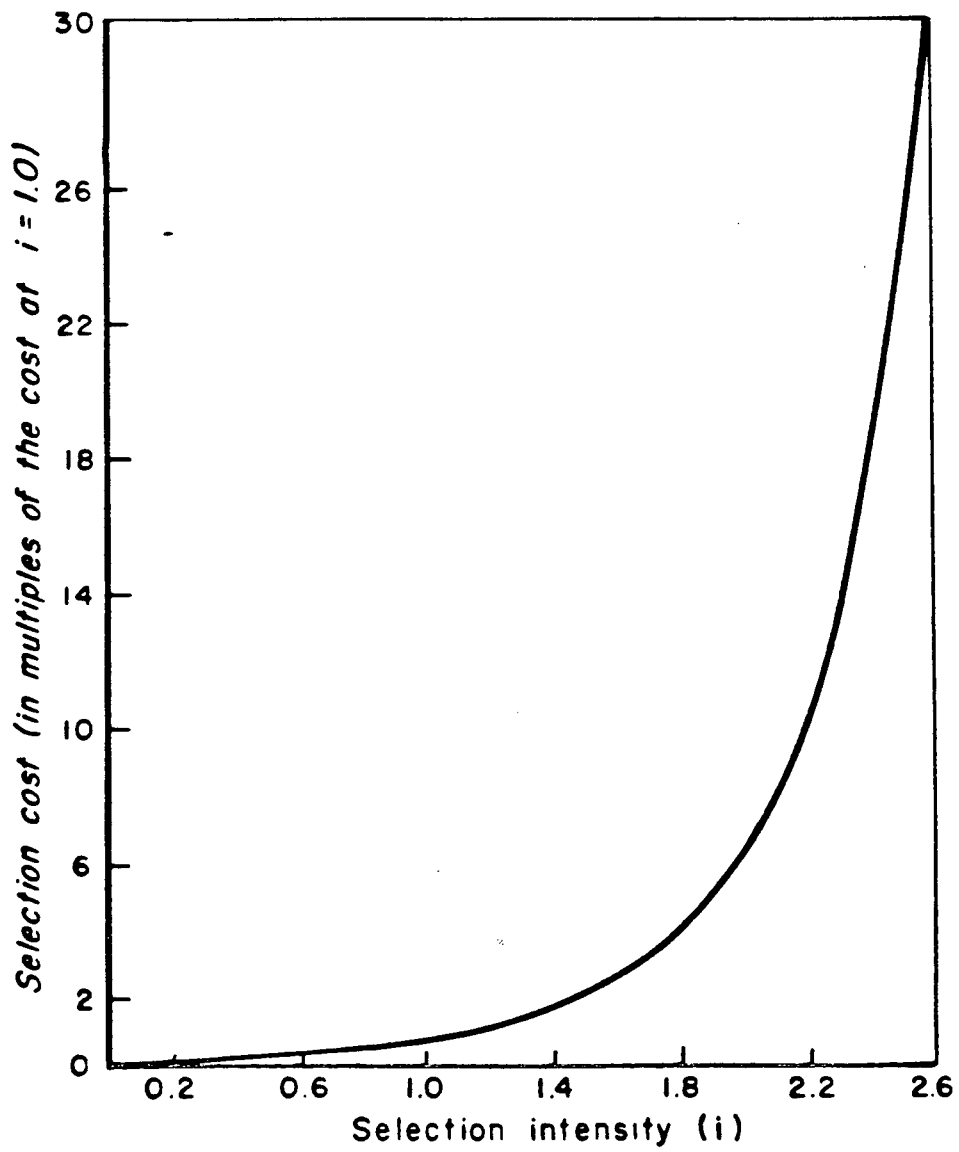
Figure 1. Relative cost increase as a function of
increasing selection intensity.

comparison trees in current procedures is to minimize edaphic or other microsite bias by comparing the growth rates of several trees in a localized environment. (The assumption is that phenotypic trees are more efficient in accumulating resources which are equally available to nearby check trees.) In practice, there is no measure of this assumption. Spacing and microsite differences are not quantified. The effects of variation in age, spacing and other environmental influences may also contribute significantly to differences observed in phenotypic characteristics between candidate trees and other dominant neighbors.

Intraspecific Competition

Competition can be defined as the demand by more than one individual for a limited vital resource. In forest stands distribution of the resource is never even. Although weaker members of the forest community may make more efficient use of those resources they acquire, the large individuals are capable of accumulating a proportionately larger share of the resource (Baskerville, 1965). Unfortunately, competition is not a totally unambiguous concept. Some portion of a tree's competitive status is probably genetic, another portion may be attributed to fortuitous spacing or position in the stand and perhaps other contributions to competitive status are possible.

Foresters have long been aware of the relation between numbers of trees per unit area and growth rates of individual trees. With the recent proliferation of computer simulation models, the mathematical expression of competition as a function of tree parameters and distances or areas occupied has become fashionable. These competition indices have helped increase the sophistication of yield predicting models.

In addition, they call attention to the individual tree and its relation to its neighbors, a characteristic which suggests the possibility of examining the competitive ability of the individual in relation to other members of the population. In view of the requirements for better information as to the position of a particular phenotype in the population when improvement selection intensity is important, the use of competition index as a covariate to volume growth appears to offer a rational, statistical approach to increasing our confidence in the level of improvement selection possible for a given intensity of selection.

Objectives

The objectives of this thesis are:

1. To examine some statistical methods for improving quantitative selection in wild and thinned stands of western hemlock, using existing competition indices as a covariate to growth.

2. To evaluate 70 mm crown photography techniques for estimating growth and to establish a selection procedure based on crown parameters.

3. To evaluate, a posteriori, phenotypically selected western hemlock plus trees with respect to growth and crown parameters.

4. To suggest operational plus tree selection guidelines to incorporate the findings of this study.

With detailed information on permanent sample plots it is possible to examine the relationship between growth rate and competition. The growth rate of the individual is assumed to be genetically controlled. The competition level is assumed to be expressed by an individual. Determination of the superiority is by examination of the statistical structure of the population.

The data for the study consist of re-measurement records for 12 permanent sample plots maintained by MacMillan-Bloedel, Ltd. They

represent both thinned and unthinned second growth stands. These plots were selected to allow a maximum extension of the techniques to field conditions, as many future selections will probably be made in thinned young growth stands. Data for selected plus trees also came from Mac-Millan-Bloedel.

The study is not intensively genetic in nature. Improvements from alternate selection techniques, such as, family selection, tandem selection, etc., are not considered. The primary intent is to examine statistical techniques as possible adjuncts in an intensified single tree selection scheme.

LITERATURE REVIEW

Selection Methods

There are a number of selection methods employed in tree improve-
ment programs. Among them are family selection, tandem selection, clonal
selection and mass or phenotypic selection. All are based on statistical
analysis of components of variance. The first three mentioned systems
are applied to progeny of the original selections. The most important
method used in the initial selection of trees for inclusion in a first
generation seed orchard is phenotypic selection. Present methods of
phenotypic selection in British Columbia, include check tree, parent
tree and roadside selection; all are very low in reliance on statistical
procedures. Although all are dependent on the cruiser's ability to
choose superior phenotypes, the check tree method is relatively less
subjective. All methods are heavily dependent on progeny tests for
estimate of improvement. For this study only the check tree method
is considered further.

As practiced in coastal British Columbia, check tree cruising in-
volves the subjective identification of a candidate followed by measure-
ment of specific characteristics of the candidate and nearby dominant
trees. For example, heights and diameter may be obtained. In the
simplest case, measurements are compared with the mean of two dominants.
A candidate which fails to exceed the mean of the check trees by a speci-
fied amount is not included in the improvement program. This amounts
to evaluating the selection differential between the candidate and two
of its neighbors.

The check tree method attempts to correct for the influence of local environment in the selection of plus trees. Instead of determining the mean for the population and comparing the candidate to that standard, the phenotype is compared to the mean of several nearby dominant trees. Figure (2) illustrates the statistical basis of this selection procedure. Unfortunately, the mean of the dominants with respect to the population is not known and so intensity of the selection is not known. Indeed, intensity is used in an ambiguous manner. If the estimated number of trees in an area reviewed is 1,000 per each selection then an intensity of one in a thousand is quoted. Figure (3) illustrates the case where the selection differential is made with respect to the mean of the population and is the intensity as described in equation (1). This is a more rigorously statistical process.

A model of the selection can be written:

$$y = m + k \quad * \quad (s) \tag{2}$$

Where y = value of the measured characteristic; m = mean for the population; s = sample standard deviation; and k = a constant. The constant k is the studentized score for the observation. The equation may be re-written in the form:

$$k = (y - m)/s \tag{3}$$

The constant k is analogous to i in equation 1.

Ledig (1974) discussed the possibility that the comparison dominants are related to the candidate tree. If they are, the probability of rejecting superior trees is increased significantly. The mean for relatives might be expected to be well above the mean for unrelated trees. Ledig further indicates that a baseline regression technique may well avoid this problem.
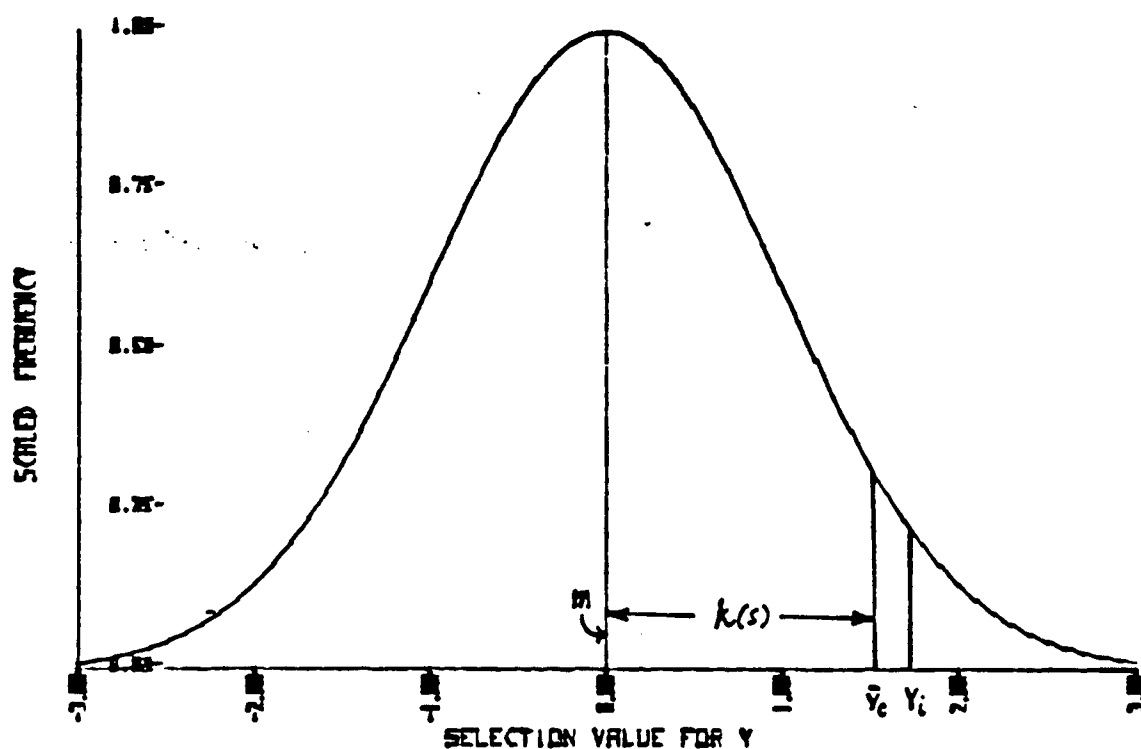
Figure 2.   Mean value (Ȳc) for check trees compared to mean (m)
            of sample population in a frequency distribution;
            k(s) is unknown.
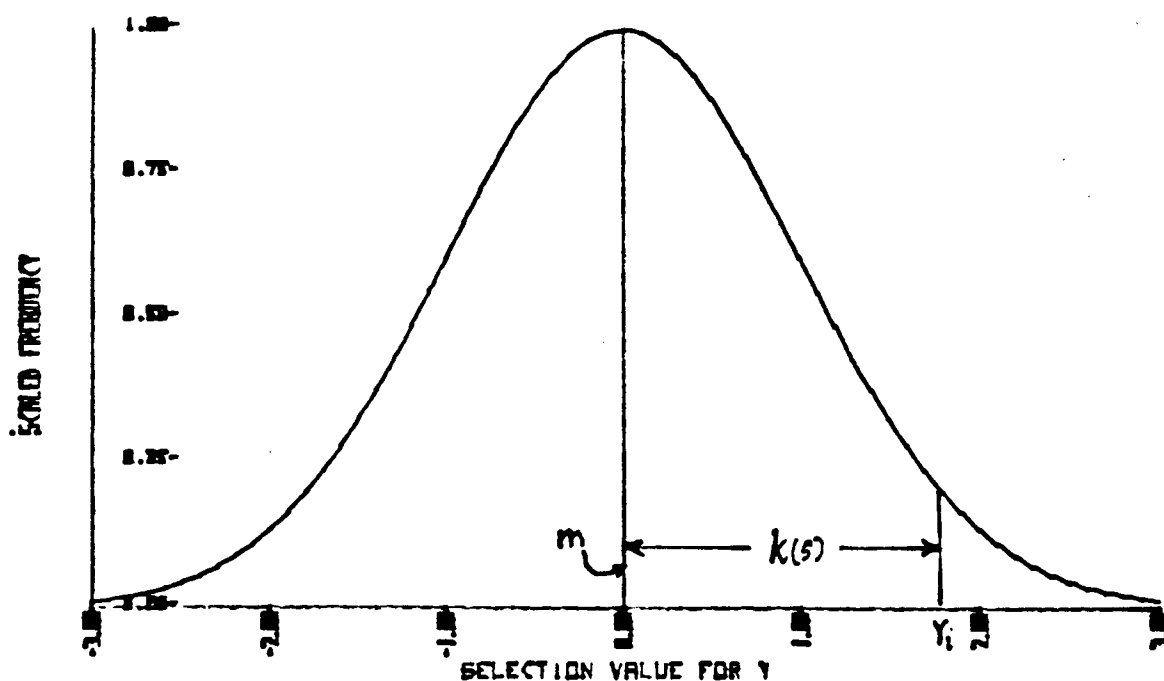
Figure 3.   Selection differential in a frequency distribution
            of sample population; k(s) is estimated for sample.

Intensive Initial Selection

There is a reasonable precedent for using statistical methods in processing plus tree cruise data. Brown and Goddard (1961) emphasized growth and crown relationships in their selection program for the southern pines. They used a regression equation, determined from 10 dominants and codominants as a baseline for individual tree volumes. Superior growth efficiency was identified by a positive residual of a selection candidate compared to the regression line. The authors noted that if the same amount of wood can be produced on the bole by slimmer, more efficient crowns, then production of more wood per acre is possible.

Final selection was not based solely on the growth efficiency. Several characteristics were measured and given weight in a final selection scheme. Still the efficiency was a key portion of the initial selection program.

Campbell[1] selected Douglas-fir plus trees in the mid-1960's for Weyerhaeuser Company by relating growth rate to a measure of present live crown extension and the length of dead branch stubs.

In effect, the technique was an indirect evaluation of past inter-tree competition since weight was given to a subject with narrow, live crown and short, dead branches. Progeny tests of height growth at age four from these selections and from phenotypically selected trees showed a superiority of the competition selected trees. Recently, Weyerhaeuser has developed a regression method for selection of both Douglas-fir and western hemlock. An equation is produced for each selection plot. It includes growth of competing and subject trees. The predicted growth of the subject tree is compared to the regression line prediction.

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[1]Personal communication, 1977.

The Weyerhauser Method has been the subject of some controversy, but clearly reflects the concern of this thesis.

Robinson and van Buijtenen (1971) used a summation of multi-trait, weighted scores to select Pinus taeda (L.) plus trees. Among the variables were growth efficiency (crown area/dbh), dry matter (volume x specific gravity) and form. Regression equations were used to establish a check tree volume baseline. Expected volumes for each plus tree candidate were then compared to the actual volume and large positive residual used to assess efficiency of growth. Regressions were calculated based on height, age, and crown measurements. As the baseline data was accumulated over a period of time, the number of check trees per selection declined. The authors concluded that their regression only method was most applicable when check trees were more widely scattered and stand density was low. In these cases, few if any check trees are measured. In dense stands check trees were still measured and individual regressions used as the baseline.

Competition

Competition, as used in this study, is defined as the active demand by two or more organisms for a common resource. Competition is commonly classified as either interspecific or intraspecific (Kormondy, 1969). While the former is of importance in the establishment of regeneration or managing mixed stands, for this study intraspecific competition is considered most important. A complete model of competition would include light, moisture, nutrients and environmental influences in a dynamic manner. The competition considered here exists when available resources are reduced below an optimal level for individual tree growth. The causes of reduced growth (lack of sufficient resources) are dependent

on the number of competing individuals and the amounts and distribution of resources. The effects of competition are reduced growth. Current attempts to quantify competition depend on observation of effects. They include measurements of spatial distributions of trees in two dimensions and measures of size of individuals. Regardless of claims by modellers current indices are measures of past effects of competition. Most of the indices are concerned with on the ground location of the stems. Ground spatial measures of competition may be divided into several categories, among them stand density, point density and single tree, distance dependent expressions.

Stand density measures have been reviewed by Curtis (1970). Reineke's (1933) stand density index and Chisman and Schumacher's (1940) tree area ratio (TAR) are examples. These measures express site occupation as a proportion of normal or open-grown stand conditions for a species. Many of these may be reduced to linear combinations of variables ex-. pressing occupation in terms of diameter square sums. Since they represent stand averages and not the individual case, they are not useful in the investigations of individual tree response to competition.

Point density measures attempt to express stand density at a point. Basal area prisms and angle gauges have commonly been used to arrive at expressions of point density. Spurr's (1962) index is an example of this genre, yet it has some shortcomings for direct application. Competition (and, therefore, zone of influence) does not extend indefinitely about the individual. Its extent varies with age, size, and species among other variables. Computation of point density for an individual tree is, therefore, not strictly defined mathematically. As there is no clear definition of the extent of the zone of influence

for individual trees, so too, there is more ambiguity as to the boundary of plots.

Attempts to determine the competitive status of individual trees include available growing space defined by polygons. First described by Brown (1965) this geometrical spatial index takes account of irregularities in spatial distribution of stems. More recent attempts to describe growing space and competition have been made by several authors (Jack, 1967; Adlard, 1974; and Fraser, 1977). Analysis of periodic annual increment using a polygon spacing index and basal area gave good regression equations for predicting periodic growth. But the index contributed significantly to only 4 of the 10 plot models (Adlard, Table 1); diameter or basal area were the main contributors to prediction of growth.

One of the possible limits to the use of current competition indices concerns the variables used to define them. Distances between individual plants is an extrinsic variable (i.e., is not a measure on the individual itself), which describes irregularities in spacing. Zone area or polygon area are intrinsic, determined by the diameter and/or height of the tree. These intrinsic variables reflect the effects of competition, even if they are disguised in the form of open-grown crown extent (a function of diameter and height). That the competition between trees for growth requirements exists is beyond doubt. There is considerable vagueness about the exact nature of interactions. There are a large number of variables which seem to be relevant to an expression of competion. There is also a good deal of ambiguity in the assessment of the causes and the effects of competition.

Competition Indices

The single-tree, distance-dependent indices of competition have undergone rapid development paralleling their application in various computer simulation models. These indices generally relate zones of influence of individual trees to the physical area occupied by open grown trees of similar diameter or volume. Competition load on a given tree is then estimated as a ratio of space available to the predicted, open-grown space. As these indices relate to individual trees they are obviously candidates to expressing the differences in competition between trees. Figure 4 is a composite representation of the following indices.

Arney's (1971) index for Douglas-fir represents competition as the relative occupation of a subject tree's growing space. The growing space for each tree is defined as the expected size of an open-grown tree of equal diameter. The relationship between open-grown crown width and DBH was used to determine the maximum growing space or zone of influence for a tree. The index is expressed:

$$CSI_j = 100 * \sum \left(\frac{AO_{ij} + A_j}{A_j} \right) \qquad (4)$$

where A_j represents the open-grown area for the subject and AO_{ij} the area of overlap of the ith competitor with the jth subject tree. Arney denoted this a percentage overlap. This may be slightly misleading in that a 0 to 100% scale is not obtained, rather it is a scale of 100(%) minimum with undefined upper limit.

Bella (1970) developed a model of competition which expresses the relationship between subject and competitor by an exponential function.
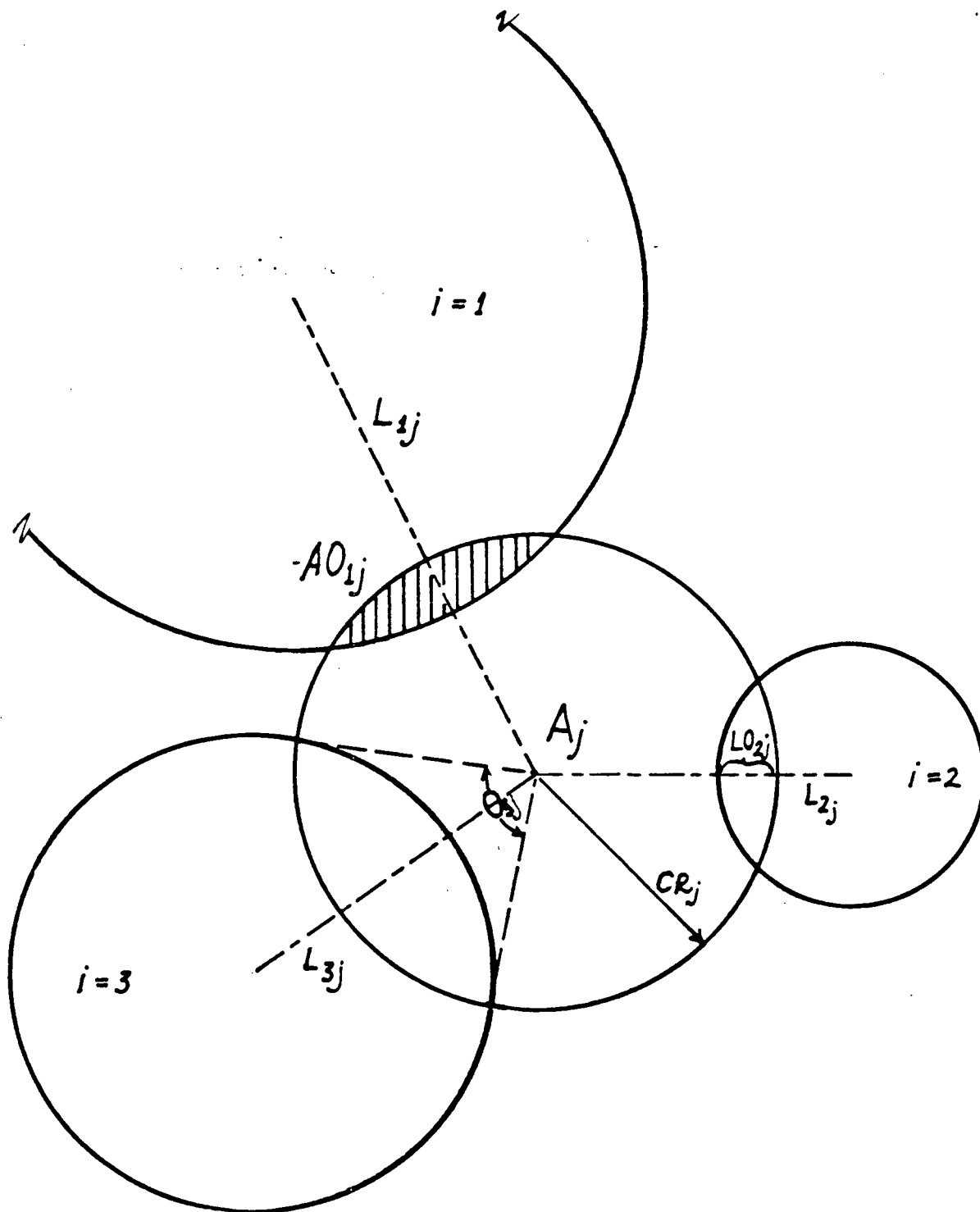
Figure 4. Parameters of competition Indices.
where: A = area of influence, CR = Crown radius of
an open grown tree, AO = area or Zone overlap, Lij =
distance between stems, i = competitor, j = subject
θij = sector angle, LOij = linear overlap.

Using the findings of Baskerville (1965), Bella modelled the effects of species tolerance by using an exponential weighting of the relative diameters to the growing space overlap. His index is:

$$CI_j = \sum \left[\left(\frac{AO_j}{A_j} \right) * \left(\frac{D_i}{D_j} \right)^{ex} \right] \qquad (5)$$

where D_j is the diameter of the subject tree, D_i is the diameter of the competitor, ex is a weighting parameter determined by an iterative process.

Ek and Monserud (1974) also used a weighting to account for relative tree sizes. However, they included both height and diameter measurement in the determination of the proper weight. This means that the weighting is much more proportional to the volume, but computationally depends on more extensive individual tree data.

$$CI_j = \sum \left(\frac{AO_{ij}}{A_j} * \frac{S_i}{S_j} \right) * \text{tol} \qquad (6)$$

where S_i, S_j express subject and competitor sizes respectively, and tol is a measure of the tolerance of the species.

Hegyi (1974) developed a competition index independent of crown overlap, crown extent. His index was formulated as:

$$CI_j = \sum \left(\frac{D_i}{D_j} * \frac{1}{L_{ij}} \right) \qquad (7)$$

where L_{ij} represents the distance between the ith subject and the jth competitor. Although this appears simplistic by comparison to some of the other indices, in combination with a simulation program it performs quite well and is not computationally expensive. The assumption

of linearity in the competitive ability of trees of different sizes may be quite adequate to represent the situation in even-aged stands and well managed plantations. The advantages of few measurements and few calculations in the application of this index make it attractive.

Lin's (1969) index is somewhat different from the preceding indices. The area about an individual tree is divided into quadrants. Each quadrant is assigned one quarter of the total growing space for the subject. A maximum of one competitor per quadrant is evaluated in the computation of each tree's index. The range of this index is 0 to 100% and indicates the amount of space available to the subject rather than the amount of reduction. This is a true percentage scale. Competitors are selected in each quadrant in a manner similar to the selection of trees by a basal area prism. The tree in each quadrant which subtends the largest angle at the subject tree is chosen as the competitor for that quadrant. Lin's index is:

$$GSI_j = \sum_{i=1}^{4} \left(25 - \theta_i - 2.15 \ * \ 0.3467 \ * \ \frac{D_i + D_j}{D_j} \right) \quad (8)$$

where θ_i is the observed angle, 2.15 is the minimum angle for competition to exist.

Newnham (1964) used an angular measure to define the competition between trees. His model assumed that crown interactions at the periphery reflected the intensity of competition. His index is formulated as follows:

$$CI_j = \frac{1}{2\pi} \sum \left(\theta_{ij} \ * \ \frac{CW_i}{CW_j} \right) \quad (9)$$

where θ_{ij} is the interior angle subtended in the jth subject's expected circle of competition by the intersection of the ith competitor's circle of influence.

Quenet (1976) used an index which is independent of the size of the subject tree. As with some early indices this one does not limit the distance to a competitor expressly. It is calculated:

$$CI_j = \sum \left(\frac{Di}{Lij} \right) \qquad (10)$$

where all symbols are as previously defined.

The final index which was considered was Staebler's (1951). In this model the linear overlap of growing space along circle radii was used to express the competition between trees.

$$CI_j = \sum \left(\frac{LOij}{2Ri} \right) \qquad (11)$$

where LOij is the linear over lap and Ri is the radius of the competition circle based on open grown crown width.

These were the indices which were computed for each tree at Turnour Island. There was no information on individual heights so that a height-diameter relation was used to generate S_{ij} for trees in the Ek-Monserud model. At the time of generation no iterative evaluations of exponent was made on the Bella index. These compromises were conceded to be the best in the time available.

Comparisons of the performance of competition indices are few. In their respective simulation environments each has proven itself adaptable to the goal of the modeler. Only Staebler's among these indices

was specifically designed to stand alone. Most of them rest on earlier formulations of ecological dispersion or research relating the performance of individual trees under a variety of thinning, spacing, fertilization and mortality regimes. The majority are based on the concept of a limiting competition circle or area described mathematically by intrinsic measures of the current tree size and extrinsic distances between individuals.

Most of the indices (ex. Lin's and Newnham's) are mathematically limited at the low end, but the upper end is undefined. Lin's index is a percentage index and functions inversely with respect to all the other indices. As previously mentioned Arney's index is termed a percentage index, but is not. Another of the indices which has definable mathematical characteristics is Newnham's. This index is limited in the open grown case to 0 and in the maximum would approach 4. This can be visualized by imagining a small tree surrounded by four larger trees growing in a very nearly square pattern each overlapping its growing space completely. More overlap is impossible in that the competitors would begin overlapping each other more than would be consistent with their own size! The exception in two storied stands accounts for possible larger values. (Only three observations had a value greater than 4 at Turnour Island.)

Three studies comparing competition index performance are cited in the literature. Beck (1974) used a model expressing 5-year diameter growth $(\ln(DG + 1))$ as a function of site index, age, diameter and one of four competition expressions; (1) basal area obtained by use of an angle gauge, (2) plot basal area, (3) Gerrard's (1969) competition quo-

tient and (4) Bella's competition index. Gerrard's index proved the
most valuable addition to common terms. Bella's index was not far
different with added R^2 = 12.4% compared to 14.3%. Newnham and Mucha
(1971) reviewed a wider selection of the competition indices. Bella's
index was selected as the best for predicting diameter growth with the
reservation that it underestimated mortality and was complicated to
calculate. In the study both a weighting-factor FC and the adjusting
exponent ex, (refer to Appendix I) were determined by iterative pro-
cedures. A second model selected by the authors included two competi-
tion measures. In a regression model both linear overlap and angular
overlap were included. These were the indices of Staebler and Newnham.
The authors conclude that the selection of predictive models using
competition indices are still subjective. And, until considerable
understanding of the biological mechanics (sic) of competition among
trees is accumulated decisions will remain subjective.

Daniels' (1976) compared the performance of three of the competi-
tion indices, those of Arney, Ek-Monserud and Hegyi. A modified com-
petitor selection technique - using a 10 BAF rule, the same as the one
used for selecting competition in this thesis - was described. The
three indices plus six modifications of Hegyi's index were correlated
with diameter increment and height increment. Ek-Monserud's index had
the highest correlation with diameter increment though the modified
Hegyi's index was little different (-0.424 versus -0.415). Hegyi's
index did surprisingly better in height increment correlation (-0.456
versus -0.276). Unfortunately the note does not indicate the time
interval involved in calculating increment. The author also chooses

to correlate competition and diameter increment which fails to account for the purely geometric decline in radial growth under constant basal area expansion. Daniels' indicates his belief that Hegyis' index is independent of species and has an advantage in computational simplicity. He indicates further that it may find utility as a measure of point density.

Crown Competition

The crown is the center of the tree's physiological activity. Photosynthesis, respiration, and metabolism are most important in the crown. The rate of production of metabolic products is certainly genetically influenced and has become the center of some attention in genetic improvement studies (Ledig, 1975).

Understanding basic biological production processes is important to understanding crown function. Nevertheless, simple qualitative observations indicate the importance of the crown to the success of the individual tree. The social position of the crowns of trees in the development of stands have long been noted in their progression from codominant to intermediate to suppressed and finally mortality. More precise measurement of the status of the crown with respect to its neighbors could supply valuable information concerning the growth, competition or ultimate decline of individual stems. Assmann (1970) devotes a large portion of his book to the description of crown relations. The role of the crown as a tool of aggression in the competition for light and space is treated extensively. Theoretical spatial requirements of circular crowns are discussed. Forms and geometrical shapes are described as they may relate to growth. Most important for a study in the selection of superior trees, Assmann notes the necessity of

considering the efficiency of individual crowns for production of wood. It seems evident that trees may occupy the same amount of space in a stand and produce different amounts of wood. If crown form or efficiency is genetically determined as is demonstrated for certain races of Scots pine (Pinus sylvestris, L.), this should be a character of interest in tree improvement (Assmann, 1970).

Crown competition has also been recognized by practicing foresters and is often the basis for making silvicultural prescriptions (Assmann, 1970). Naturally, crown competition has developed as a tool among computer model builders (Mitchell, 1975a). Osborn (1968) found that ratios of crown width and live crown length to total tree height provided the best measure of density in western hemlock stands aged 45 to 160 years. However, these variables proved relatively poor in explaining 5-year radial and basal area growth in his study.

Hatch et al. (1975) developed an individual tree competition model based on the crown surface area exposed to sunlight and the distance from breast height to the base of the live crown. The model measures the relative competitiveness of the subject tree and predicts its relative growth potential rather than calculating the competitive pressure exerted on the subject by surrounding trees as in most other models.

Both Osborne and Hatch and coworkers assumed that crown form is symmetrical and conical. In reality, crown shapes are typically asymmetrical; the degree of crown deformation appears closely related to size and distance from competitors. Furthermore, a review of crown shape by Assmann (1970) revealed that a variety of species had parabolic or spherical rather than conic crowns. Mitchell (1975a) reached similar

conclusions for Douglas-fir, even for open growth trees under no com-
petition. His simulation model treats growing space at the individual
branch level, thus incorporating realistic variation in crown dimension.
In addition, the model considers foliage retention and volumes. This
model has demonstrated the viability of crown characteristics as pre-
dictors of individual tree growth.

The profound influence of crown size, shape and position in the
stand on diameter growth are well recognized by the practical forester.
The correlation between height growth and crown class is also obvious.
Mitchell (1975a) has illustrated the relation of potential to achieved
height growth for the range of crown classes of Douglas-fir (Figure
5).

Other recent studies have cast doubt on the wisdom of accepting
prima facia the forestry dictum which indicates that height growth
is not affected by density or competition. Curtis and Reukema (1970)
observed mean top height differences of sufficient magnitude to warrant
re-evaluation of site index in Douglas fir. The studies indicated
that changes in site index between ages 5 and 35 were associated with
establishment densities and could not be accounted for by soils or
topographic differences. Differences in apparent site index were attri-
buted principally to effects of differing intensity of competition on
height growth of dominant and codominant trees. Husch et al. (1972
p.353-354) also notes height-density dependence in some species.

Crown variables offer a functional relation to the growth of indi-
vidual trees. It might even be expected that a future development of
physiological information as to biological efficiency of needles or
needle retention times could be added directly to models of individual

crowns. This approach has an advantage over a strictly mathmatical model in that the new information may be incorporated in the model without returning to basic model building and evaluation.
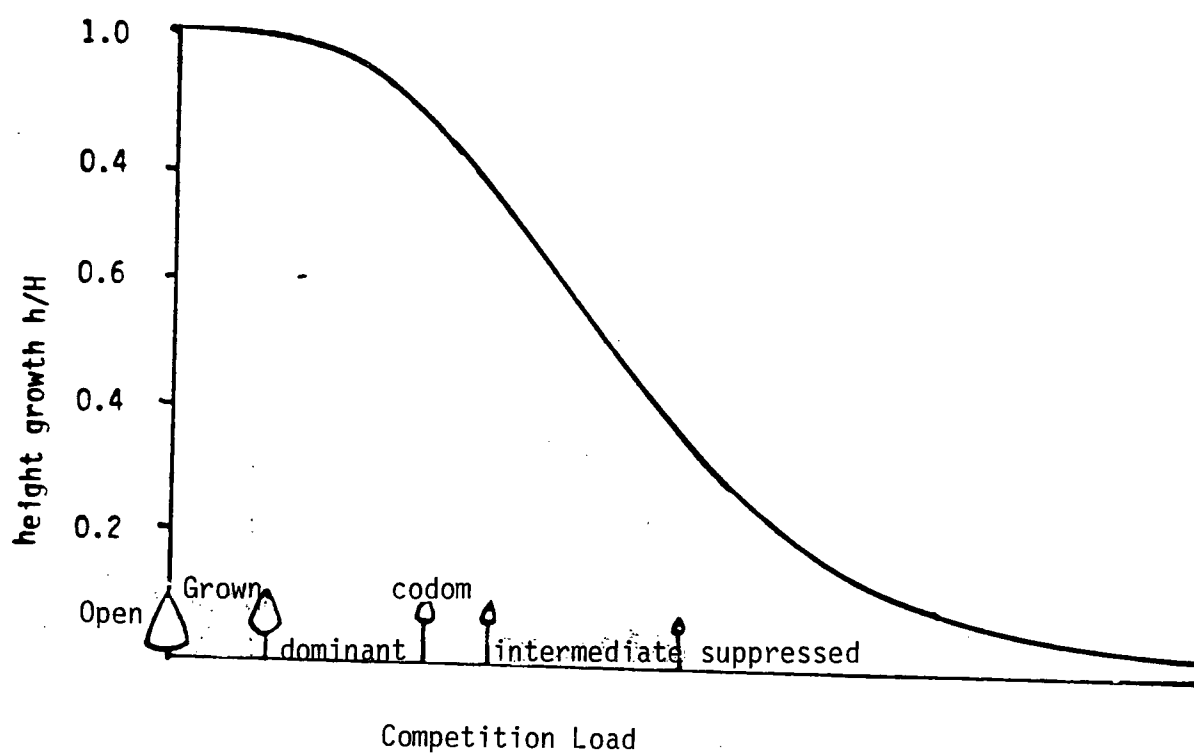
Competition Load

where h = height of individual tree and H = height of
an open grown tree, and tree ideograms indicate
the upper limit of an indicated crown class.

Figure 5.   (Adapted from Mitchell 1975a)
    The effect of competition for growing space on
        height growth.

MATERIALS AND METHODS

This study had as a goal (objective number 1) intensive modelling of growth, competition, and (indirectly) genetics of individual trees on permanent sample plots. In addition, it was hoped to extend the work to existing plus trees and to develop field methods for future selections. MacMillan-Bloedel, Ltd., has many permanent sample plots with growth records for 20 years or more. There were also in existence a number of phenotypically chosen plus trees cruised by the company's personnel over the years. It was decided that the first tests would be done with the selected sample plots of nearly pure western hemlock. Initial model results were to be applied to the phenotypic selections. The study was contracted to MacMillan-Bloedel, Ltd. by the Canadian Forestry Service under a scientific subvention.

Permanent Sample Plots

Permanent sample plots located on Turnour Island (Figures 6 and 7) were chosen as the basis for this study because of their age, uniformity of site and the length of recorded data available. Two plots were established in 1932, the remainder in 1949 and 1950. At establishment they were well-stocked, predominantly young western hemlock. The stands have been measured at five-year intervals and stem maps were constructed for all the plots at or shortly after plot establishment. The plots were divided for analysis into three groups by age and location:
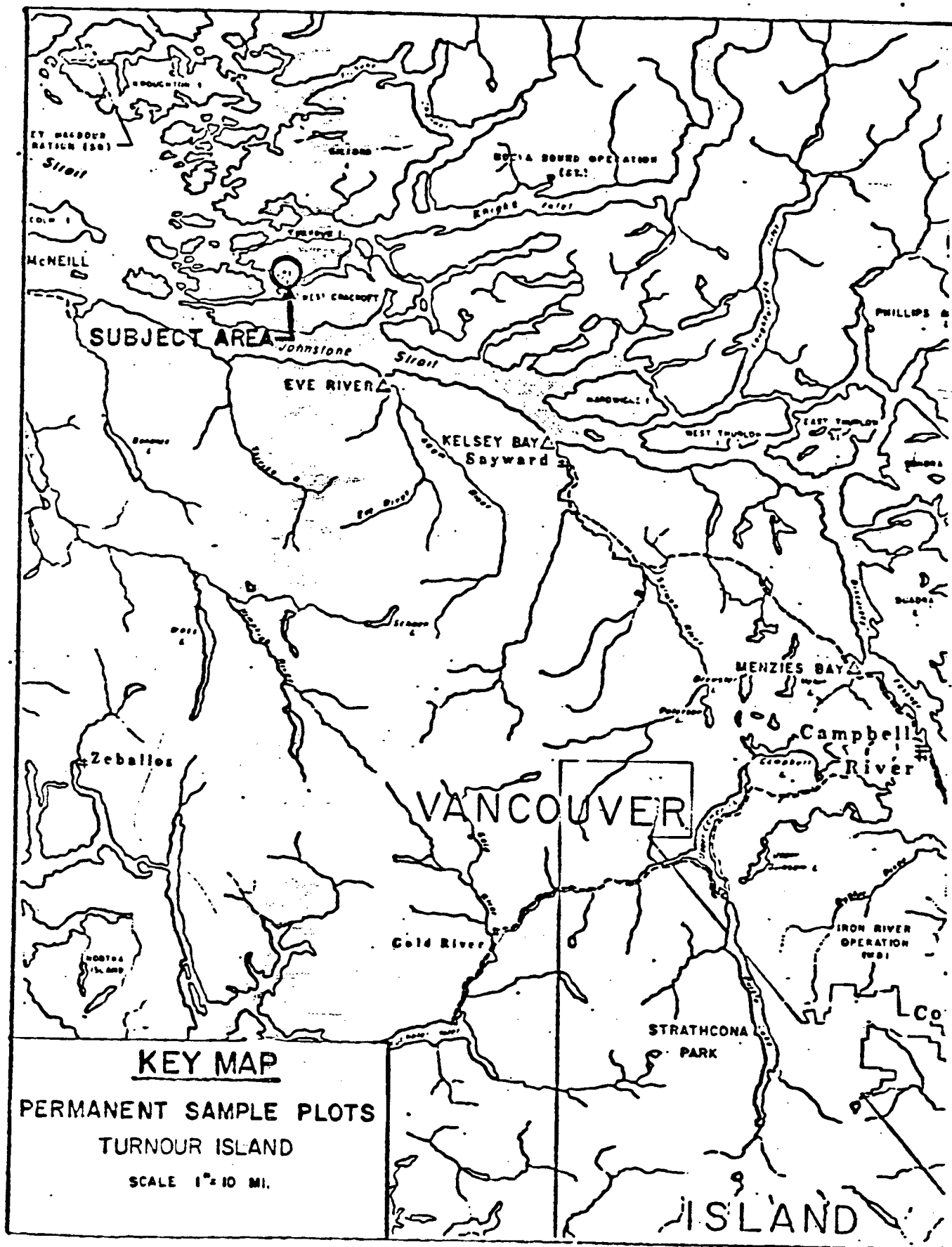
Figure 6.

LOCATION OF STUDY PLOTS

Location of Turnour Island and permanent sample plots
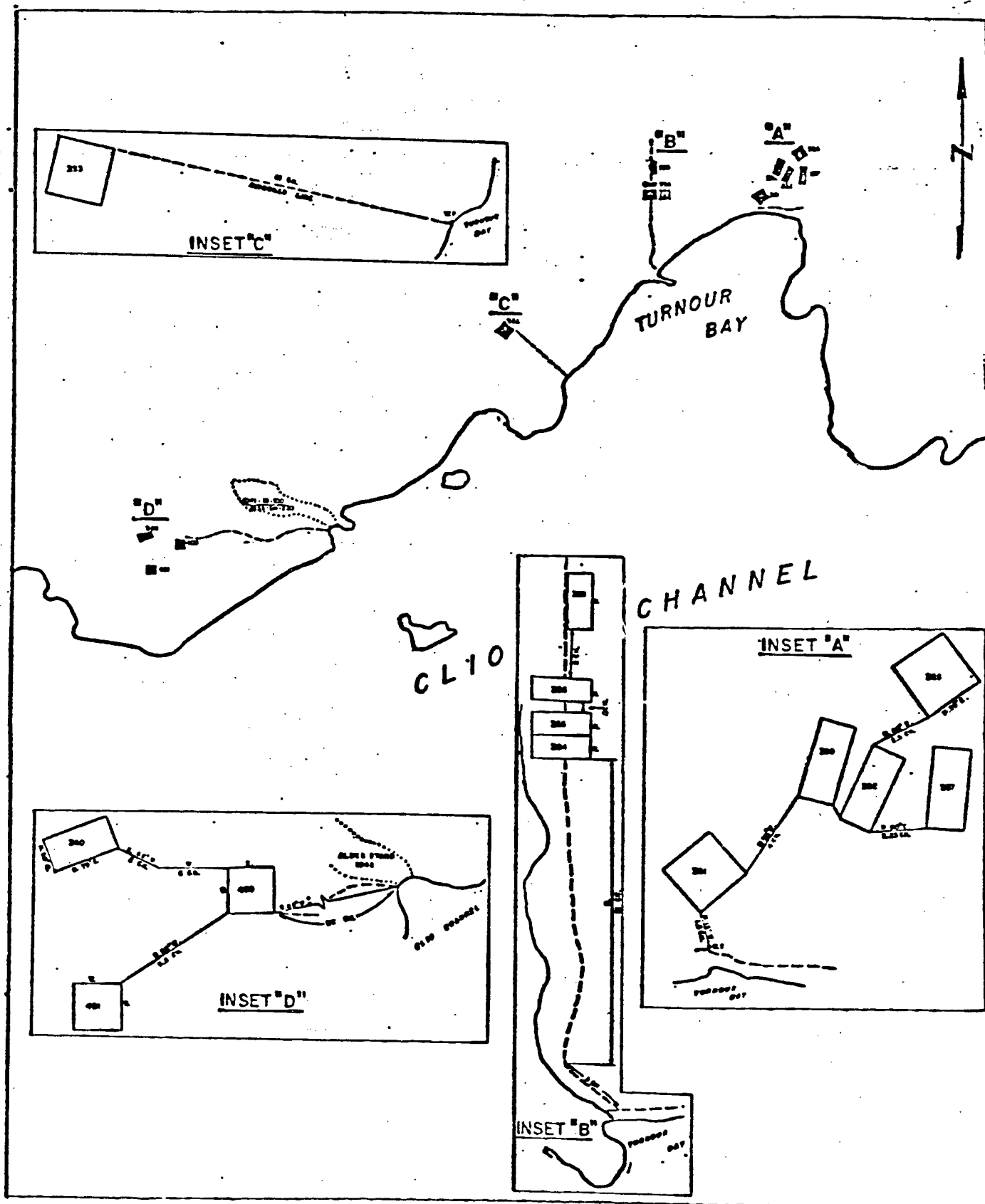
Figure 7.

DETAIL OF PLOT DISTRIBUTION

<u>Group I</u>

Breast height age 60 - 65, located near Turnour Bay tidal flats. All but one plot have been thinned at least once since 1950. They are plots 350, 351, 352, 357, (all thinned), 358 (unthinned).

<u>Group II</u>

Breast height age 45 - 50, located parallel to a single drainage, plots 354 and 359 (thinned), 355 (lightly thinned), and 356 (unthinned).

<u>Group III</u>

Breast height age 80 - 100. These stands contained a larger proportion of other species, (age of the plot is indicated in parenthes): plots 353 (80), 400 (100), and 401 (100) (all thinned).

A summary for the plots based on the original plot and an internal buffered subplot is presented in Table (1). (See table & notes.)

<u>Computation of Indices</u>

Eight distance-dependent, inter-tree competition indices were selected for this study on the basis of their high potential for application in operation, growth prediction systems in British Columbia (Hegyi, 1975, Glew, et al., 1976). The indices were computed for trees lying within a buffered region of each plot. Computational algorithms were modified and programmed by Hegyi and Oxtoby (1976). Mitchell's model (1975a) seemed to be the most realistic of those emphasizing crown competition. His concepts were used to test western hemlock plus tree selection criteria based on crown photography.

Distribution histograms of frequency versus competition index were plotted in an attempt to understand more precisely the ranges of competition values for each index. For some of the indices theoretical limits could be calculated or estimated as was discussed in the literature

TABLE 1. DATA SUMMARY FOR PURE STANDS OF WESTERN HEMLOCK AT
TURNOUR ISLAND

Plot #	Year Thinned	Original Stems	Current Stems	Total Area AC	Density St/Ac	Buffered Area AC	Density St/Ac
GROUP I							
350	50,65	340	145	.5	290	.30	306
351	'50	303	109	.5	218	.30	194
352	'59	376	127	.5	254	.30	213
357	'50	281	160	.5	320	.30	233
358	'55	367	190	.5	360	.31	403
GROUP II							
354	'59	434	159	.26	577	.16	462
355	'59	485	195	.26	750	.16	775
356		418	225	.26	865	.11	755
359	'54	425	100	.26	384	.13	377

TABLE 1. DATE SUMMARY FOR PURE STANDS OF WESTERN HEMLOCK AT
TURNOUR ISLAND (CONTINUED)

PLOT #	DIAMETER INCHES MEAN (SD)	BASAL AREA Square-feet MEAN (SD) X100	BUFFERED AREA BA / AC
GROUP I			
350	12.0(4.06)	88.3(58.9)	270
351	14.8(3.70)	127.0(64.4)	240
352	15.8(4.30)	146.0(76.6)	311
357	13.5(4.06)	108.0(63.3)	251
358	11.6(3.92)	81.5(56.4)	328
GROUP II			
354	9.97(2.72)	56.3(30.5)	260
355	7.73(2.88)	37.1(29.5)	288
356	7.74(2.90)	37.2(28.9)	281
359	11.2 (3.61)	76.9(50.7)	286

review. Graphing the relationship allows us to identify extreme values and detect discontinuities if they should exist for an index. Figure 8(a-h) illustrates the results of graphing all 8 indices.

Additional Data Collection

In early June 1976 the plots were visited by experienced plus tree cruisers of MacMillan-Bloedel Ltd. and phenotypic selections on each plot were made. The trees were selected using procedures as close to operational techniques as possible given that trees on the plot were to be selected. These were to be compared with trees selected later by computed models. Thinned plots were included in the study since many existing, thinned stands are suitable for plus tree selection.

In addition, 25 trees were selected using an estimation of competition computed by MacMillan-Bloedel's hemlock simulator (Company proprietary). Stem distributions were field checked and errors corrected on stem maps. Ground measurements of crown area projection (CPRO) were made on the phenotypic trees.

The phenotypic trees were climbed and marked for identification in aerial photographs. Breast height increment cores and some additional upper stem cores were obtained and plot record diameters and ages were verified. The cores were sent first to Dr. R. W. Kellogg at Western Forest Products Laboratory of the Canadian Forestry Service for analysis of specific gravity; the results to be used to determine specific gravity of phenotypes. They were then measured by an Addo-X operator at U.B.C. for radial growth. These measurements were used to cross check the diameter increment recorded on the MacMillan-Bloedel field sheets.
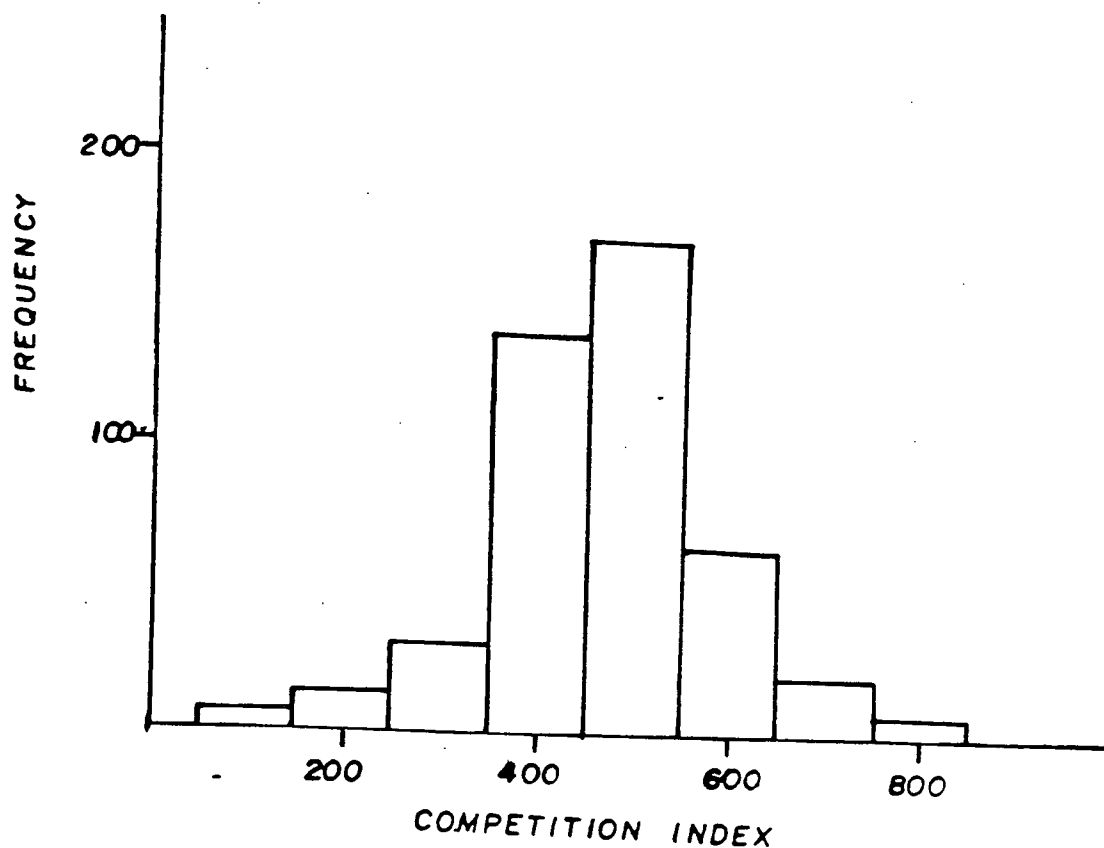
Figure 8a. Frequency distribution of Arney's
Competition Index for all trees on Turnour
Island plots.
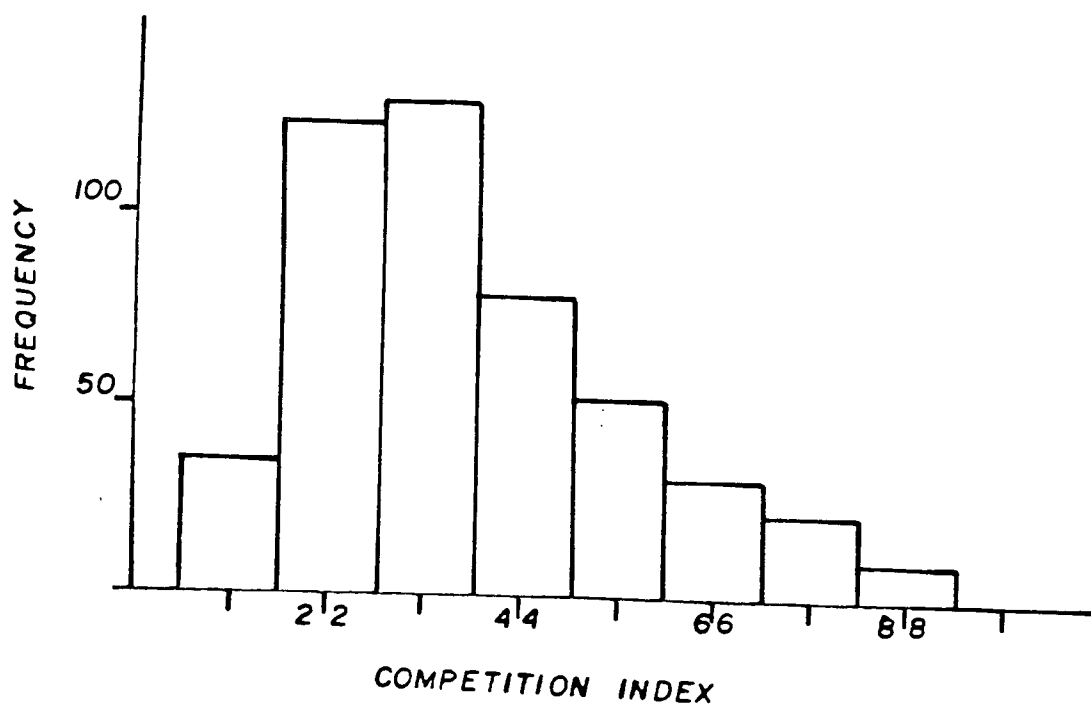
Figure 8b. Frequency distribution of Bella's
Competition Index for all trees on Turnour
Island plots.
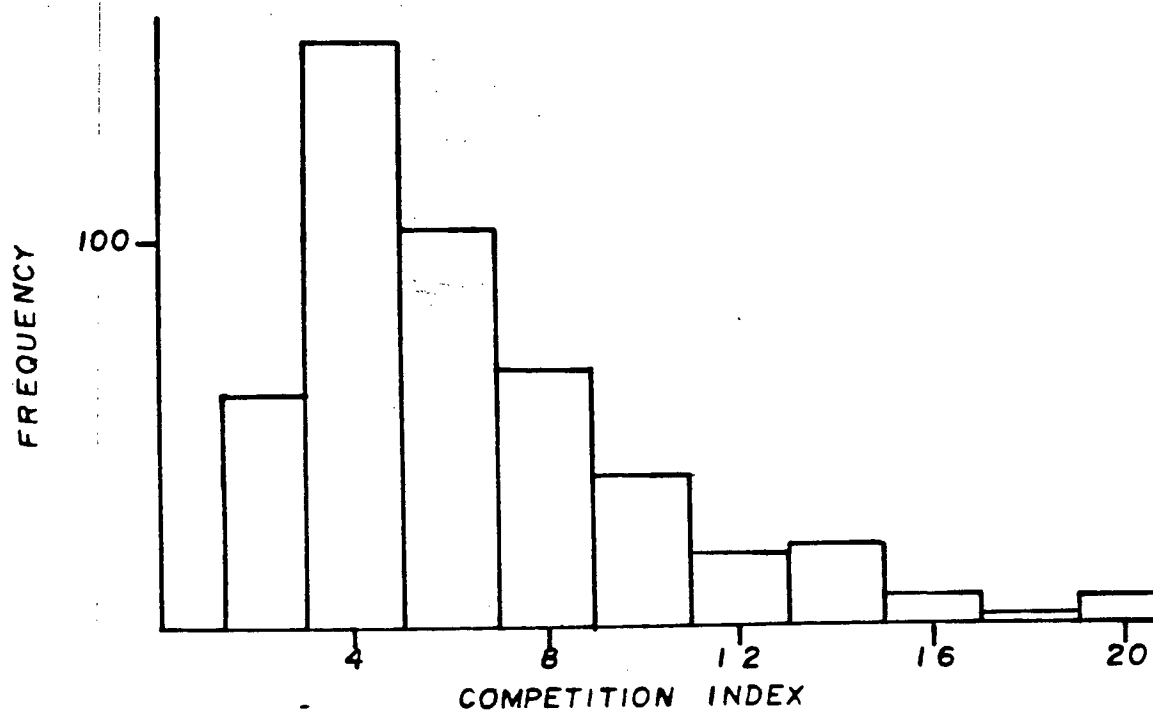
Figure 8c. Frequency distribution of Ek-Monserud's Competition Index for all trees on Turnour Island plots.
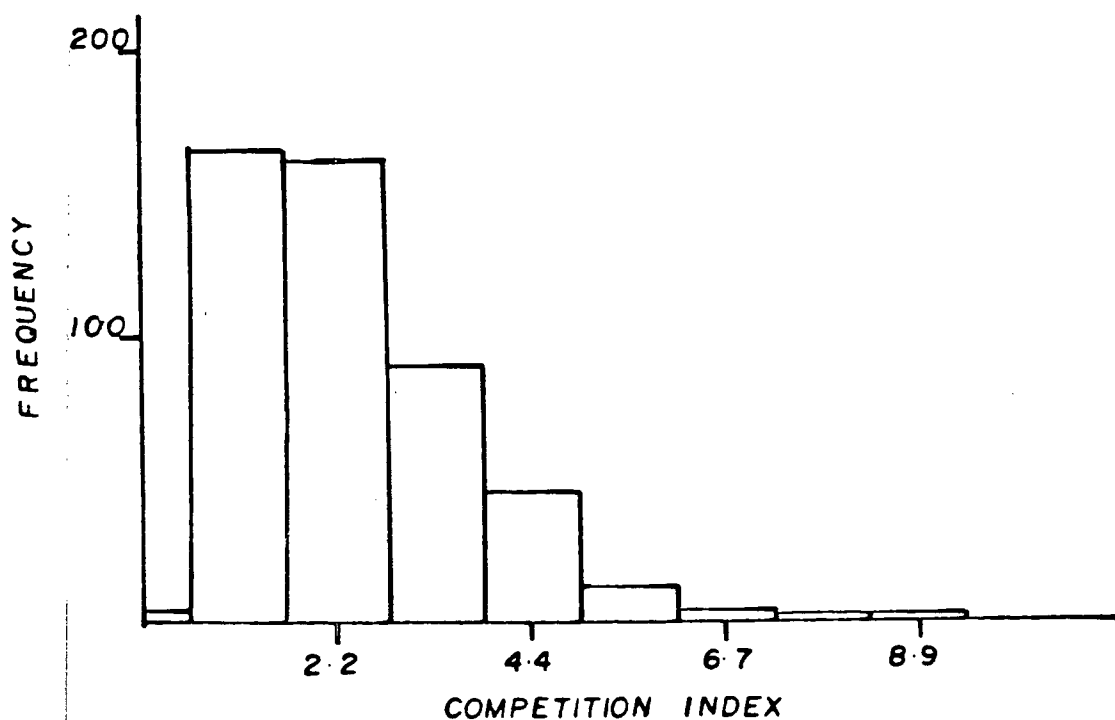
Figure 8d. Frequency distribution of Hegyi's Competition Index for all trees on Turnour Island plots.
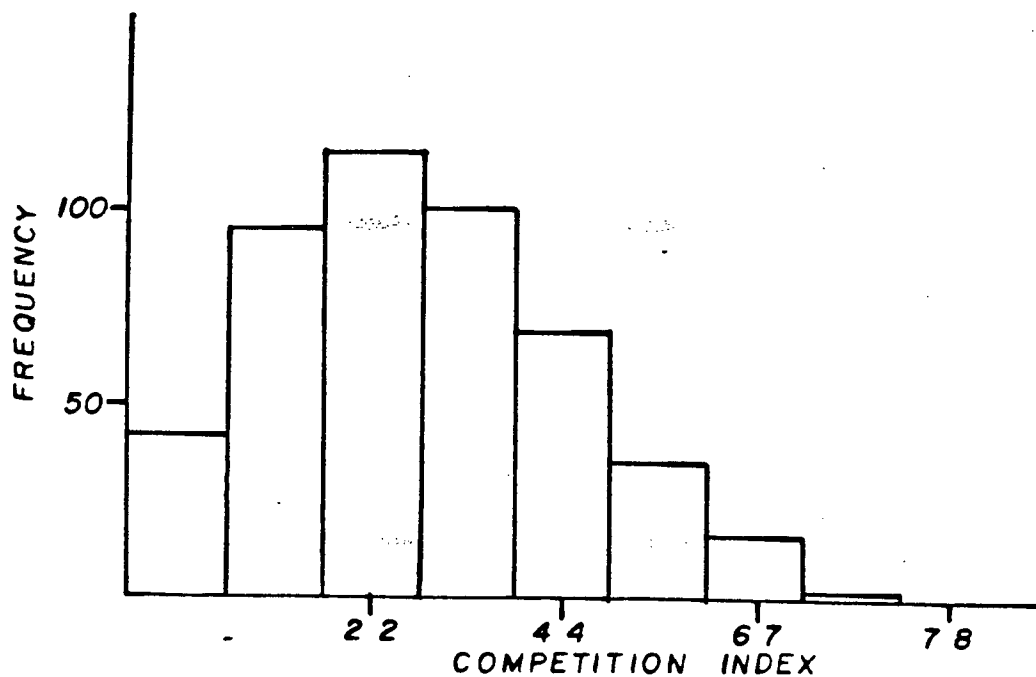
Figure 8e. Frequency distribution of Lin's
Competition Index for all trees on Turnour
Island plots.
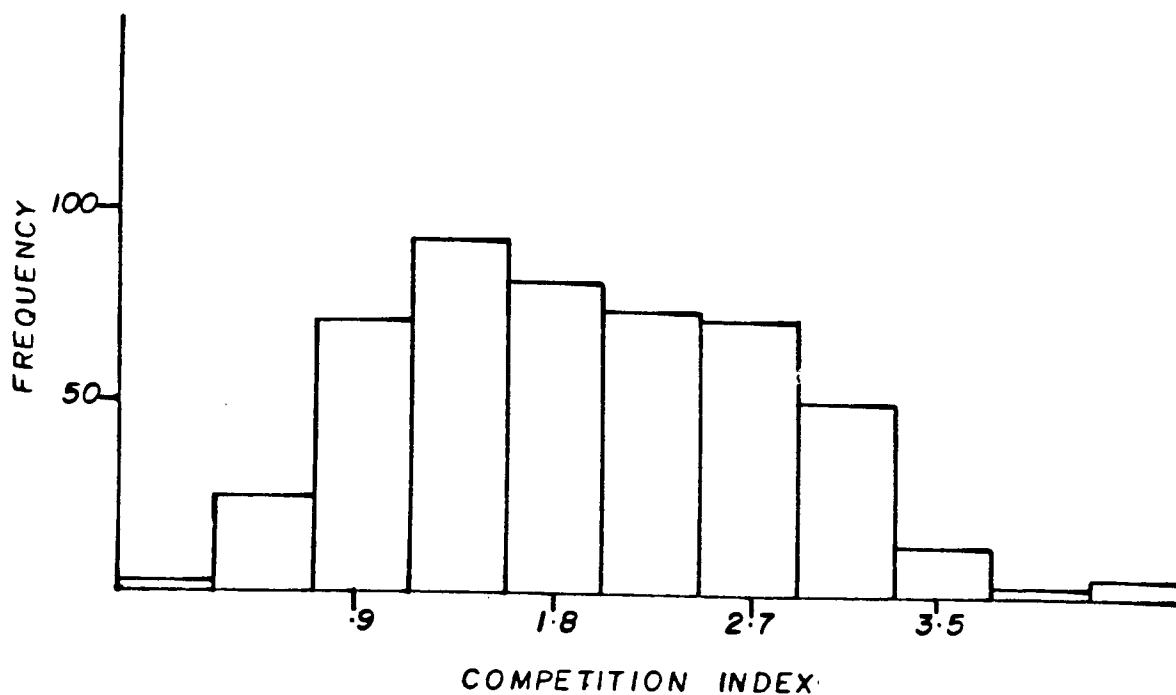
Figure 8f. Frequency distribution of Newnham's
Competition Index for all trees on Turnour
Island plots.
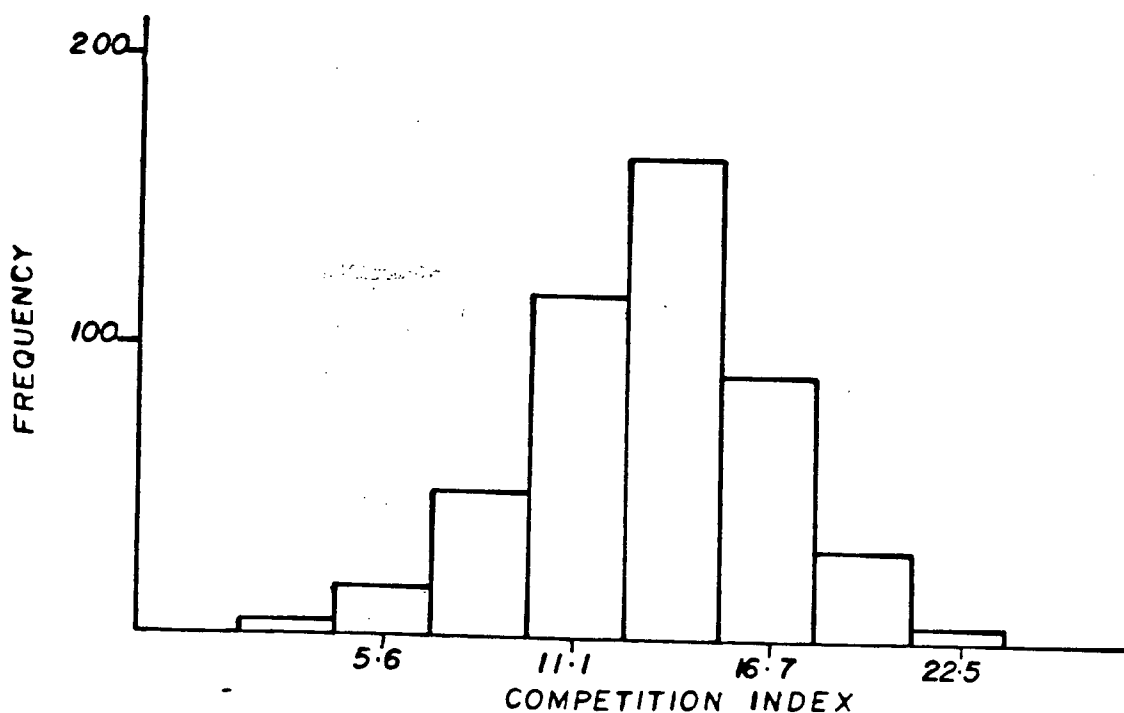
Figure 8g. Frequency distribution of Quenet's
Competition Index for all trees on Turnour
Island plots.
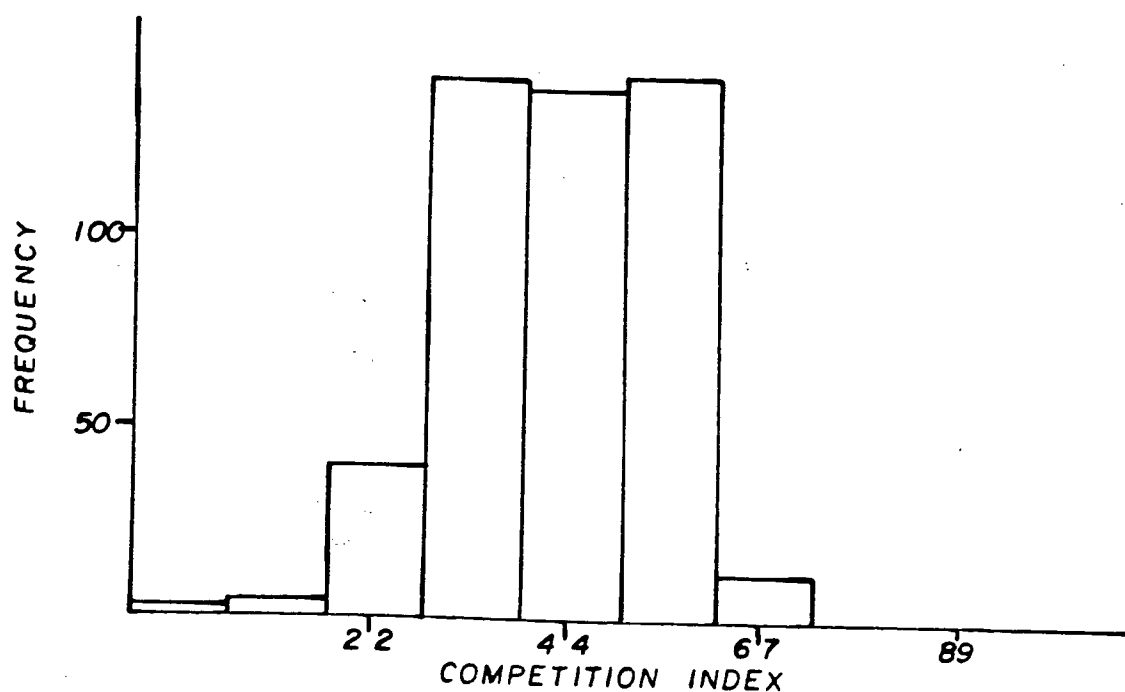
Figure 8h. Frequency distribution of Staebler's
Competition Index for all trees on Turnour Island
plots.

Low-level photographs were taken of each plot from a helicopter (Mitchell, 1975b). Plot centers were marked by a "double" weather balloon, helium filled (Figures 9 and 10). The British Columbia Forest Service (BCFS) supplied a 20-foot boom equipped with synchronized, twin 70 mm cameras and a technician for operating this stereophotographic system. The system is designed to give high resolution stereophotographs suitable for measurement of crown dimension when slow, uniform speed and low, constant flight altitude are maintained (Figure 10). The boom was mounted on a contractor's helicopter (Figure 11). Both color reversal and black and white film were exposed and processed by the BCFS. The photographs were then scanned, identified with their respective plot numbers and taken to a commercial, photointerpretation laboratory (Integrated Resource Photography Ltd., Vancouver, B. C.). The stereo pairs were mounted and a corrected, stereo model was established. In a few cases it was necessary to use consecutive photos from a single camera to obtain suitable stereo models due to asynchrony in exposures. Measurements of crown area at and crown heights above, the estimated level of canopy closure were made on all visible trees within a plot. Unfortunately, the flight altitude was inadequately maintained. Because of the short photo base of the boom this lack of control resulted in large differences in the reliability of the measurements for height and some errors in estimation of crown areas. Photo coverage could have been better; too few exposures were made, many series terminated before the subject plot was at the center of an exposure. Due to these problems, the estimated total tree heights were not usable. This was a major disappointment in the project, but costs did not allow the correction of the problem.

Figure 9.

Balloon location in the Crowns, oblique view
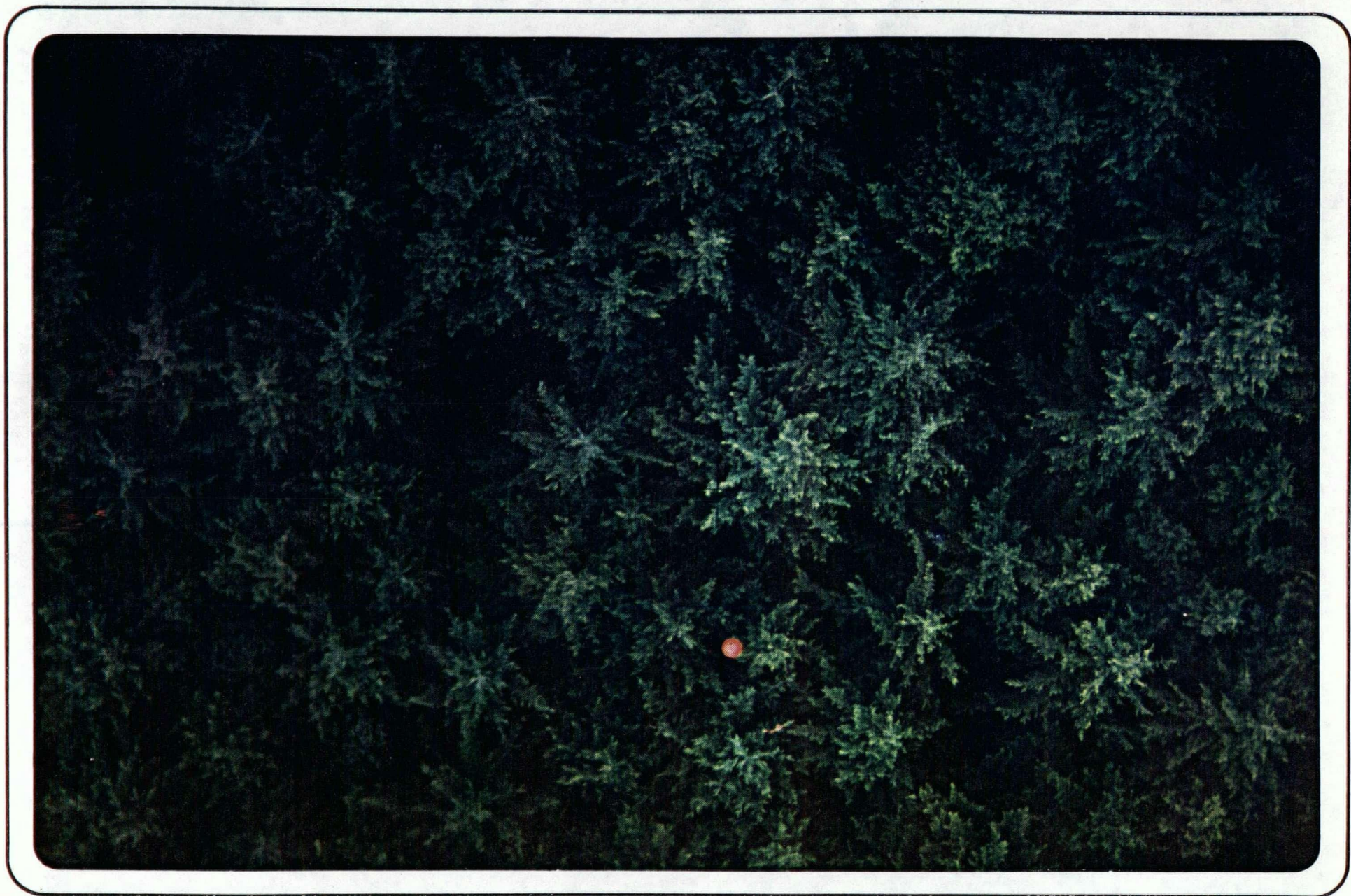
Figure 10.

Vertical view, center of plot marked by balloon

Figure 11.

Loading Film in the Helicopter photo boom

Existing Phenotypically Selected Plus Trees

In July, 1976, measurements of a sample of the existing plus trees were made. The locations of these trees represented a broad spectrum of habitat types throughout the coastal western hemlock zone on Mac-Millan-Bloedel Timber Farm Licenses (TFL's). Near each plus tree at least one check tree was selected for apparent crown efficiency and position of the crown in the canopy; dominant check trees were preferred, but some codominants were purposely selected. Height, diameter, crown radii, and competitor distribution were measured for each plus and check tree. Growth on the selected trees was determined from Addo-X measurements performed at U.B.C.

RESULTS AND DISCUSSION

Considerable effort went into the creation of statistically rele-
vant decision models. Eventually, successful models emerged. The pro-
cess which led to different models seems to be as important as the actual
results, because serious reservations developed to the use of basal
area increment as a decision variable when volume is the true variable
of interest. Therefore, attention is focused on the process of developing
decision models for the selection of superior trees. In statistics, we
are frequently faced with accepting or rejecting a particular observation
as a reasonable member of a population. We have information on the
population and the values of the observations on individuals. This is
a problem in statistical inference. The rules and procedures of statis-
tical inference can be applied to the selection of superior phenotypes.

Several practical problems must be dealt with in applying statis-
tical decision rules to a set of observations. The population must
be clearly defined. This is not a trivial problem (Steele and Torie,
1964). In the case of selection of western hemlock plus trees, it is
easy to eliminate spruce trees growing on the plot, but not so easy
to recognize "residual"[1] western hemlock.[2]

---

[1]The word residual is used commonly in two ways. First, it refers to
trees left after a harvesting operation and which have a decided advan-
tage in stand competition especially in western hemlock. Second, it
is used in statistics to indicate the distance of an individual observa-
tion from a mean or a regression line. In this paper "residual" trees
will always be referred to in quotes.

[2]It is clear that "residual" hemlock are not members of the "population"
as they have a decided head start on the even aged seedlings.

A sample plot chosen for measuring components of growth should have a uniform distribution of nutrients, moisture and light. If the sampled plot conditions are optimal, competition index represents the effects of the environmental variation on the growth of the individual tree and the residual represents genetic variation. It is true that current competition may be partly genetically determined and additional variation includes the influence of age, microsite and minor crown position differences among other factors. These factors serve to emphasize the importance of selection of uniform sample plots since the objective is to isolate as much of the genetic variance in the residual as is possible. While it is recognized that an actual partitioning of genetic and environmental effects is not possible, a model should attempt to isolate a biologically rational component affecting tree growth.

Selection of a model on which to establish limits for inferential decisions should be consistent with biological realities. Thus, one objective (#1) of this study was to investigate statistical criteria for selection of western hemlock based on the regression of growth on competition. The use of a simplistic model such as selection based only on the growth rate or total size would not be consistent with the objectives, even though this could be considered a possible model for the establishment of a selection rule. Competition indices seems to be a rational covariate to growth in attempt to describe genetic superiority.

Description of Growth - Competition Index Relationships

Scatter plots of the growth competition relationship are illustrated in Figures 12 to 15. Throughout this study growth is measured as the difference between squared diameters at the two measurement periods. This is the equivalent of basal area growth (BAGR).

Conversion to metric area units is made by multiplication by 5.067 cm^2/in^2. Conversion to square feet is by multiplication using .00545415 ft^2/in^2. These conversions were not made as they are constants and not really crucial to selection.

To further illustrate the value of information concerning growth competition relationships the Turnour Island data was sorted into ascending values for competition and divided by competition into several strata on three of the plots using Bella's index of competition. Means and standard deviations were computed for the strata. The result of this procedure is illustrated in Figures 16 to 18. Not surprisingly, both the mean and the standard deviation change from stratum to stratum.

Two points have been made: 1) there is a functional relation between BAGR and competition index, and 2) there is a spread about the line representing this relation.

A simple model of the functional form of growth competition may be gained by examining these figures. There is an obvious curvilinear relationship for these as well as others examined (with the exception of Lin's index which increases with increasing competition and seems linear). A brief analysis of limiting situations for the majority of indices can add to the picture. First, the competition free situation; while the exact value is not certain, we know that growth is not infinite when there is no intraspecies competition. Second, in relatively even-aged stands there must be an upper limit to competition. Again we are not certain at what exact value competition is a maximum, but beyond some point growth ceases and mortality is probably imminent. Altogether this suggests an overall quadratic model with both x and
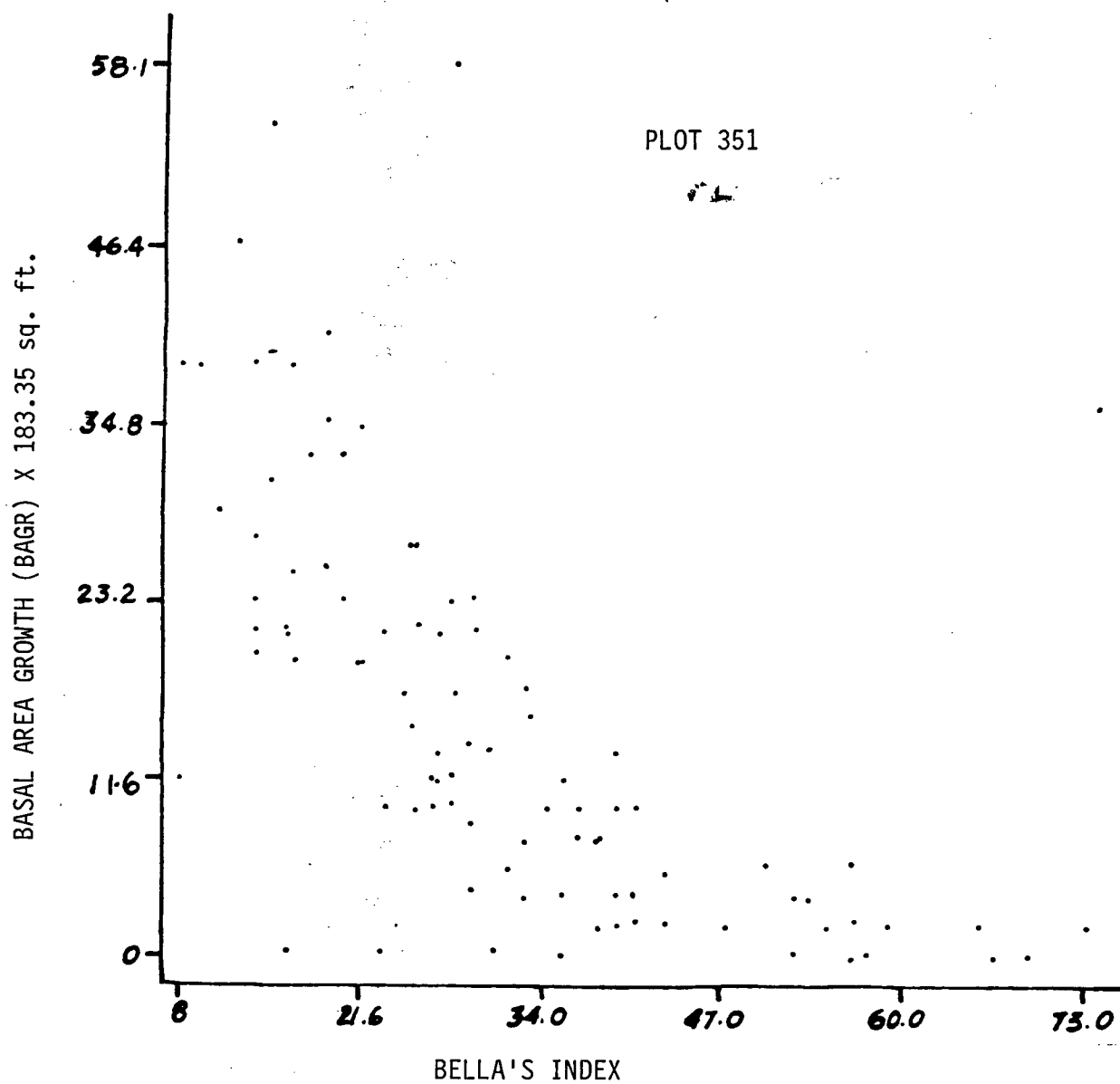
Figure 12.   Scatter Plot of Bella's Index versus periodic
growth (BAGR), Plot #351 Turnour Island.
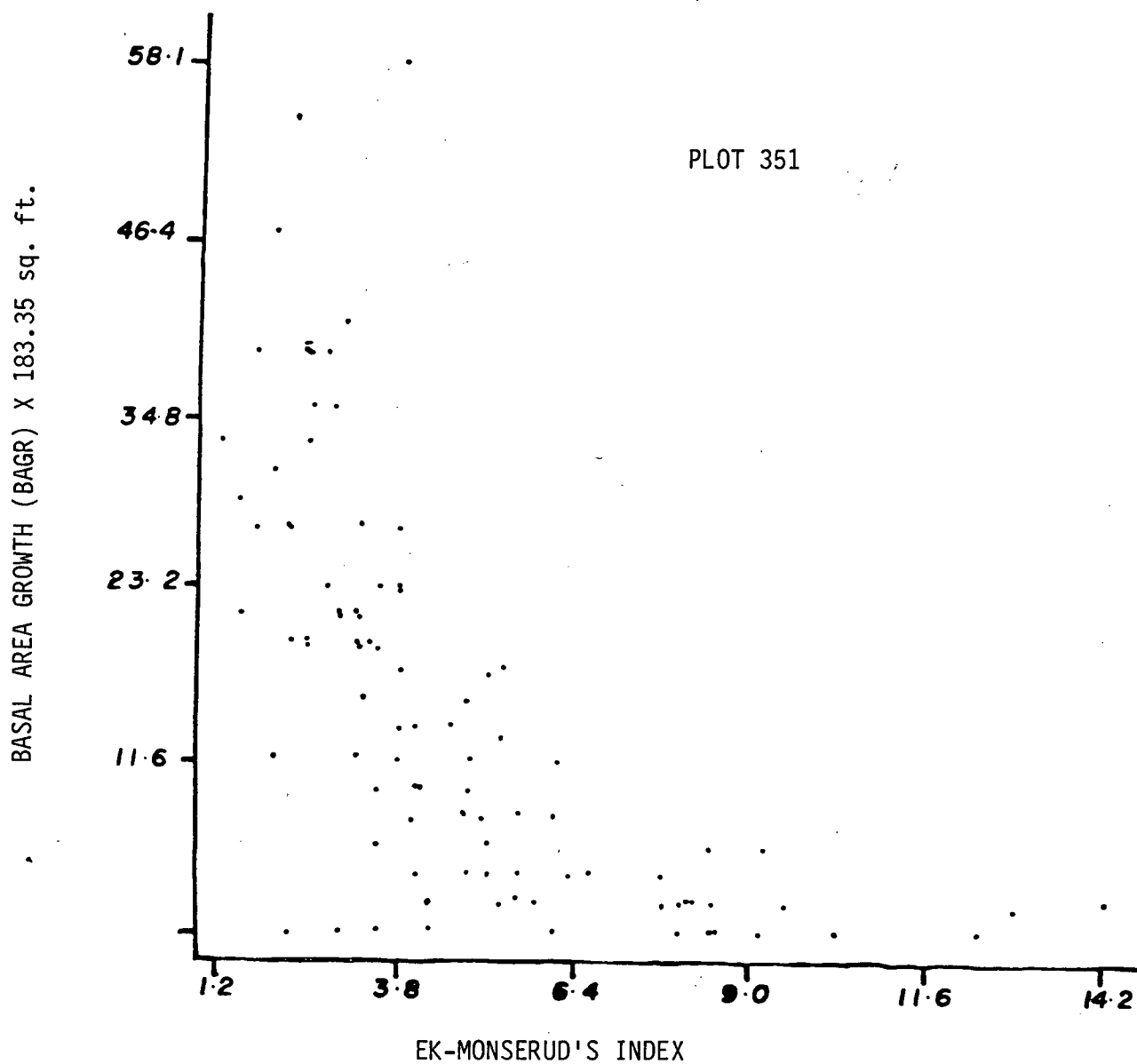
Figure 13.   Scatter Plot of Ek-Monserud's Index versus
periodic growth (BAGR), Plot #351 Turnous Island.
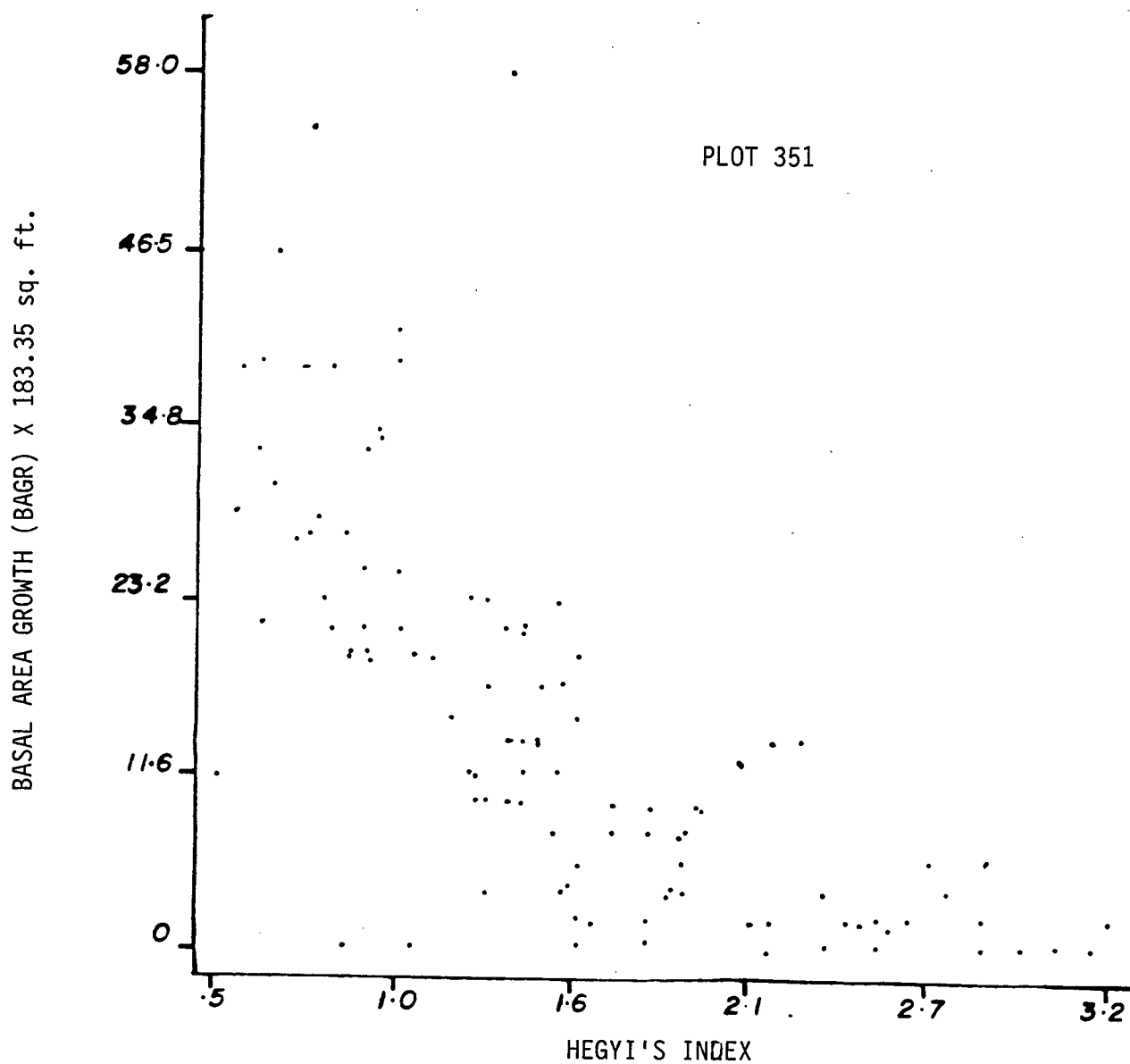
Figure 14. Scatter Plot of Hegyi's Index versus periodic growth (BAGR), Plot #351 Turnour Island.
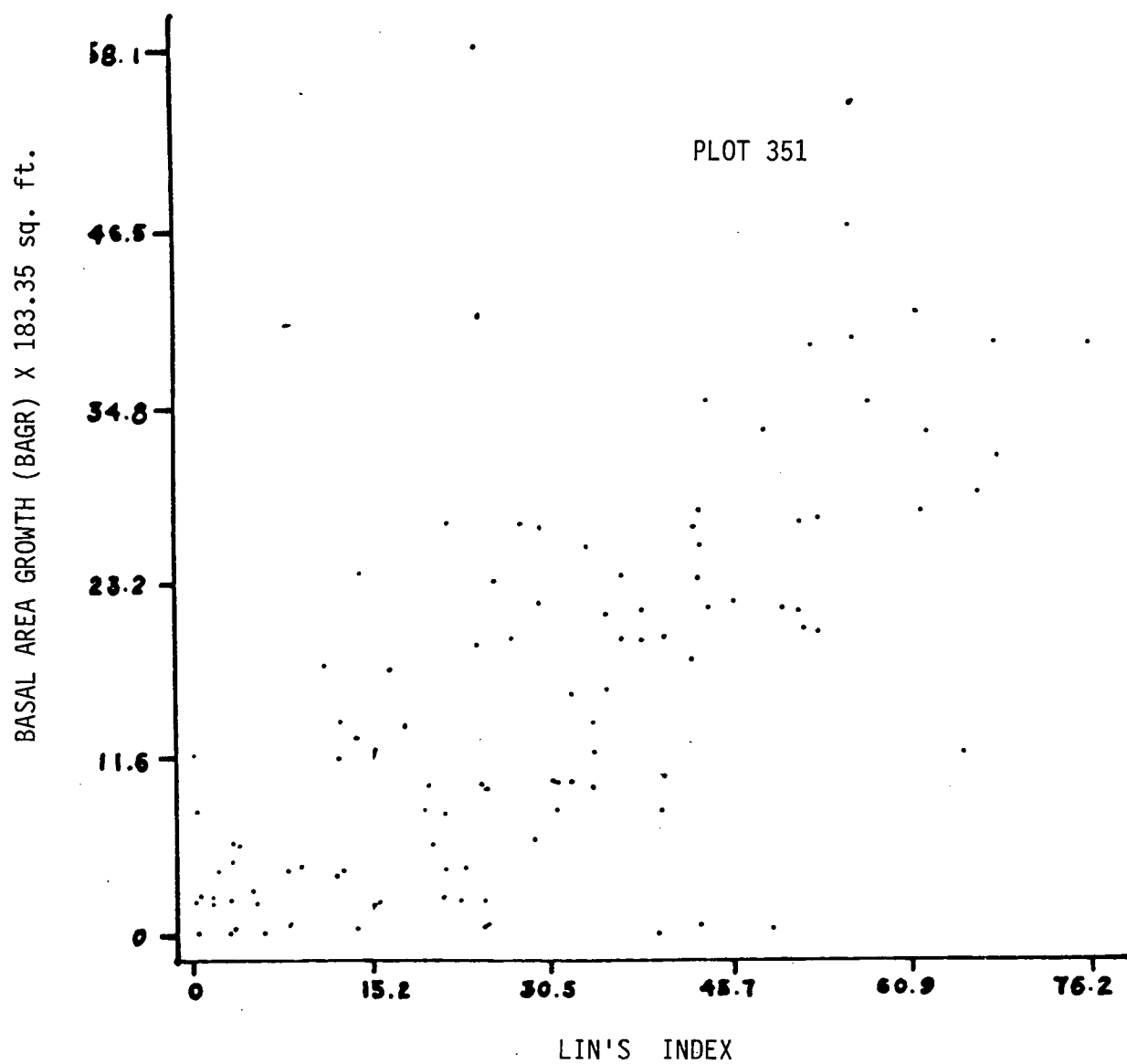
Figure 15.   Scatter plot of Lin's Index versus periodic
growth (BAGR), Plot #351 Turnour Island.

y intercepts, it does not rule out linear models or more generalized logarithmic models. From a general picture of competition we proceed to examine the nature of individual competition indices and their case dependence on computer and simulation models.

Competition Indices in a Superior Tree Selection Process

It is possible to include other parameters in a competition model of growth. Among the candidate parameters initial dbh is often used. For simulation purposes, models must have good or excellent growth predictive ability. To be most effective both the genetic and environmental variation should be explained in a single model. For this reason, one or more initial size parameters are often included. Typically, five-year periodic growth rates may be predicted by such models with R^2 values of .70 to .90 or higher. R^2 is a measure of the proportion of the variance of growth which is explained by a regression. A growth model would have the general form

$$Y = f \ (CI \ (d,s),D) + e \qquad \qquad (12)$$

where Y is periodic basal area growth, CI is the competition index, a function of d, the subject and competitor diameter, s their spatial distribution; and D, the initial diameter. The unexplained portion is represented by e. In the development of computer simulation growth prediction is paramount. Functional or causal roles of predictors is secondary.

For the purpose of plus tree selection a model which maximizes growth predictive power could be completely inappropriate. Our goal is the development of a selection criterion which is closely associated

with the genetic superiority of an individual. This suggests a model incorporating the environmental portion of influences which control growth and segregating those influences which could be genetic. In statistical terms, the expected growth in the population is accounted for by explicit terms of the regression equation and the genetic variation is associated with the residual. If a model is driven by an initial size term (e.g., diameter), any genetic variation tends to be masked since this term is a result of both genetic and environmental factors and it becomes illogical to expect to identify plus trees using regression or any other statistical procedure. As a result the following model was chosen:

$$Y = f \ (CI \ (s,d)) + e \qquad (13)$$

where these terms still have their original denotations.

The Selection Value and Regression Models

Once the functional models have been proposed, a process for selecting individual trees is easily obtained. In the simplest case a confidence interval for each tree is obtained. This value can be used to select superior trees. For a linear model of growth versus competition, confidence limits for the growth of an individual tree can be expressed:

$$CL = Y \pm \sqrt{1 + 1/n + (x-\bar{x})^2} \cdot S_{yx} \qquad (14)$$

where Y = BAGR and X = a competition index. $\bar{X}$ is the mean and S_{yx} indicates the sample standard deviation from regression. Using this relation the residual for any observation may be standardized. Comparison of residuals for any value of competition can then be made. One way
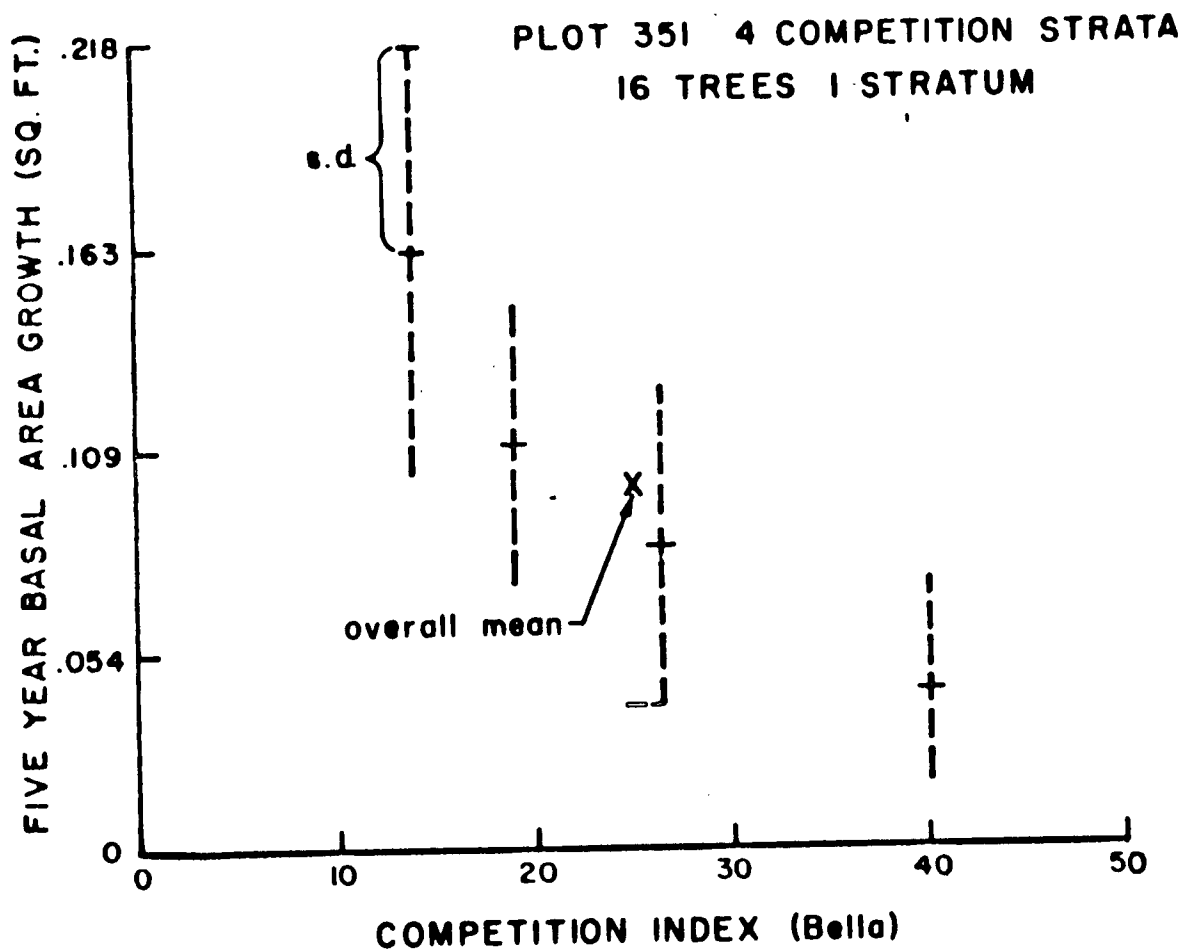
Figure 16. Stratification of competition versus basal area growth Bella's Index Plot 351.
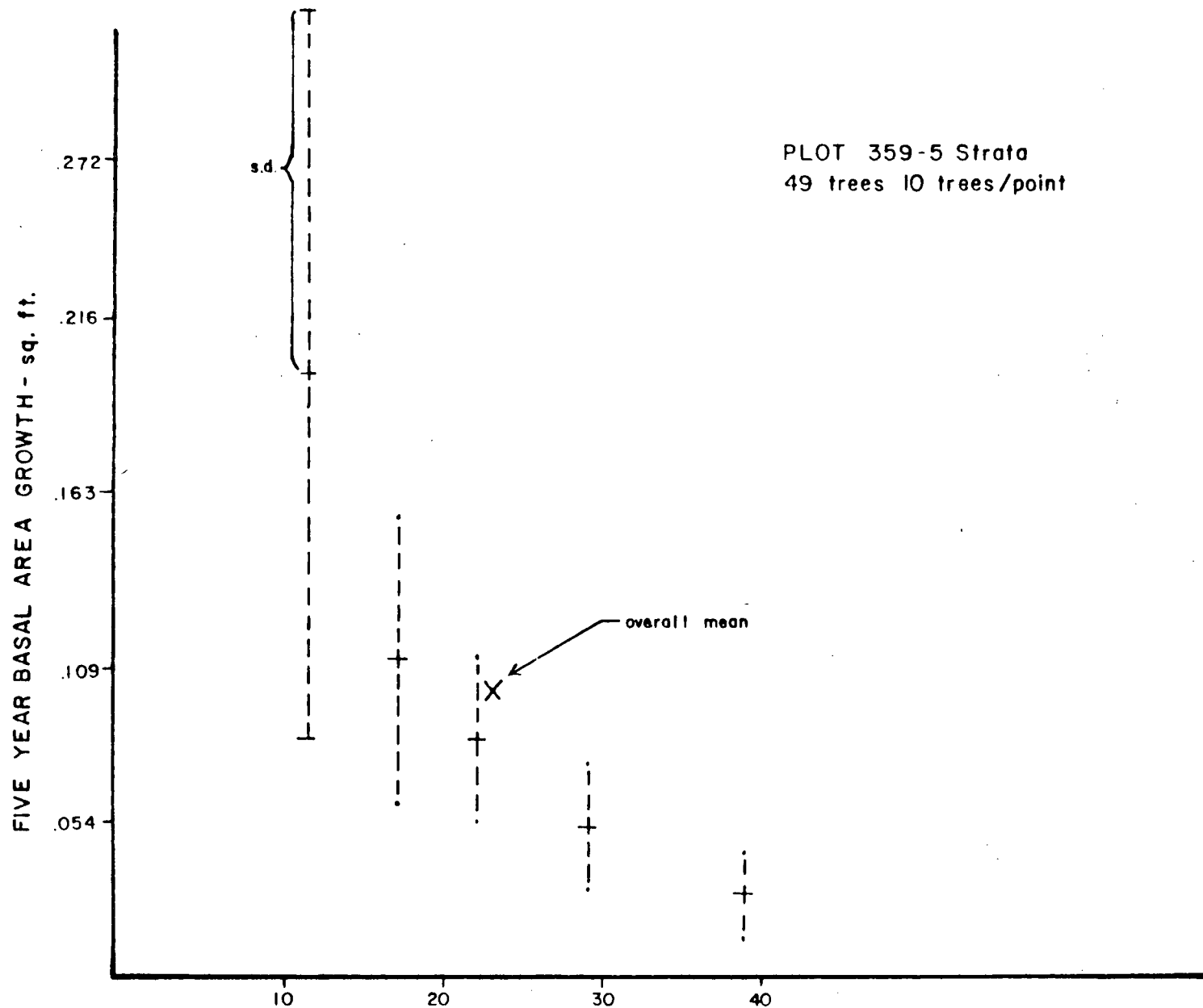
Figure 17.   Periodic basal area growth versus Bella's Competition index.
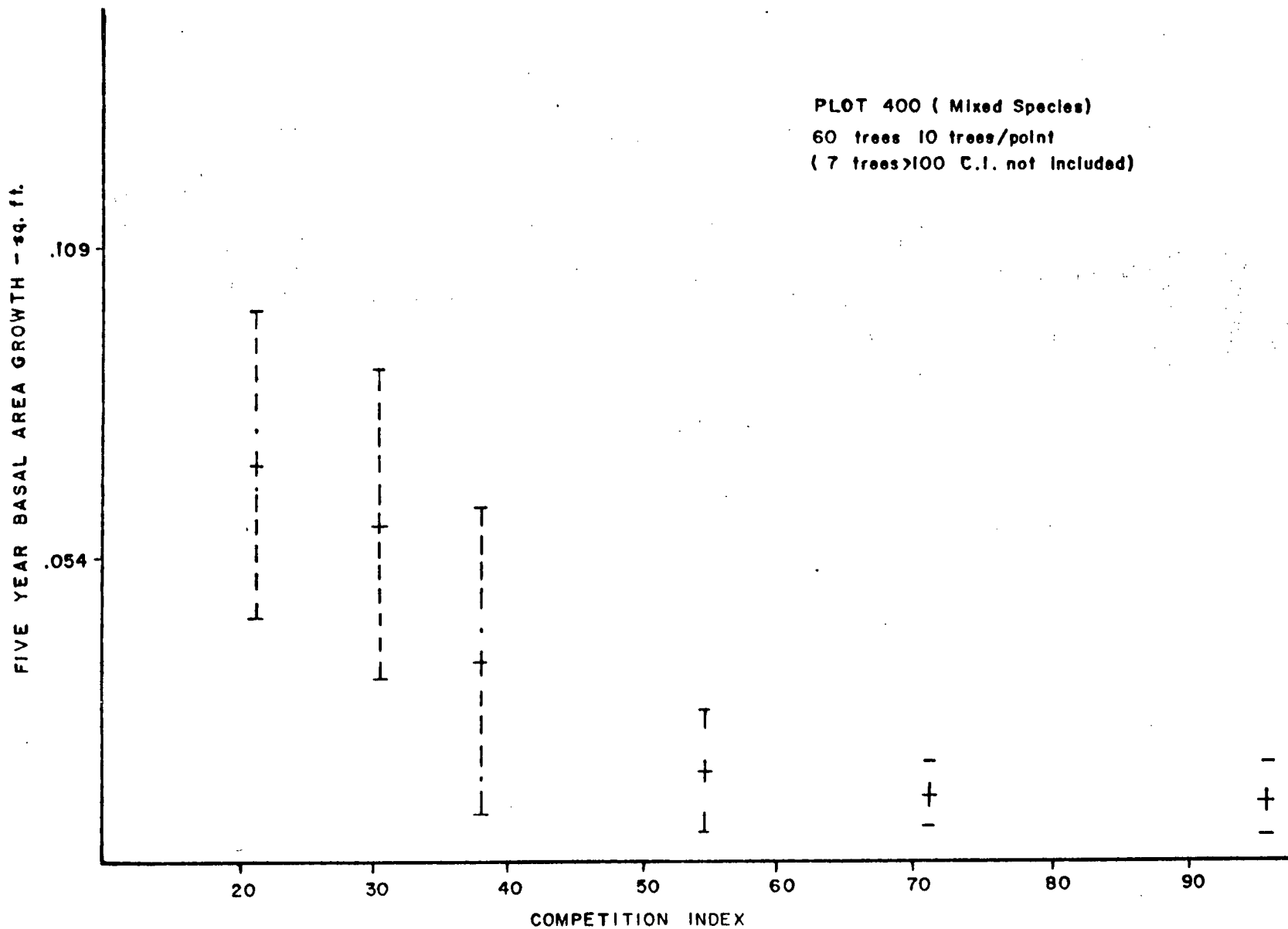
Figure 18. Periodic basal area growth versus Bella's competition index.

of obtaining the selection value is to divide each residual by the CL (confidence limit) for the corresponding competition value. (Standardization of the variables prior to regressing them is another way.) Procedures for calculating confidence limits and hence obtaining a selection value are part of the most current computer regression packages.

As we have seen the relation for most of the competition indices is not a simple linear one, nor is the variance of growth rate constant for all values of competition (see Figures 12-18). Direct application of linear regression models of relation and confidence intervals is not appropriate. Statistically, both the curvilinear relation and the non-uniform variance can be handled by common computer routines and still yield a selection value.

A number of regression models were investigated. Data from four of the plots and all indices were processed and the results analysed for distribution of residuals, standard errors, and probability of residuals. Complete output is analagous to crown regressions on a single plot and is included in Appendix II. The first regression model to yield reasonable results for all the criteria mentioned was:

$$Y = b_0 + b_1 (CI) + b_2 (CI)^2 + e \qquad (15)$$

The polynomial model typically gave R-square values of 0.50 to 0.60 for the better indices. Examination of the residual pattern for these models again revealed nonhomogeneous variance with respect to the indices. Referring again to the illustrations for stratified competition using Bella's index (Figures 16-18) selection probability is not the same for each strata. In order to obtain equal probability at all levels a weighted regression procedure could be used. This

procedure was suggested but not implemented as a result of the following considerations.

Initial results from computer runs using standard confidence interval selection rules, let alone weighted rules, were discouraging. Field examination of the selections revealed many small suppressed or intermediate trees were chosen. Additional selections were made in MacMillan-Bloedel, Ltd. PSP 710 near Port Alberni on Vancouver Island. The selections were reviewed by a group of simulation and tree improvement foresters in the fall of 1976. Discussions during this meeting led to a different approach to the statistics of selection. It was agreed that in dense young stands suppressed or intermediate trees were not expected to be candidate trees. These trees represent a different "population". They utilize the resources efficiently in that they survive on filtered light and reduced nutrients, but in terms of producing wood useful to man they are not efficient.

A new approach was taken to establish a model which reflects the practical forester's interest in the more dominant trees. A transformation of the equation already investigated was adopted. The procedure is much like the weighting of a regression to equalize the variance except the opposite is done. The regression maintains the information on small trees, but emphasizes the variance observed among the larger stems. The resulting equation is:

$$Y/CI = b_0/ \ (CI) + b_1 + b_2 \ (CI) + e \qquad (16)$$

Notice that the left side of equation (16) has dimensions, periodic growth/unit competition. This recalls other foresters' interest in concern for efficiency in superior tree selections (Brown and Goddard, 1961). In practical terms the model eliminates the selection of most

small, suppressed or intermediate trees. Examination of the residuals
and the trees selected coincided more closely with subjective ideas
of plus trees.

Elimination of Indices

Of the eight original indices four were eliminated quickly. Staebler's
(1951) index was an early attempt at describing spacing relations and
Quenet's (1976) index is a very simple model. These two indices failed
to explain a sufficient amount of the growth variance. Selection using
only the mean value for growth gave results quite comparable to these
two indices disregarding any effect for competition. Lin's index posed
both computational and theoretical problems. The problems are examined
in Appendix II.

Arney's index is mathematically sophisticated and has a biological
basis. Its performance in growth simulation is not questioned here.
It was eliminated in view of its consistently low correlations with
growth in the regression model developed to select plus tree candidates.

Competition Selections on Sample Plots

Figure 19 illustrates the selection interval obtained by back-
transforming equation 16 to the original basal area growth and compe-
tition values. The regression and a list of the selected plus trees
along with their selection values (standardized residuals) is presented
in Tables 2 through 13. The complete regression results of the analysis
of Plot 358 are presented in Appendix III. Bella's index illustrates
the method.

Examination of the trees selected by the competition indices indi-
cate that they are not the fastest growing in terms of periodic incre-
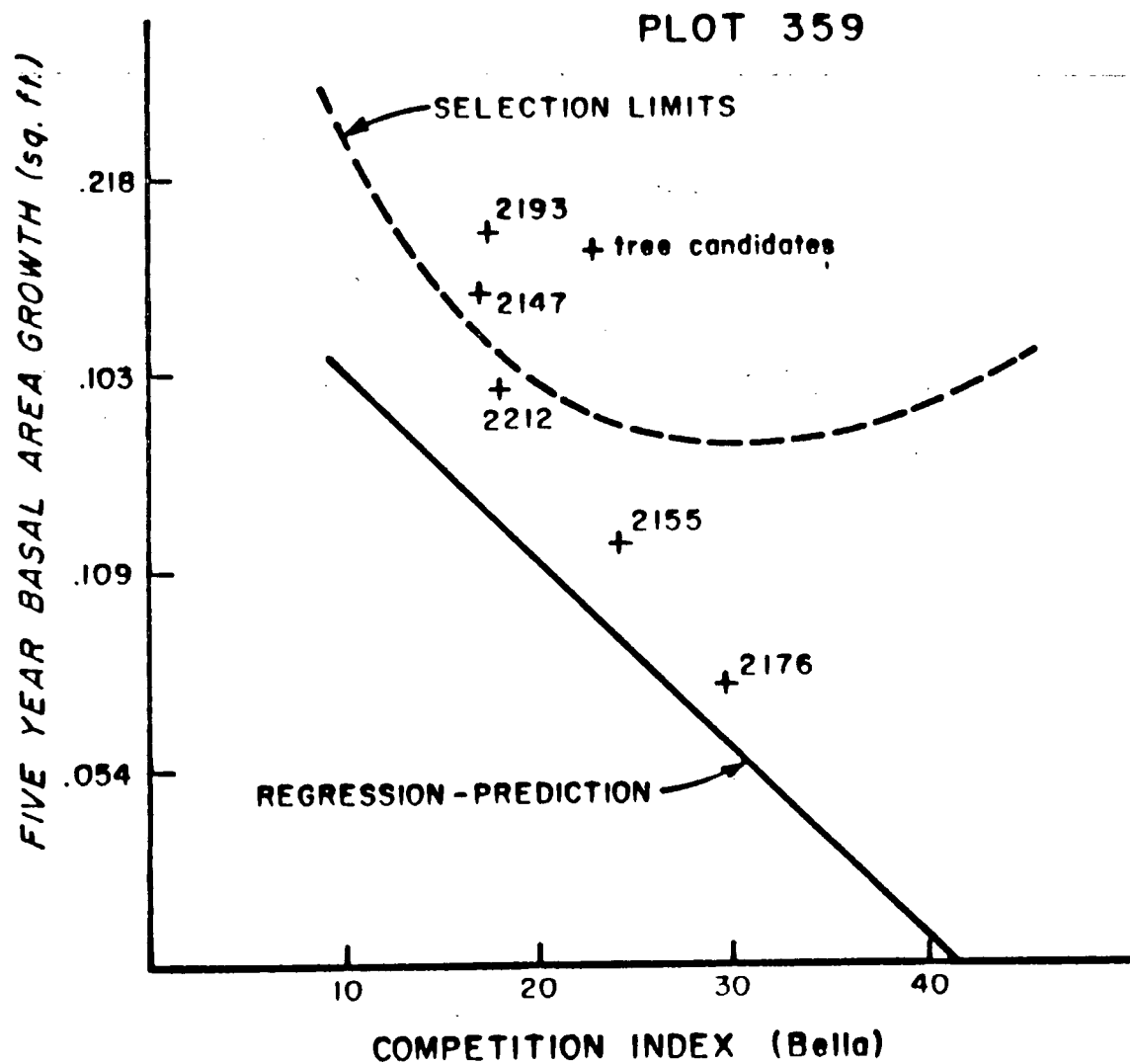
Figure 19. Back transformed equation with confidence limit.

ment nor are they the largest basal area trees. However, selected trees are high on the list of trees based on basal area growth; they might be classed as thrifty dominants or, occasionally, codominants. In general, the selected trees have competition indices which place them in the lower third of the plot of CI. A few of these trees might be classed as open-grown, but the majority do not have unlimited growing space; they support the hypothesis that a superior tree should express dominance over its competitors.

Those phenotype choices at Turnour Island which could have an index computed, are represented in Table 14. Among them only one tree has an index greater than the mean value for its plot. Two of them actually represent the tree of least competition (Bella's index). The extremely low competition value associated with phenotypes supports the idea that phenotypic selections may be growing under conditions of low competition in relation to their neighbors.

Analyses of Covariance

If each plot has its own regression equation due to original spacing or thinning or age, a tedious, expensive repetition of the process for developing models would have to be undertaken each time a new condition was encountered. Certainly this would be unacceptable economically. However, if the results from plot regressions can be combined, a base-line established, and reduced sampling schemes designed, the process may be quite economical.

Snedecor and Cochran (1967) give a clear discussion of the use of analysis of covariance for comparison of regression lines. If the relations between independent and dependent variables are investigated

Table 2. Group I - Plot 350 Competition, Selection and Regression

Competition Index	Competition Average for Plot #350	Tree Number	Selection* Value	Competition Index Value
Bella	30.0	64	2.8	27.8
		29	2.4	14.3
		53	1.5	18.2
Ek-Monserud	4.4	64	3.4	3.8
		29	2.8	2.3
		53	1.8	3.1
Hegyi	1.5	64	3.2	1.4
		29	2.5	.8
		53	1.7	1.0
Newnham	1.8	64	2.0	1.8
		29	2.6	.8

$$Y/CI = b_0/CI + b_1 + b_2\, CI + e$$

Coefficients for the Regression

Competition Index	b_1	b_2 **	b_0
Bella	- .692	-	37.4
Ek-Monserud	- 5.08	-	38.5
Hegyi	-15.8	-	39.2
Newnham	- 9.63	-	34.5

* Standard deviation units above regression. N.B. This is not the same selection value as used in quantitative genetics.

** Absence of a b_2 value indicates that the coefficient was not significantly different from 0 and did not enter the regression.

Table 3. Group I - Plot 351 Competition, Selection and Regression

Competition index	Competition Average for Plot #351	Tree Number	Selection Value	Competition Index Value
Bella	23.2	-	-	-
Ek-Monserud	3.3	238	1.7	2.6
		254	1.5	2.8
Hegyi	1.1	304	1.5	.8
		254	1.4	.9
Newnham	1.61	370	2.0	1.0
		238	1.6	.9

$$Y/CI = b_0/CI + b_1 + b_2\ CI + e$$

Coefficients for the Regression

Competition Index	b_1	b_2	b_0
Bella	- .853	-	35.9
Ek-Monserud	- 4.56	-	31.1
Hegyi	-57.5	17.8	56.3
Newnham	- 6.70	-	28.0

Table 4. <u>Group I - Plot 352 Competition, Selection and Regression</u>

Competition Index	Competition Average for Plot #352	Tree Number	Selection Value	Competition Index Value
Bella	25.1	476	1.8	12.8
		488	1.4	15.1
		437	1.1	25.6
Ek-Monserud	3.6	476	2.6	3.5
		613	2.2	2.6
		442	1.8	3.3
		488	1.7	2.4
Hegyi	1.2	476	2.6	.8
		613	1.7	.7
		442	1.6	1.0
		437	1.2	1.2
Newnham	1.66	488	1.5	1.1
		442	1.1	1.0
		613	1.1	.7

$$Y/CI = b_0/CI + b_1 + b_2\ CI + e$$

<u>Coefficients for the Regression</u>

Competition Index	b_1	b_2	b_0
Bella	- .0435	-	37.2
Ek-Monserud	- .943	-	41.4
Hegyi	-17.1	-	38.6
Newnham	-34.1	6.51	52.3

Table 5. <u>Group I - Plot 357 Competition, Selection and Regression</u>

Competition Index	Competition Average for Plot #357	Tree Number	Selection Value	Competition Index Value
Bella	30.3	1873	2.1	14.2
		1906	1.7	24.6
Ek-Monserud	4.5	1873	2.8	3.1
		1959	1.8	3.6
		1906	1.6	3.2
Hegyi	1.5	1873	2.0	.8
		1906	1.7	1.2
		1959	1.2	.9
Newnham	1.7	1873	1.4	.3
		1906	1.2	1.3

$$Y/CI = b_0/CI + b_1 + b_2 \, CI + e$$

<u>Coefficients for the regression</u>

Competition Index	b_1	b_2	b_0
Bella	- .694	-	33.4
Ek-Monserud	- 3.93	-	30.5
Hegyi	-13.2	-	33.1
Newnham	-12.2	-	33.1

Table 6. <u>Group I - Plot 358 Competition, Selection and Regression</u>

Competition Index	Competition Average for Plot #358	Tree Number	Selection Value	Competition Index Value
Bella	35.7	2110	2.5	19.8
		2220	1.7	20.1
		2212	1.3	17.0
Ek-Monserud	5.8	2097	2.2	3.9
		2110	1.9	2.9
		2093	1.8	4.9
Hegyi	2.1	2110	2.4	1.2
		2093	1.7	2.0
		2212	1.6	1.2
		2298	1.5	1.3
Newnham	1.8	2346	1.4	0.5
		2054	1.2	0.8

$$Y/CI = b_0/CI + b_1 + b_2\ CI + e$$

<u>Coefficients for the Regression</u>

Competition Index	b_1	b_2	b_0
Bella	- 1.35	.0108	41.5
Ek-Monserud	-11.6	.623	51.0
Hegyi	-23.9	3.34	42.3
Newnham	-23.6	3.83	36.6

Table 7. Group II - Plot 354 Competition, Selection and Regression

Competition Index	Competition Average for Plot #354	Tree Number	Selection Value	Competition Index Value
Bella	29.4	883	2.7	16.9
		1016	1.6	22.1
		992	1.4	26.4
Ek-Monserud	4.5	883	2.7	3.7
		896	2.1	1.6
		1027	1.6	3.0
Hegyi	1.6	883	3.5	1.2
		922	1.8	1.6
		1012	1.4	1.5
Newnham	1.7	883	3.0	.9

$$Y/CI = b_0/CI + b_1 + b_2 \, CI + e$$

Coefficients for the Regression

Competition Index	b_1	b_2	b_0
Bella	- 2.88	.0328	65.0
Ek-Monserud	- 5.34		37.1
Hegyi	-72.9	15.9	85.2
Newnham	-57.3	13.0	67.6

Table 8. <u>Group II - Plot 355 Competition, Selection and Regression</u>

Competition Index	Competition Average for Plot #355	Tree Number	Selection Value	Competition Index Value
Bella	41.6	1039	1.8	14.1
		1219	1.3	13.8
Ek-Monserud	6.5	1219	1.9	2.5
		1039	1.8	2.6
Hegyi	2.5	1207	no trees chosen	-
Newnham	1.7	1039	1.3	.4

$$Y/CI = b_0/CI + b_1 + b_2 \ CI + e$$

<u>Coefficients for the Regression</u>

Competition Index	b_1	b_2	b_0
Bella	- 2.07	.0182	58.1
Ek-Monserud	-13.6	.771	57.4
Hegyi	-51.0	8.36	76.8
Newnham	-57.1	14.6	55.2

Table 9. Group II - Plot 356 Competition, Selection and Regression

Competition Index	Competition Average for Plot # 356	Tree Number	Selection Value	Competition Index Value
Bella	40.0	1574	2.4	24.0
		1592	1.3	17.4
		1742	1.2*	44.3
Ek-Monserud	7.5	1574	2.6	4.5
		1592	1.9	3.3
		1639	1.9	3.2
Hegyi	3.1	1574	2.2	2.5
		1592	1.4	1.3
		1665	1.4	2.4
		1639	1.2	1.2
Newnham	1.7	1592	2.3	.8
		1639	1.9	.5
		1574	1.7	.5

$$Y/CI = b_0/CI + b_1 + b_2 CI + e$$

<u>Coefficients for the Regression</u>

Competition Index	b_1	b_2	b_0
Bella	- 1.32	.0105	39.8
Ek-Monserud	- 5.53	.21	33.0
Hegyi	-13.1	1.32	32.6
Newnham	- 8.05	-	21.0

* Tree will be checked in the future for mismeasurement.

Table 10. <u>Group II - Plot 359 Competition, Selection and Regression</u>

Competition Index	Competition Average for Plot #359	Tree Number	Selection Value	Competition Index Value
Bella	25.4	2193	1.7	16.4
		2147	1.2	17.4
Ek-Monserud	4.0	2147	1.7	3.0
		2193	1.4	2.4
		2212	1.1	3.0
Hegyi	1.4	2193	1.3	.8
		2212	1.3	1.2
		2147	1.1	1.0
Newnham	1.8	2147	1.6	1.3
		2193	1.4	.8
		2212	1.0	1.3

$$Y/CI = b_0/CI + b_1 + b_2 \ CI + e$$

<u>Coefficients for the Regression</u>

Competition Index	b_1	b_2	b_0
Bella	- 0.936	-	39.0
Ek-Monserud	-16.5	1.25	58.4
Hegyi	-20.1	-	42.7
Newnham	-12.3	-	37.7

Table 11. Group III - Plot 353 Competition, Selection and Regression

Competition Index	Competition Average for Plot # 353	Tree Number	Selection Value	Competition Index Value
Bella	37.2	749	1.8	16.9
		683	1.2	36.1
		723	1.2	24.4
Ek-Monserud	4.6	749	1.8	2.7
		670	1.6	3.5
		723	1.4	3.3
Hegyi	1.7	749	1.6	.8
		683	1.5	1.7
Newnham	1.9	723	1.4	1.6
		749	1.3	.5
		750	1.2	1.3

$$Y/CI = b_0/CI + b_1 + b_2 \, CI + e$$

Coefficients for the Regression

Competition Index	b_1	b_2	b_0
Bella	- 1.30	.0137	43.7
Ek-Monserud	-16.4	1.1	60.2
Hegyi	-42.0	8.63	55.0
Newnham	-23.6	3.62	41.9

Table 12. Group III - Plot 400 Competition, Selection and Regression

Competition Index	Competition Average for Plot #400	Tree Number	Selection Value	Competition Index Value
Bella	66.5	199	1.9	29.4
		206	1.7	28.8
		116	1.3	31.1
Ek-Monserud	10.3	206	1.6	4.1
		295	1.5	3.7
		119	1.1	4.8
Hegyi	2.9	119	1.8	2.0
		206	1.4	1.4
		116	1.3	2.0
Newnham	-	-	-	-

$$Y/CI = b_0/CI + b_1 + b_2\ CI + e$$

Coefficients for the Regression

Competition Index	b_1	b_2	b_0
Bella	- .447	.00196	23.2
Ek-Monserud	-2.23	.0517	19.4
Hegyi	-9.18	.878	22.9
Newnham	4.62	-	15.8

Table 13. <u>Group III - Plot 401 Competition, Selection and Regression</u>

Competition Index	Competition Average for Plot #401	Tree Number	Selection Value	Competition Index Value
Bella	38.8	97	2.2	25.5
		106	2.0	31.2
		152	1.9	28.8
		69	1.6	21.9
Ek-Monserud	6.2	268	2.2	3.7
		265	2.0	3.8
		69	1.5	3.0
		106	1.5	2.9
Hegyi	2.0	152	2.1	1.4
		106	2.1	1.3
		97	1.9	1.3
Newnham	1.7	106	2.1	1.1
		265	1.9	1.5
		97	1.9	1.5
		268	1.8	.9
		152	1.7	1.0

$$Y/CI = b_0/CI + b_1 + b_2 CI + e$$

<u>Coefficients for the Regression</u>

<u>Competition Index</u>	b_1	b_2	b_0
Bella	- .510	.0035	18.7
Ek-Monserud	- 3.48	.150	18.8
Hegyi	-17.1	2.60	27.2
Newnham	- 4.20	-	12.8

Table 14. <u>Selection Values for Phenotypic choices: Bella's Model.</u>

Group	Plot	Mean Bella's Index	Tree No.	Bella's Index	Selection Value
I	350	30.0	31	11.2	-0.10
II	354	30.0	904	32.6	0.58
			954	15.3	1.63
	355	41.6	1039	14.1	1.80*
	359	25.4	2147	17.4	1.24*
			2160	23.9	0.37
			2165	24.3	0.44
III	353	37.2	670	13.0	-0.18
			749	16.9	1.77*
	401	38.8	265	20.8	1.43
			268	19.2	1.31

<u>*</u>/ Tree selected by competition index, also.

in different times or environments, analysis of covariance answers the questions, "Can the results be considered the same?" If not, in what respects are they different? In addition, analysis of covariance can be viewed as a method to improve our examination of the relation of randomized experiment treatments. Thinning levels and levels of basal area and age may be considered the treatments on these plots. Differences which arose in regression lines which can be attributed to these "treatments" might be correctable in field applications of the selection method.

In applying the analysis of covariance to the plot data only the relatively pure hemlock stands were considered. The older, mixed stands were eliminated because, 1) there was indication that the classical methods actually correspond to the competition based methods in these stands, and 2) the species mixture must certainly color the competition value assigned to individual trees; some trees being mainly influenced by fir or spruce. Additional reflection on the application of indices indicated that all indices should be re-examined and models rechecked. For this reason scatter plots of the now quite well edited data were made and correlations between the indexes and different transformations of the dependent variable were examined again. Figures 20 to 24 illustrate some of the plot data. The best model for each index was selected and some preliminary analyses of covariance run on combinations of plots from Group I and Group II. Several of these analyses are presented in Tables 15 to 22.

It should be noted that somewhat better results were obtained for Lin's index using untransformed growth (BAGR) and transformation of the index by arcsin improved performance, neither of these transfor-

Figure 20. Natural log transformation of BAGR versus Bella's
Index for plot #350.
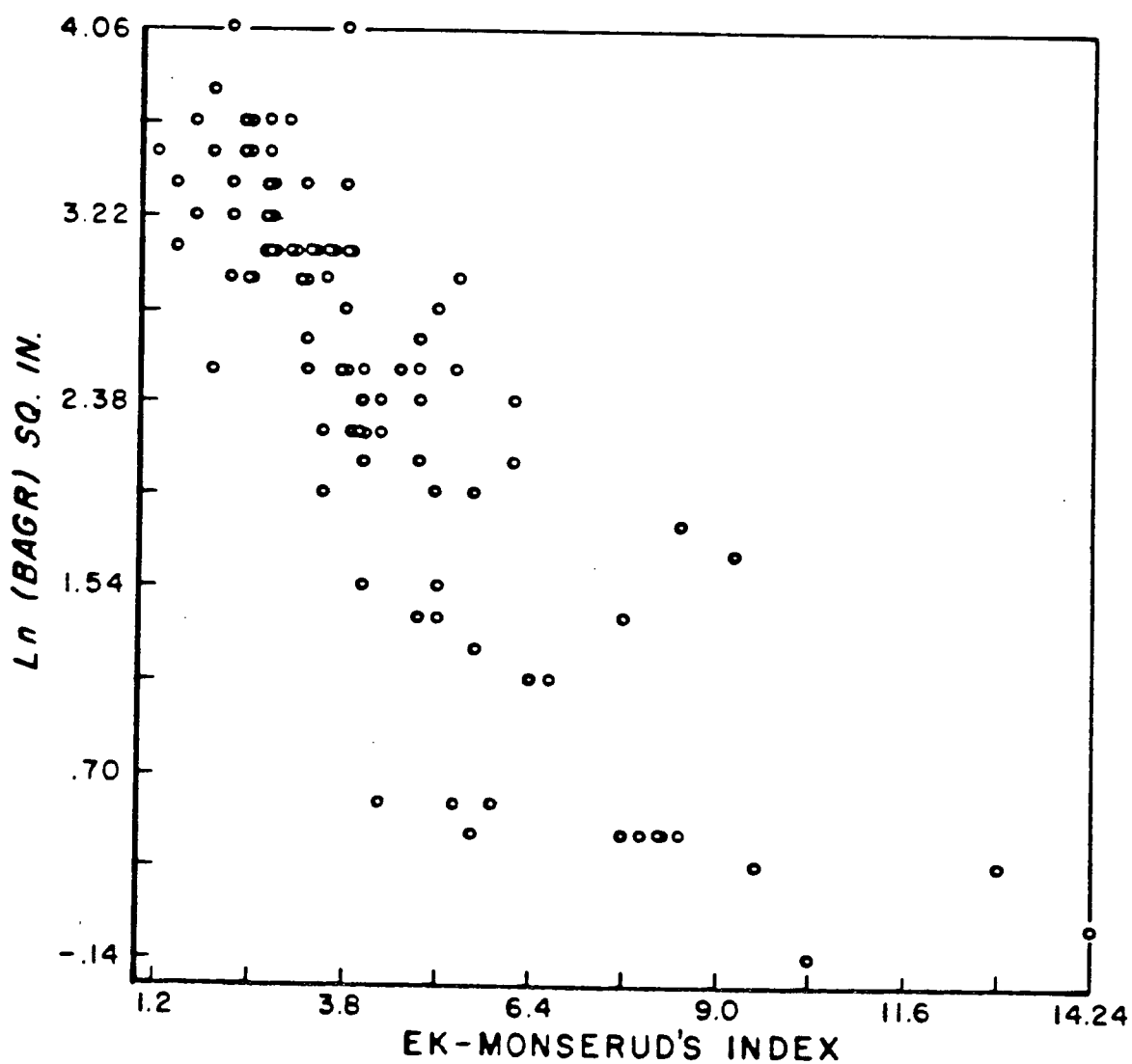
Figure 21.   Natural log transformation of BAGR versus
Ek-Monserud's Index for plot #350.

_Figure 22. Natural log transformation of BAGR versus
Hegyi's Index for plot #350.
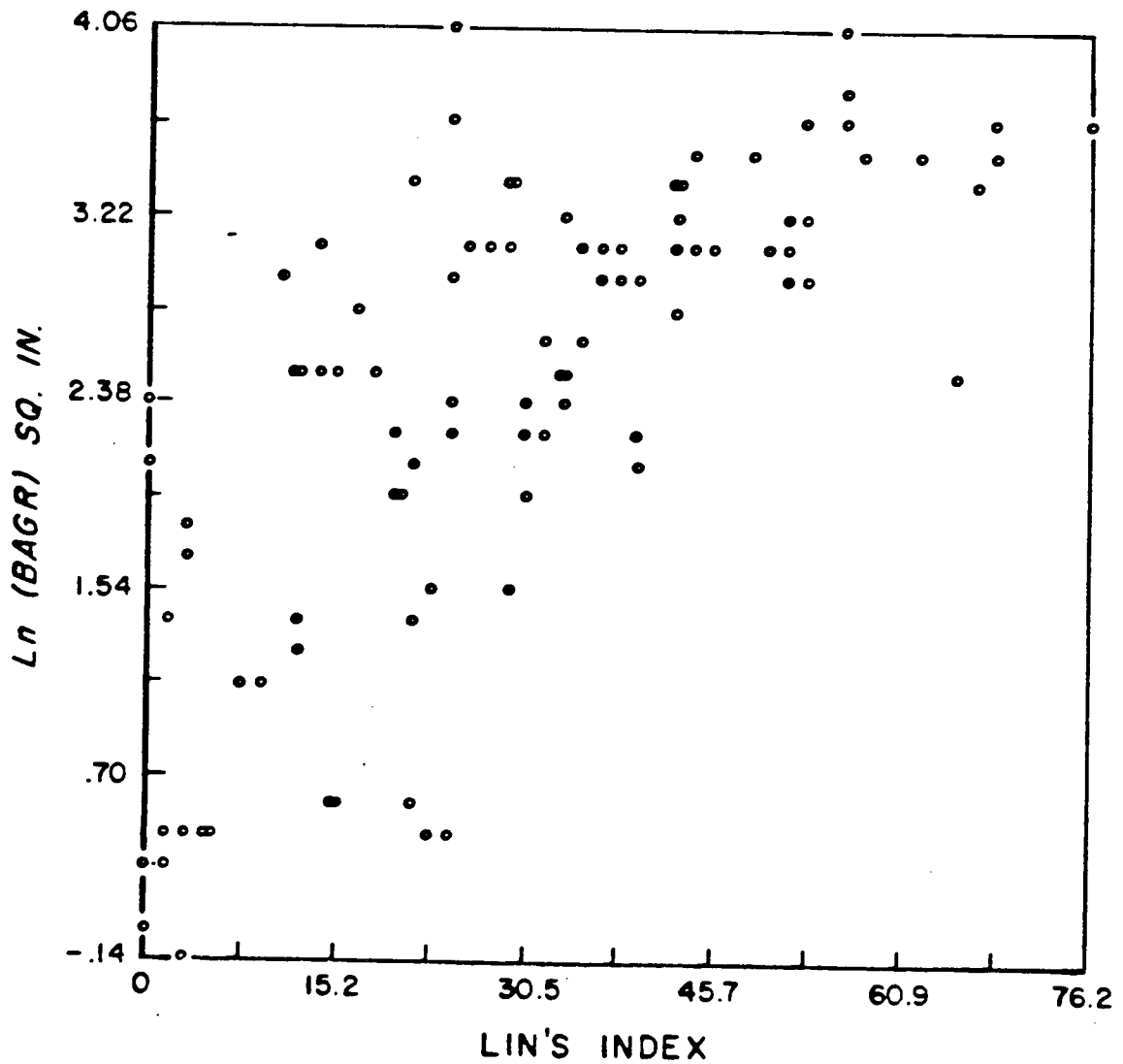
Figure 23. Natural log transformation of BAGR versus
Lin's Index for plot #350.
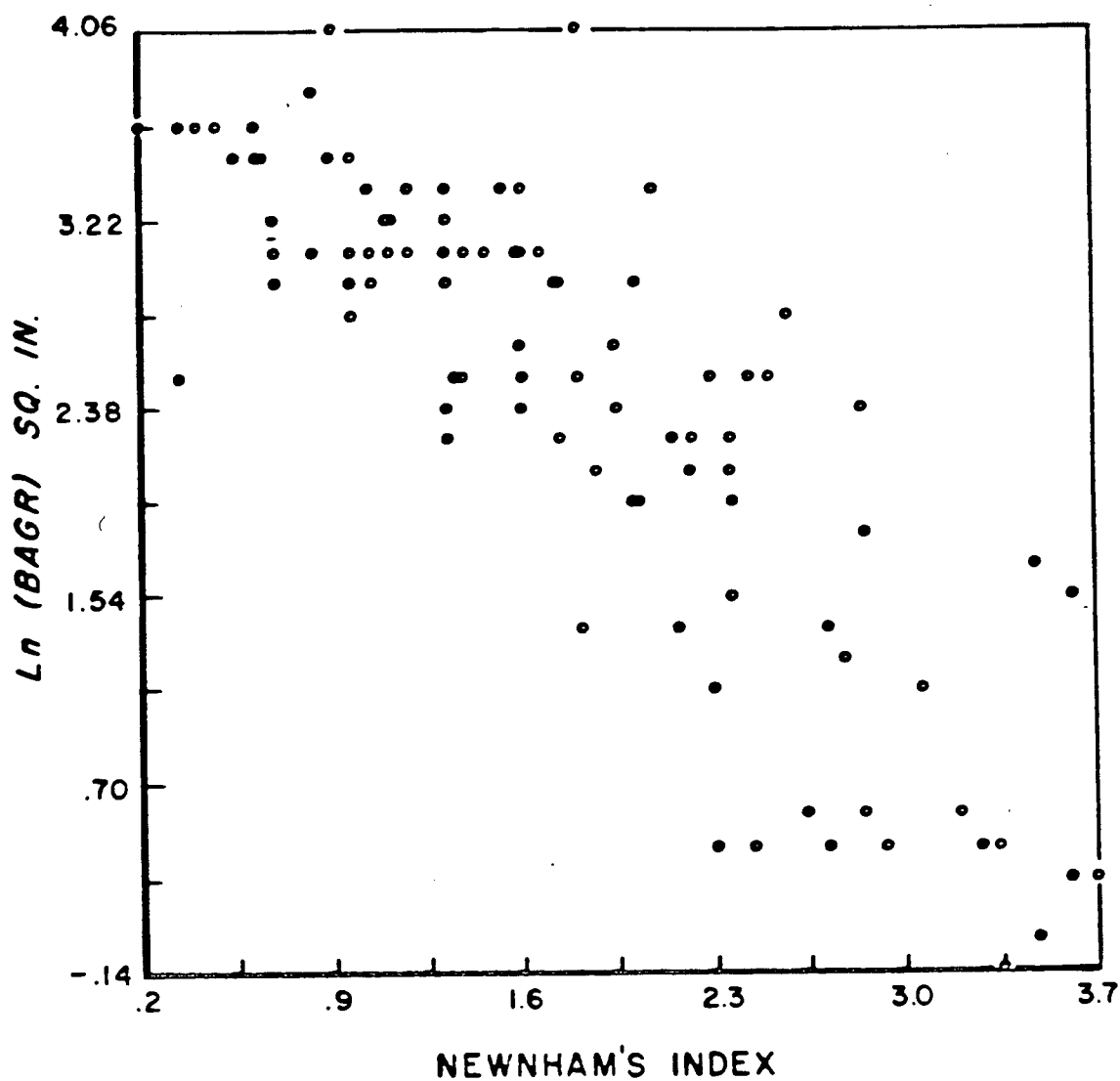
Figure 24.   Natural log transformation of BAGR versus
             Newnham's Index for plot #350.

Table 15. <u>Analysis of Covariance Group I Plots Bella's Index</u>

SOURCE	DF	SUM SQRS	MEAN SQR	F-STAT	SIGNIF
BETWEEN MEANS	4	32.344			
COVARIATE	1	227.91	227.91	564.94	.0000**
ERROR	402	162.18	.40342		
EQUAL SLOPES	4	2.1032	.52581	1.3074	.2666 NS
ERROR	398	160.07	.40219		
EQUAL ADJ MEANS	4	4.2286	1.0571	2.6205	.0346*
ERROR	402	162.18	.40342		
TOTAL	407	422.43			

<u>COEFFICIENTS</u>

COVARIATE	COEFF	T-STAT	SIGNIF
BELLA'S INDEX	-.0562	-23.8	.0000

<u>REGRESSIONS</u>

PLOT #	(1) 350	(2) 351	(3) 352	(4) 357	(5) 358
N	92	62	64	70	120
CONSTANT	4.34	3.86	4.04	3.69	3.72
BELLA'S	-0.0651	-0.0536	-0.0576	-0.0520	-0.0527
SE OF REGR	0.542	0.589	0.571	0.738	0.687
R-SQR	0.75	0.36	0.53	0.49	0.60

NS   The statistical test indicates no significant difference among parameters

*   The statistical test indicates a significant difference

**   Probabilities too small to print, there is a significant statistic

Table 16. Analysis of Covariance Group I Plots Ek-Monserud's Index

SOURCE	DF	SUM SQRS	MEAN SQR	F-STAT	SIGNIF
BETWEEN MEANS	4	32.344			
COVARIATE	1	202.28	202.28	432.97	.0000
ERROR	402	187.81	.46718		
EQUAL SLOPES	4	4.3784	1.0946	2.3751	.0516 NS
ERROR	398	183.43	.46087		
EQUAL ADJ MEANS	4	3.5581	.88951	1.9040	.1089 NS
ERROR	402	187.81	.46718		
TOTAL	407	422.43			

COEFFICIENTS

COVARIATE	COEFF	T-STAT	SIGNIF
EK-MONSERUD'S INDEX	-.33438	-20.8	.0000

REGRESSIONS

PLOT #	(1)350	(2)351	(3)352	(4)357	(5)358
N	92	62	64	70	120
CONSTANT	4.02	3.78	4.07	3.96	3.51
EK-MONSERUD'S	-0.367	- .352	-0.402	-0.418	-0.288
SE OF REGR	0.610	0.611	0.621	0.762	0.737
R-SQR	0.679	0.313	0.442	0.452	0.536

Table 17. Analysis of Covariance Group I Plots Hegyi's Index

SOURCE	DF	SUM SQRS	MEAN SQR	F-STAT	SIGNIF
BETWEEN MEANS	4	32.344			
COVARIATE	1	191.16	191.16	186.32	.0000
ERROR	402	198.92	.49483		
EQUAL SLOPES	4	11.335	2.8337	6.0121	.0001
ERROR	198	187.59			
EQUAL ADJ MEANS	4	4.0148	1.0037	2.0284	.0897NS
ERROR	402	198.92	.49483		
TOTAL	407	422.43			

COEFFICIENTS

COVARIATE	COEFF	T-STAT	SIGNIF
HEGYI'S INDEX	-1.03	-19.7	.0000

REGRESSIONS

PLOT #	(1)350	(2)351	(3)352	(4)357	(5)358
N	92	62	64	70	120
CONSTANT	4.50	3.78	4.21	3.86	3.57
HEGYI'S	-1.43	-1.03	-1.35	-1.14	-0.823
SE OF REGR	0.613	0.621	0.594	0.751	0.772
R-SQR	0.68	0.29	0.49	0.47	0.49

Table 18. Analysis of Covariance Group I Plots Lin's Index

SOURCE	DF	SUM SQRS	MEAN SQR	F-STAT	SIGNIF
BETWEEN MEANS	4	32.344			
COVARIATE	1	127.61	127.61	195.46	.0000
ERROR	402	262.47	.65290		
EQUAL SLOPES	4	7.6238	1.9059	2.9766	.0192
ERROR	398	254.84	.64031		
EQUAL ADJ MEANS	4	15.252	3.8129	5.8399	.0001
ERROR	402	262.47	.65290		
TOTAL	407	422.43			

COEFFICIENTS

COVARIATE	COEFF	T-STAT	SIGNIF
LIN'S INDEX	.0331	14.0	.0000

REGRESSIONS

PLOT #	(1)350	(2)351	(3)352	(4)357	(5)358
N	92	62	64	70	120
CONSTANT	1.20	1.75	1.59	1.59	0.885
LIN'S	0.0402	0.0244	0.0281	0.0205	0.0394
SE OF REGR	0.755	0.634	0.701	0.968	0.850
R-SQR	0.51	0.26	0.29	0.12	0.38

TABLE 19. <u>Analysis of Covariance Group I Plots Newnham's Index</u>

SOURCE	DF	SUM SQRS	MEAN SQR	F-STAT	SIGNIF
BETWEEN MEANS	4	32.344			
COVARIATE	1	226.35	226.56	556.95	.0000
ERROR	402	163.53	.40678		
EQUAL SLOPES	4	4.7440	1.1860	2.9728	.0193
ERROR	398	158.78	.39895		
EQUAL ADJ MEANS	4	34.214	8.5536	21.027	.0000
ERROR	402	163.53	.40678		
TOTAL	407	422.43			

<u>COEFFICIENTS</u>

COVARIATE	COEFF	T-STAT	SIGNIF
NEWNHAM'S	-.938	-23.6	.0000

<u>REGRESSION</u>

PLOT #	(1)350	(2)351	(3)352	(4)357	(5)358
N	92	62	64	70	120
CONSTANT	4.18	3.81	3.90	3.54	3.71
NEWNHAM'S	-1.01	-0.729	-0.778	-0.835	-1.09
SE OF REGR	0.595	0.547	0.526	0.824	0.622
R-SQR	0.69	0.45	0.60	0.36	0.67

TABLE 20. Analysis of Covariance Group II Plots Bella's Index

SOURCE	DF	SUM SQRS	MEAN SQR	F-STAT	SIGNIF
BETWEEN MEANS	3	51.132			
COVARIATE	1	211.41	211.41	515.88	.0000
ERROR	325	133.19	.4098		
— — — — — — —					
EQUAL SLOPES	3	3.8911	1.2970	3.2301	.023
ERROR	322	129.30	.40154		
— — — — — — —					
EQUAL ADJ MEANS	3	2.2789	.75963	1.8536	.137 NS
ERROR	325	133.19	.40981		
— — — — — — —					
TOTAL	329	395.73			

COEFFICIENTS

COVARIATE	COEFF	T-STAT	SIGNIF
BELLA'S INDEX	-0.0514	-22.7	.0000

REGRESSIONS

PLOT #	354	355	356	359
N	74	124	83	49
CONST	3.90	3.85	3.24	4.21
BELLA'S	-0.00568	-0.00547	-0.0430	-0.0662
SE REGR	0.619	0.644	0.704	0.485
R-SQR	0.56	0.67	0.59	0.66

TABLE 21. <u>Analysis of Covariance Group II Plots Lin's Index</u>

SOURCE	DF	SUM SQRS	MEAN SQR	F-STAT	SIGNIF
BETWEEN MEANS	3	51.132			
COVARIATES	1	138.07	138.07	217.29	.0000
ERROR	325	206.52	.63545		
EQUAL SLOPES	3	1.7311	.57703	.90729	.433 NS
ERROR	322	204.79	.63599		
EQUAL ADJ MEANS	3	21.790	7.2632	11.430	.0000
ERROR	325	206.52	.63545		
TOTAL	329	395.73			

<u>COEFFICIENTS</u>

COVARIATE	COEFF	T-STAT	SIGNIF
LIN'S INDEX	0.0398	14.7	.0000

<u>REGRESSIONS</u>

PLOT #	(1) 354	(2) 355	(3) 356	(5) 359
N	74	124	83	49
CONSTANT	1.13	0.313	0.326	1.16
LIN'S	-0.0307	-0.0429	-0.0425	-0.0376
SE OF REGR	0.829	0.859	0.831	0.449
R-SQR	0.21	0.42	0.41	0.71

TABLE 22. <u>Analysis of Covariance Group II Plots Newnham's Index</u>

SOURCE	DF	SUM SQRS	MEAN SQR	F-STAT	SIGNIF
BETWEEN MEANS	3	51.132			
COVARIATES	1	217.18	217.18	553.97	.0000
ERROR	325	127.41	.39205		
EQUAL SLOPES	3	4.1788	1.3929	3.6396	.0131
ERROR	322	123.24	.38272		
EQUAL ADJ MEANS	3	58.021	19.340	49.332	.0000
ERROR	325	127.41	.39205		
TOTAL	329	395.73			

<u>COEFFICIENTS</u>

COVARIATE	COEFF	T-STAT	SIGNIF
NEWHAM'S	-1.06	-23.5	.0000

<u>REGRESSIONS</u>

PLOT #	(1) 354	(2) 355	(3) 356	(5) 359
N	74	124	83	49
CONSTANT	4.06	3.72	3.14	4.05
NEWNHAM'S	-1.09	-1.23	-0.981	-0.836
SE OF REGR	0.633	0.608	0.717	0.403
R-SQR	0.54	0.71	0.56	0.77

mations radically improves R-square or reduces standard error over the log model. For comparison's sake it was deemed better to report all indices under the log transformation.

The model for analysis of covariance was based on the natural log of basal area growth. As before basal area growth was determined as:

$$BAGR = (D_{75})^2 - (D_{70})^2 \qquad (17)$$

where subscript indicates the year of measurement. Basal area in square feet is obtained by the usual factor .005454 (i.e., graph scales are 1/.005454 or 183.35 times the area growth in square feet), and square cm can be obtained by multiplying the value by 5.0671. The best models were obtained using natural log transformations of the dependent variable. The comparison of R-square values was deemed appropriate as the intent of these analyses was to assay the validity of one model in combining data on several plots. The comparison is made in Table 23. The best relationships appear to be Bella's index and Newnham's. Complete covariance analysis of these indices were run. Again Lin's index was included because of its specificity to western hemlock. (Figures 25 through 26 illustrate regressions on all plots for Newnham's index.)

Table 23. R-Square Comparisons for Competition Indices

PLOT	350	351	352	357	358	354	355	356	359
INDEX									
BELLA	$.75^1$	$.36^2$	$.53^2$	$.49^1$	$.60^2$	$.55^1$	$.67^2$	$.58^1$	.66
EK-MSRD	.68	.31	.44	.45	.53	-	-	-	-
HEGYI	.68	.29	.49	$.48^2$	.49	-	-	-	-
LIN	.51	.26	.29	.12	.38	.21	.42	.41	$.71^2$
NEWNHAM	$.69^2$	$.45^1$	$.60^1$	.36	$.67^1$	$.54^2$	$.71^1$	$.56^2$	$.77^1$

Note: raised numerals indicate highest and second highest value.

The analysis of covariance tables were interpreted as follows: 1) the value of the covariance analysis is tested, if the covariate is not significant at this point the analysis is abandoned; 2) slopes of individual lines within the group are tested, significance at this point indicates that separate regression models are required statistically and further analysis should be abandoned (for this grouping); 3) on plots with equal slope further analysis can be made on the levels of the lines. This final test indicates that there is a factor acting uniformly on the sampled population and in the case of the logarithmic model adopted here a multiplicative factor is indicated.

For purposes of illustration, the analysis of covariance was rerun on three Group I plots using Newnham's index, (Table 24). In this case slopes are the same and only levels are different. To combine plots for selection the lines from the individual plots are corrected for differences in level. The adjusted means presented in Table 24 are subtracted from the grand mean for all observations. This difference
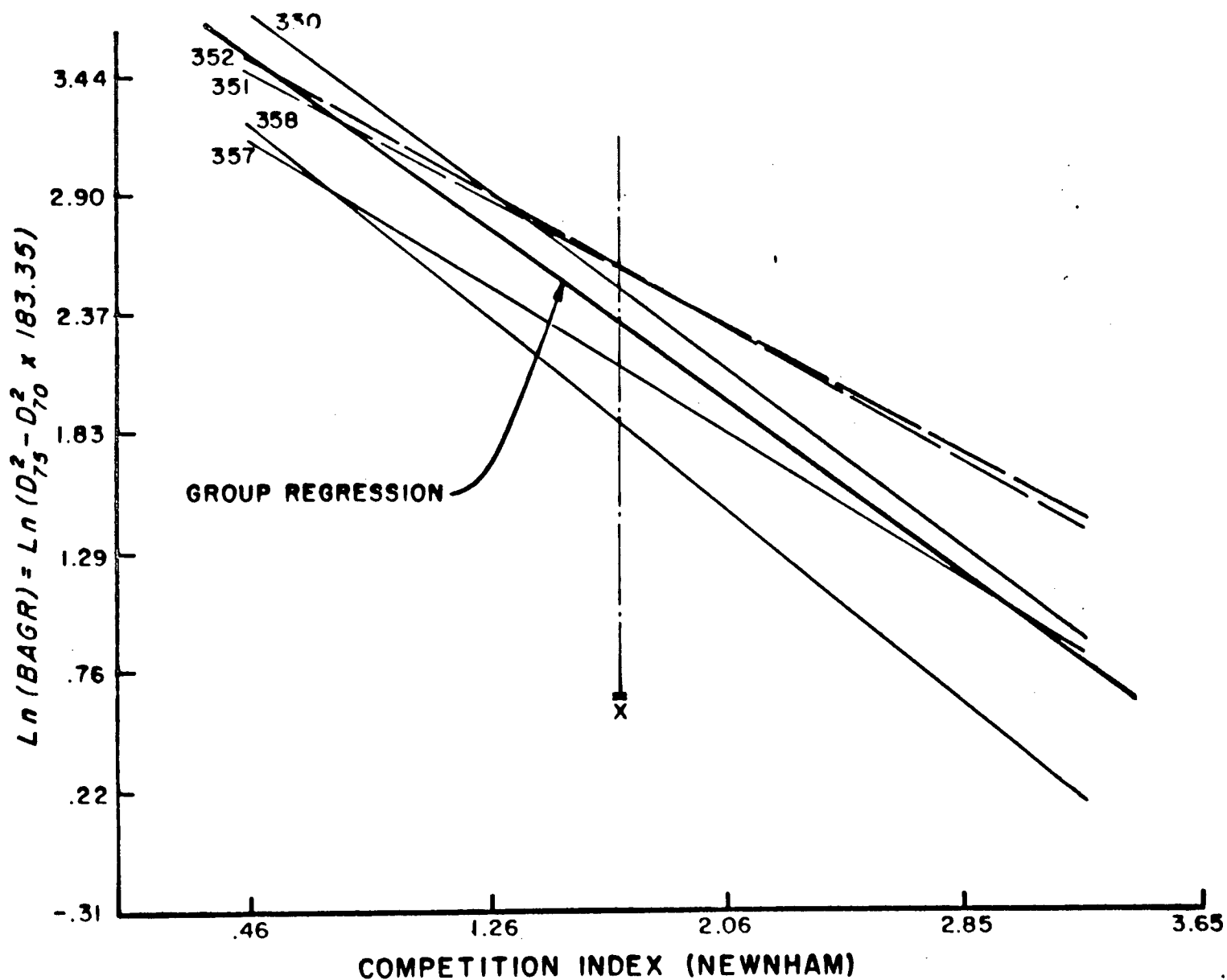
Figure 25.   LN (BAGR) versus Competition equation lines Newnham's Index,
             Group I plots.
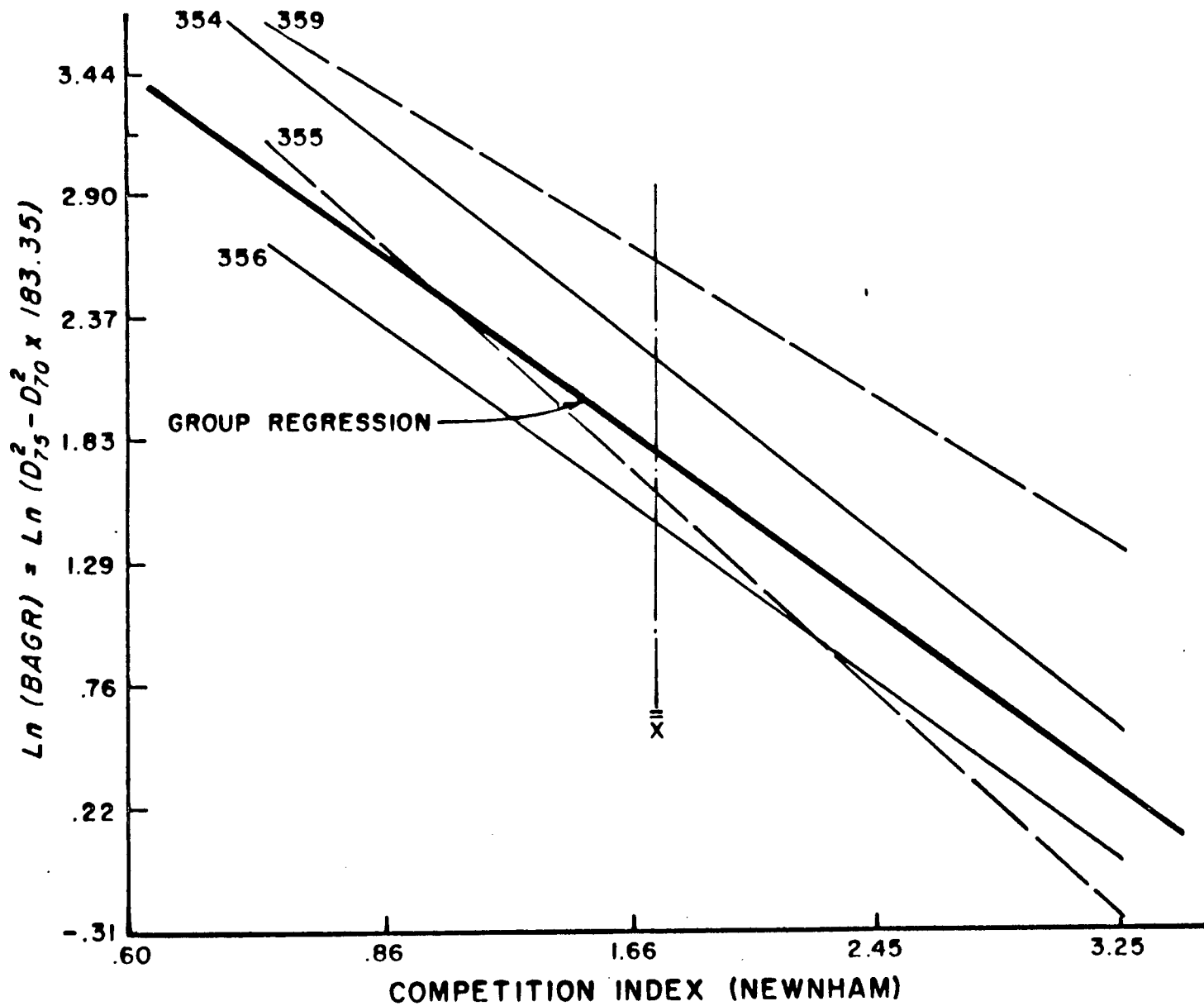
Figure 26. Ln (BAGR) versus Competition equation lines Newnham's Index, Group II plots.

Table 24. Reduced Set Group II Plots Adjustment Analysis

SOURCE	DF	SUM SQRS	MEAN SQR	F-STAT	SIGNIF
BETWEEN MEANS	2	38.225			
COVARIATES	1	111.54	111.54	284.38	.0000
ERROR	202	79.229	.39222		

- - - - - - - - -

EQUAL SLOPES	2	1.0597	.52986	1.3557	.2601 NS
ERROR	200	78.169	.39084		

- - - - - - - - -

REGRESSION EQUAL ADJ MEANS ERROR

- - - - - - - - -

TOTAL	205	229.02			

COEFFICIENTS

COVARIATE	COEFF	T-STAT	SIGNIF
NEWNHAM'S INDEX	-.963	-16.86	.0000

REGRESSIONS

PLOT #	354	356	359
MEAN	2.19	1.52	2.57
ADJ MEAN	2.20	1.47	2.63
GRAND MEAN	2.01	2.01	2.00
ADJUSTMENT	0.188	0.537	0.625
CONSTANT	4.06	3.14	4.05
NEWNHAM'S INDEX	-1.09	-0.981	-0.836
SE OF REG	0.63	0.72	0.40
R-SQR	0.54	0.56	0.77

Table 25. Adjusted Regression on Group II Plots

SOURCE	DF	SUM SQRS	MEAN SQR	F-STAT	SIGNIF
REGRESSION	1	111.87	111.87	288.06	.0000
ERROR	204	79.229	.38838		

- - - - - - - - -

TOTAL	205	191.10			

COEFFICIENTS	COEFF	T-STAT	SIGNIF
CONSTANT	3.65	34.4	.0000
NEWNHAM'S INDEX	-.963	17.0	.0000
SE OF REG	.623		
R-SQR	.585		

is then added to observations on the corresponding plot. The adjusted growth was then entered into a regression model as the new dependent variable. Now a single model can be used to select trees from all three plots. This is an important result as it indicates that thinned and unthinned plots can be combined in a selection of parent trees. The regression model is presented in Table 25. Figure 27 illustrates the scatter of data points once the effect of average tree size is removed. The regression line is indicated.

Crown Area Model

A related approach to evaluating competition is available in Mitchell's simulation model (1975a). This model, while recognizing the effect of growing space on the development of the trees, places its major emphasis on the actual development of the crown. The idea of the crown as the photosynthetic producer of wood laid down in the annual growth ring is central to the model concept. Quantitative measures of branch elongation, needle retention and needle efficiency are all integrated in Mitchell's growth simulation model.

In the model, competitive status of a tree is expressed as the ratio of a tree's actual foliage volume to the maximum foliar volume of a tree of similar dimension growing under open conditions.

$$CI_j = \ln \frac{FV_j}{FV_c} \tag{18}$$

where CI_j = competition index of the jth subject tree. FV_j = foliar volume of the jth subject tree. FV_c = foliar volume of a comparable open-grown tree.
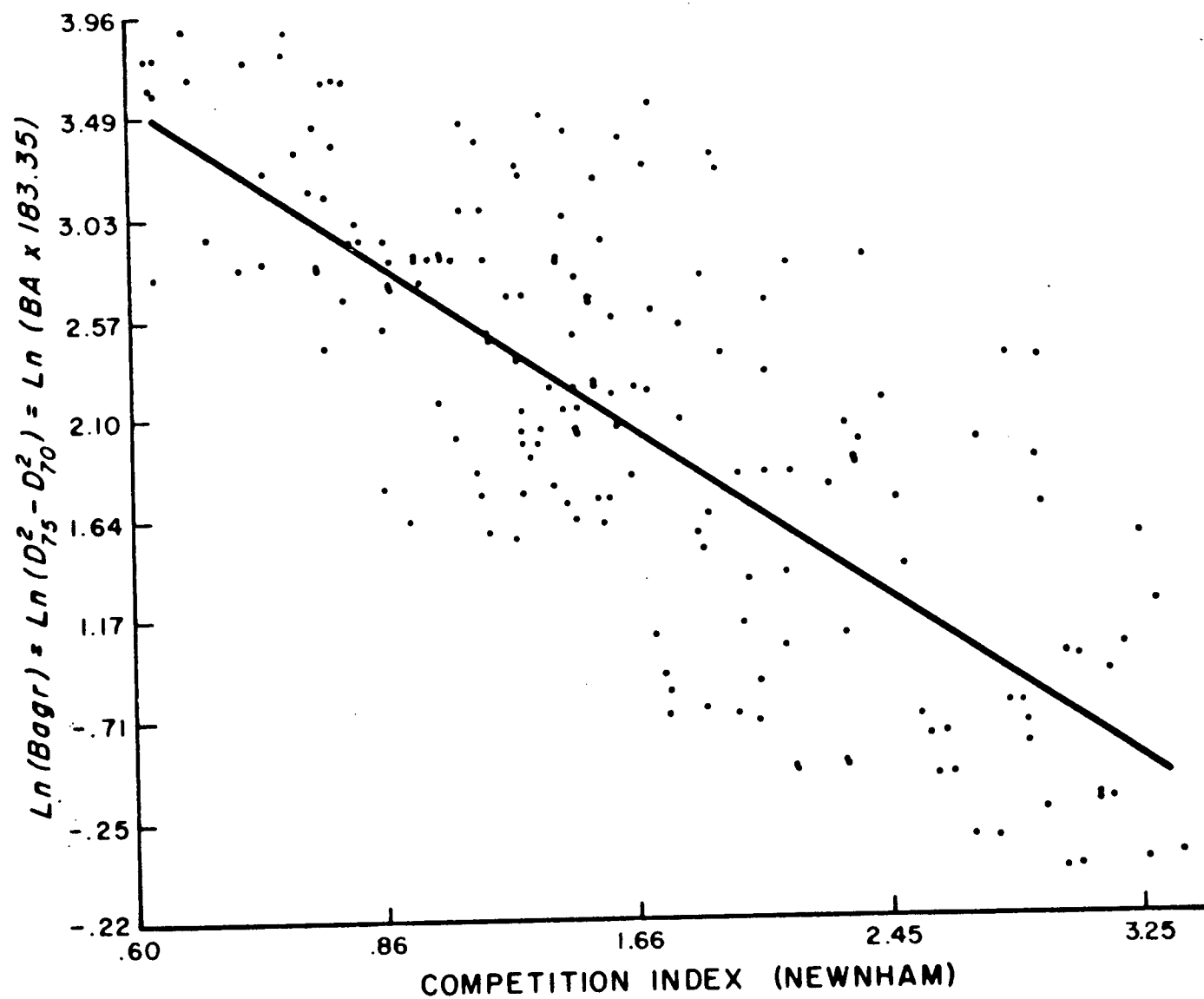
Figure 27.   Combined regression for Group I plots, Newnham's Index.

While objections to using current crown dimensions as an index
of competition have been raised (Bella, 1970), they do not apply to
Mitchell's index, since it relates current size of crown to the open-
grown condition. This process is analogous to the competition indices
which are derived from zones of influence based on the crown extent
of open-grown trees. In addition, expressions of crown dimensions and
growth are immediately noted to have the dimensions of growth per unit
of area occupied; a direct measure of the utilizable efficiency of
production of wood. An efficient crown implies one which produces wood
at the minimum expense in occupation of space. This definition differs
from Baskerville's (1965) definition of efficiency in that recoverable
wood product must be produced.

He compared the efficiency of trees of different crown classes
and found that the suppressed trees were the most efficient ones. How-
ever, the context of the investigation must be considered. In the
purely biological sense smaller trees at a given time in the development
of a stand utilize a smaller proportion of the resources required to
produce wood fiber than the larger trees. The dominants accumulate
proportionately more resources; they grow more, but are more wasteful.
If our interest and understanding of the situation is primarily the
total biomass produced on a given unit area this information may be
useful to us directly. However, if our interest is in the eventual
economic utilization of resource, we must remember that much of the
wood fiber is accumulated in small stems which are never going to be
economically valuable. Moreover, the presence of a larger number of
stems means slower growth for those stems which conceivably can become
harvestable resource. Utilizable efficiency connotes managed stand

production at high, recoverable rates.

For the purposes of this portion of the investigation, a crown competition index was not calculated for each tree. In fact, open-grown crown information necessary for calculations is not available for hemlock. Because of the method of collection of the crown data (i.e., the current crown was photographed), the period of growth used was the preceding five-year interval. It was assumed that the current crown is not much different from the crown at the start of the period and that the short duration of the period would not have seen major changes in the status of the crown. Thus, crown area is an estimate of growth potential for a short span of time. When related to other trees in the plot, crown area (CRAR) can be used as an estimator of utilizable efficiency when related to basal area growth.

Estimation of CRAR is possible from the ground, but much better estimates should be possible using low-level aerial photography. Low speed (30 mph), low-level (200') photographs should yield high resolution stereophotographs for the measurement of crown dimensions and, under good conditions, could yield information on tree heights and crown volumes (Mitchell, 1975b).

This approach was applied to the Turnour Island hemlock stands, but the crown photographs seldom showed the ground, which is necessary if tree heights and ground level changes are to be determined. Ground markers of various color and markings for plot identification were made on each plot. Only one marker actually appeared in the photographs! Individual crowns are difficult to delineate in aerial photographs of dense hemlock stands; in fact, many suppressed or intermediate crown

class trees were not visible. They are, however, a source of uncer-
tainty in the delineation of crowns of codominant and dominant trees.
In effect, most of the smaller trees, those having high competition
indices, were removed from the population being sampled as a consequence
of the method. In addition, several dominant or codominant trees had
to be excluded from the population because the actual crown extent could
not be identified (a problem arising at least in part from the lack
of control over altitude). Furthermore, positive assignment of a mea-
sured crown to an individual tree on the stem map was not always possible.
In most cases, these problems could be reduced with better flight con-
trol. As a practical technique, creating small openings near the plots
would also be worthwhile in obtaining ground registration.

Selections Based on Crown Area Models

The regression model for basal area growth increment on CRAR was
a simple linear one. The absence of many suppressed and intermediate
trees meant that it was less important to deal with their contribution
to variability than in the competition index approach; selection was
based directly on the size of the residual. There was also no problem
associated with trees growing near the border of the plot as the "index"
of environmental effects is the crown itself. Coefficients of the
regressions are presented in Table 26.

Each plot regression was examined for probability of distribution
of residuals and uniformity with respect to the independent variable,
CRAR. While a statistical test was not performed, regressions for Group
II (Plots 354 to 356 and 359) appear to have the same slope (b_1). The
pattern of change for the intercept (b_0) for these plots corresponded

with the past level of thinning and current basal area. A similar relation was suggested for the tidal flat plots of Group I. The differences between these two groups may be site and/or age variation. There was insufficient range in the data to test this hypothesis.

Table 26. <u>Crown Area-Growth Regressions</u>

$$Y = b_0 + b_1 (CA) + e*$$

Group	Plot	b_0	$(^{se}b_0)$	b_1	$(^{se}b_0)$	R^2
I	350	3.59	1.35	.102	.0074	.63
	351	.306	1.70	.100	.0085	.63
	352	.249	1.30	.106	.0076	.67
	357	2.59	1.56	.086	.0086	.50
	358	1.64	1.20	.092	.0078	.58
II	354	3.11	1.60	.128	.0164	.39
	355	.669	.646	.142	.0078	.69
	356	1.04	.795	.136	.0096	.69
	359	4.14	1.39	.134	.0119	.63
III	353	3.59	1.56	.098	.0152	.55
	400	2.69	1.34	.061	.0083	.51
	401	.870	.740	.065	.0073	.47

* Standard errors of estimation are included in computer output.

The final selection of plus trees was performed in the same manner as the competition index selections. The upper confidence limit for an individual observation was used. A list of the selected trees with their residual is presented in Table 27. The trees indicated with an

Table 27. <u>Trees Selected on Crown Area Efficiency</u>

Plot	Observation Number	Tree Number	Standardized Residual
350	41	64°	4.86*
350	17	29°	2.66
351	1	220	4.54*
351	44	317	1.63
352	6	437°	3.20
352	85	613°	3.00
353	36	693	4.53*
353	61	750°	1.83
354	32	1016°	2.52
354	57	1033	2.12
354	45	1027°	1.99
355	75	1219°	4.85*
355	1	1039°	3.52**
356	48	1590	4.43
356	8	1411	2.49
357	30	1826	3.01
357	65	1915	2.49
358	29	2110°	4.32*
358	70	2212°	2.06
358	91	2294	2.09
359	59	2204	3.85*
359	51	2193°	2.07
400	25	199°	1.75
400	42	323	1.74
401	3	12	3.02
401	17	97°	2.86

* These values are suspect. Trees are either mismeasured or older than rest of stand.

** Phenotypically selected tree.

^{o} Trees selected by one or more competition models.

asterisk (*) are of such large residual that further measurement of
age and growth should be taken to check for irregularities. In one
or two cases, large residuals were definitely associated with an indi-
vidual tree which was 5 to 10 years older than the stand average age.
These trees were removed from the succeeding analyses. However, as
only a small proportion of the trees had their total age measured, it
is possible that some of the asterisked trees are simply older trees
(advanced regeneration). Table 28 shows a comparison of phenotypically
selected candidate trees and their associated crown and competition
residuals.

Analysis of Covariance

As with the results of competition indices the results of indi-
vidual regressions obtained on each plot are discouragingly expensive
to obtain if each local population must be treated as were the permanent
sample plots at Turnour Island. There are some enticements to further
analysis. The b_1 coefficients for groups of plots (especially I and
II) are very similar and the regressions are of untransformed linear
nature. Furthermore, differences noted in intercepts can be associated
with the number of stems per acre and increment per stem, fewer stems
per acre accruing larger per stem increment. It seems advantageous
to apply the methods of analysis of covariance to the plots in Group
I and II.

Results of the analysis of covariance including regressions for
the model BAGR = constant + b(CRAR) are summarized in Tables 29 and
30. The coefficients were used to plot individual regression lines
in Figures 28-30. Examinations of the figures indicates a difference

Table 28. Competition Index and Crown Competition Selection
Values for Phenotypically Chosen Trees

Group	Plot	Tree	Bella's Index Standard Residual	Crown Competition Standard Residual
I	354	904	.58	-0.38
		954	1.63	
	355	1039	1.80*	3.52^o
		1165	**	0.53
	356	1431	**	-0.23
		1697	**	-1.10
		1725	**	-0.97
		1745	**	1.28
	359	2147	1.24*	-0.23
		2160	0.37	
		2165	0.44	
		2176		0.38
II	350	31	-0.10	1.06
		85	-1.43	-0.11
	352	519	**	-0.61
		583	**	-0.81
	357	1806	**	-0.30
		1894	**	-0.02
	358	2258	**	0.65
		2239	**	0.31
III	400	159	**	0.20
		206	**	1.22
	401	265	1.43	0.59
		268	1.31	2.43
	353	670	-0.18	-0.20
		749	1.77*	-0.13

* Tree selected by competition index.

** Trees located in buffer strip for which no competition selection
value was obtained.

^{o} Tree selected on crown area efficiency.

Table 29. Analysis of Covariance Group I Plots
             Crown Area as Covariate

SOURCE	DF	SUM SQRS	MEAN SQR	F-STAT	SIGNIF
BETWEEN MEANS	4	1982.8			
COVARIATES	1	33718.	33718.	813.6	.0000
ERROR	462	19147.	41.44		
EQUAL SLOPES	4	104.3	26.07	.6272	.643 NS
ERROR	458	19043.	41.56		
REGRESSION	1	34893.			
EQUAL ADJ MEANS	4	807.5	201.8	4.871	.000
ERROR	462	19147.	41.44		
TOTAL	467	54848.			

COEFFICIENTS

COVARIATE	COEFF	STD ERROR	SIGNIF
CRAR	.09147	.00321	.0000

REGRESSIONS

PLOT #	350	351	352	357	358
N	109	80	89	95	95
CONSTANT	4.44	2.76	1.42	2.04	1.23
CRAR	.092	.082	.098	.095	.090
SE REG	6.46	5.76	6.47	7.72	5.48
R-SQR	.65	.66	.65	.60	.67

All regressions highly significant.

Table 30.   Analysis of Covariance Group II Plots
            Crown Area as Covariate

SOURCE	DF	SUM SQRS	MEAN SQR	F-STAT	SIGNIF	
BETWEEN MEANS	3	3929.4				
COVARIATES	1	19570.	19570.	614.59	.0000	
ERROR	392	12482.	31.843			
EQUAL SLOPES	3	65.871	21.957	.68790	.55	NS
ERROR	389	12416.	31.919			
REGRESSION	1	22838.				
EQUAL ADJ MEANS	3	661.68	220.56	6.9265	.00	***
ERROR	392	12482.	31.843			
TOTAL	396	35982.				

COEFFICIENTS

COVARIATE	COEFF	STD ERROR	SIGNIF
CRAR	.12994	.0052414	.0000

REGRESSIONS

PLOT #	354	355	356	359
N	89	144	87	77
CONSTANT	4.41	1.38	.609	3.43
CRAR	.115	.133	.128	.137
SE REG	7.01	4.78	5.22	5.86
R-SQR	.40	.69	.62	.69

All regressions highly significant.
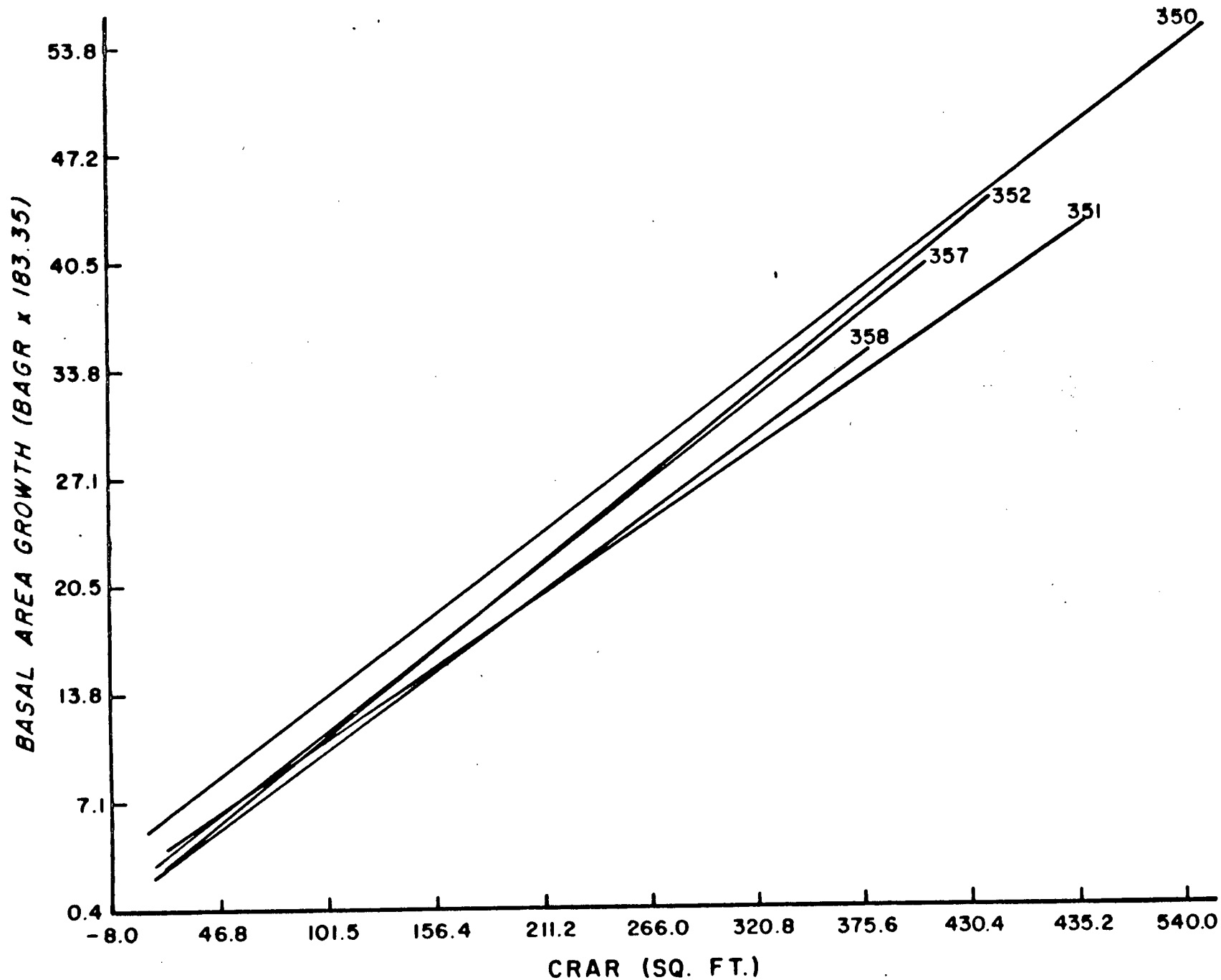
Figure 28. Regression lines for Group I plots BAGR versus Crown Area.
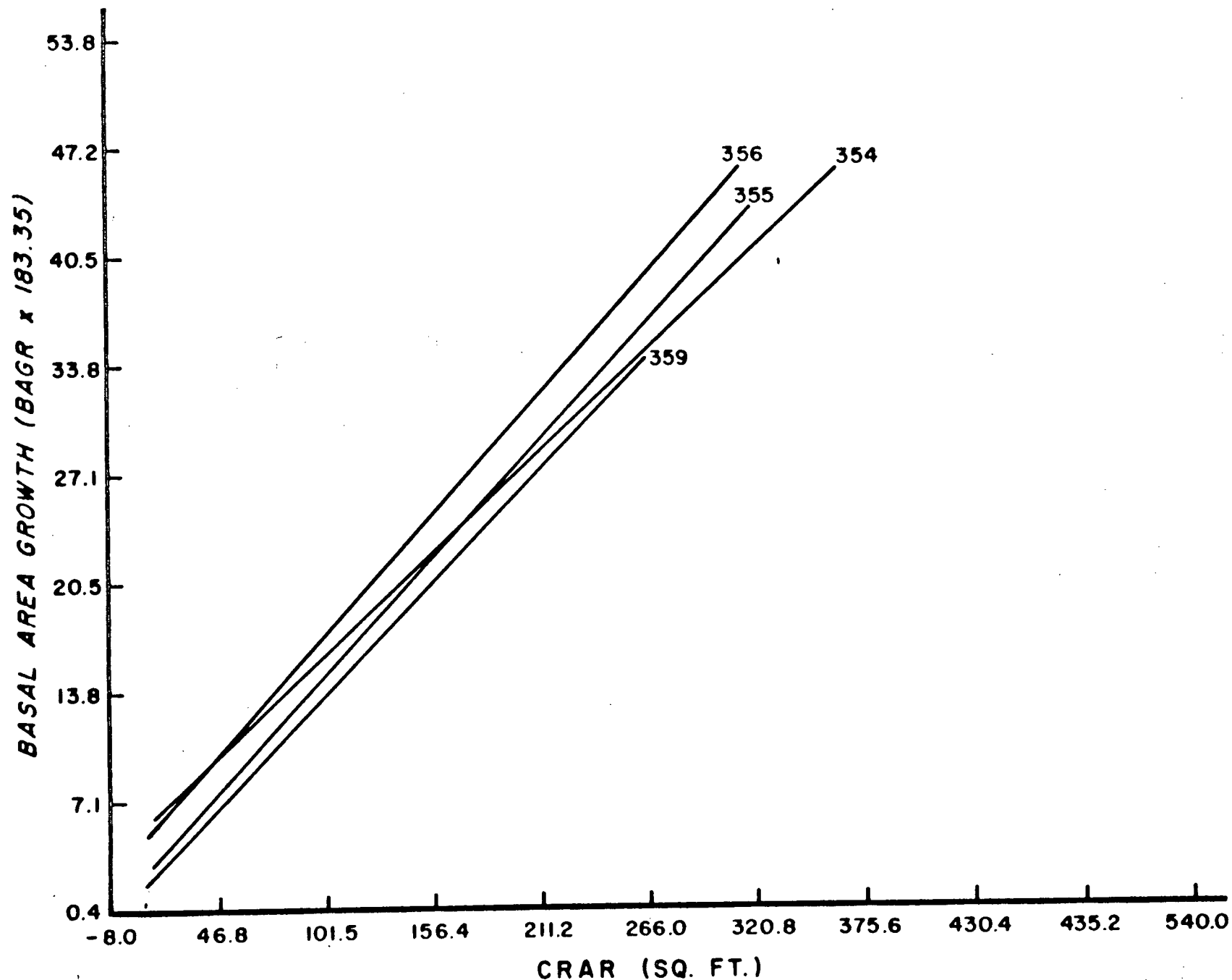
Figure 29. Regression Lines for Group II plots BAGR versus Crown Area.
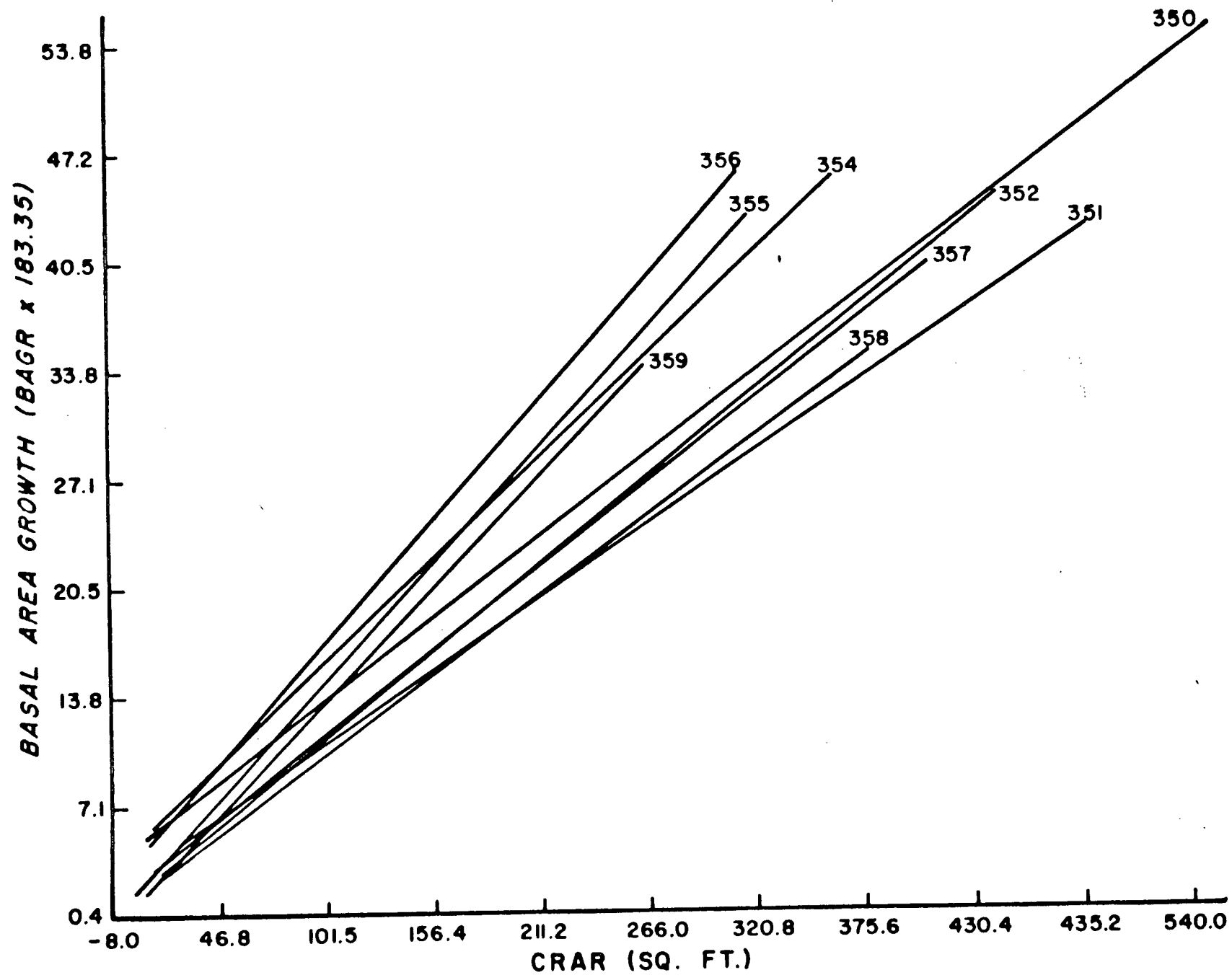
Figure 30. Regression lines for all plots in both Groups I & II BAGR versus Crown Area.

in slopes between Groups I and II (confirmed by preliminary analysis).
Covariance analyses were run on the separated Groups. Differences between
regressions are in the levels. It seems quite possible that between
group slope differences are related to age through the cumulation of
current annual increment which is being measured in this study. This
hypothesis should be tested by measurement of relations on growth plots
of slightly older and slightly younger PSP's of similar site index.

To illustrate the possibility of combining crown regressions into
a single model for selection of individual trees, the common mean was
subtracted from each adjusted mean and this value added to each obser-
vation on its corresponding plot. This process corrects each line to
the common model. A test regression was run with all plots within a
group to confirm the procedures effect. Residuals on the covariance
adjusted model were calculated and then examined. In general the same
trees were selected, as were with the individual plot regression models.
The relative sizes of residuals were maintained so that some of the
trees selected on individual plots are less outstanding when viewed
in this context. Differences in the selections are due to editing of
the data as the addition or subtraction of a constant to the regression
should not change the sizes of residuals though their standardized value
will be based on the pooled model.

It is only possible to examine genetic potential of the selected
trees in long term genetic experiments. The historical performance
of individual trees can lend some credence to our selections at Turnour
Island. The data were sorted into ascending crown area. Then a sample
of trees having positive and negative residuals, after the effect of
crown area is removed, was plotted. Figures 31 and 32 illustrate example
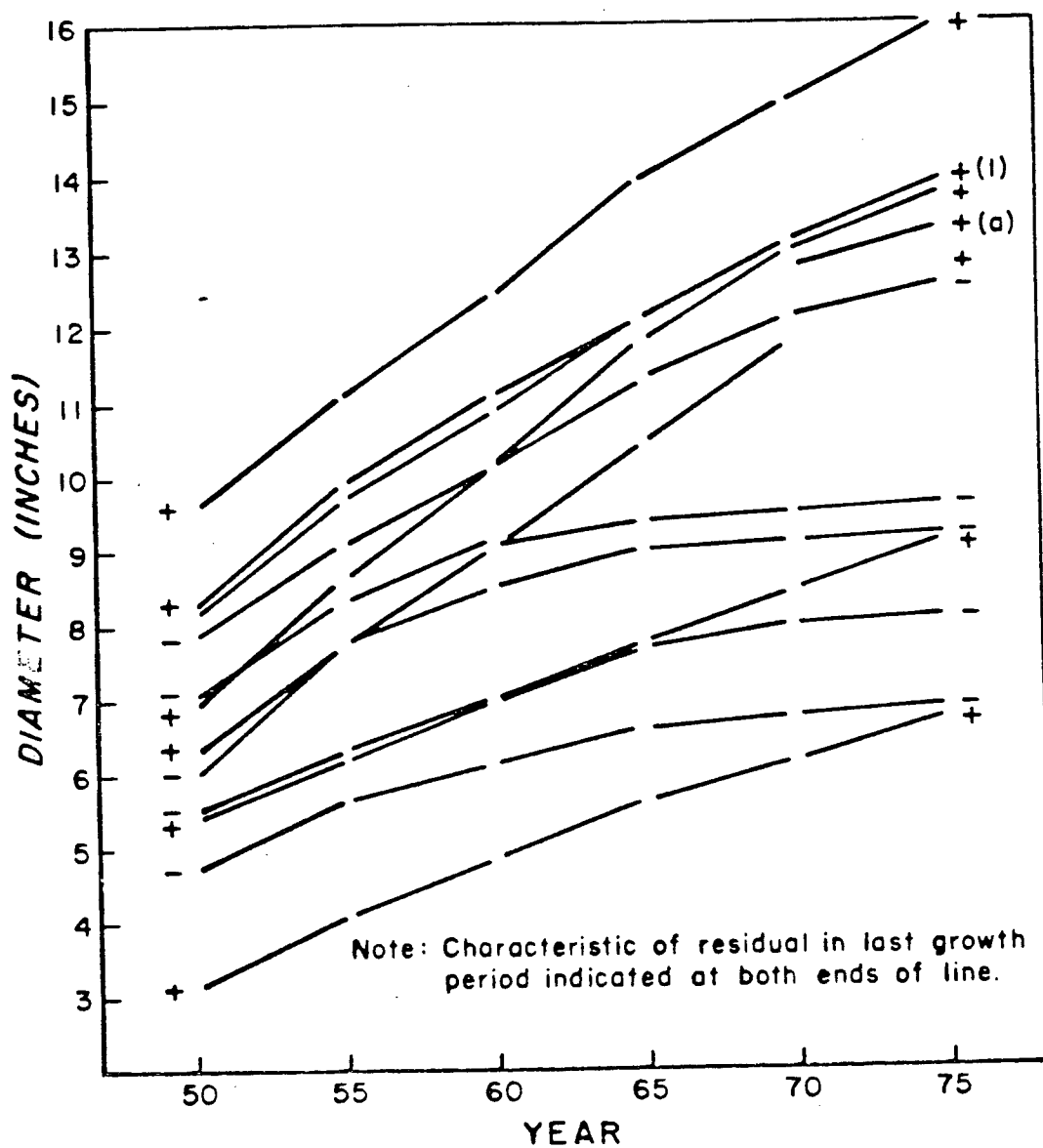
Figure 31. A Sample of cumulative diameter histories for Plot #356.
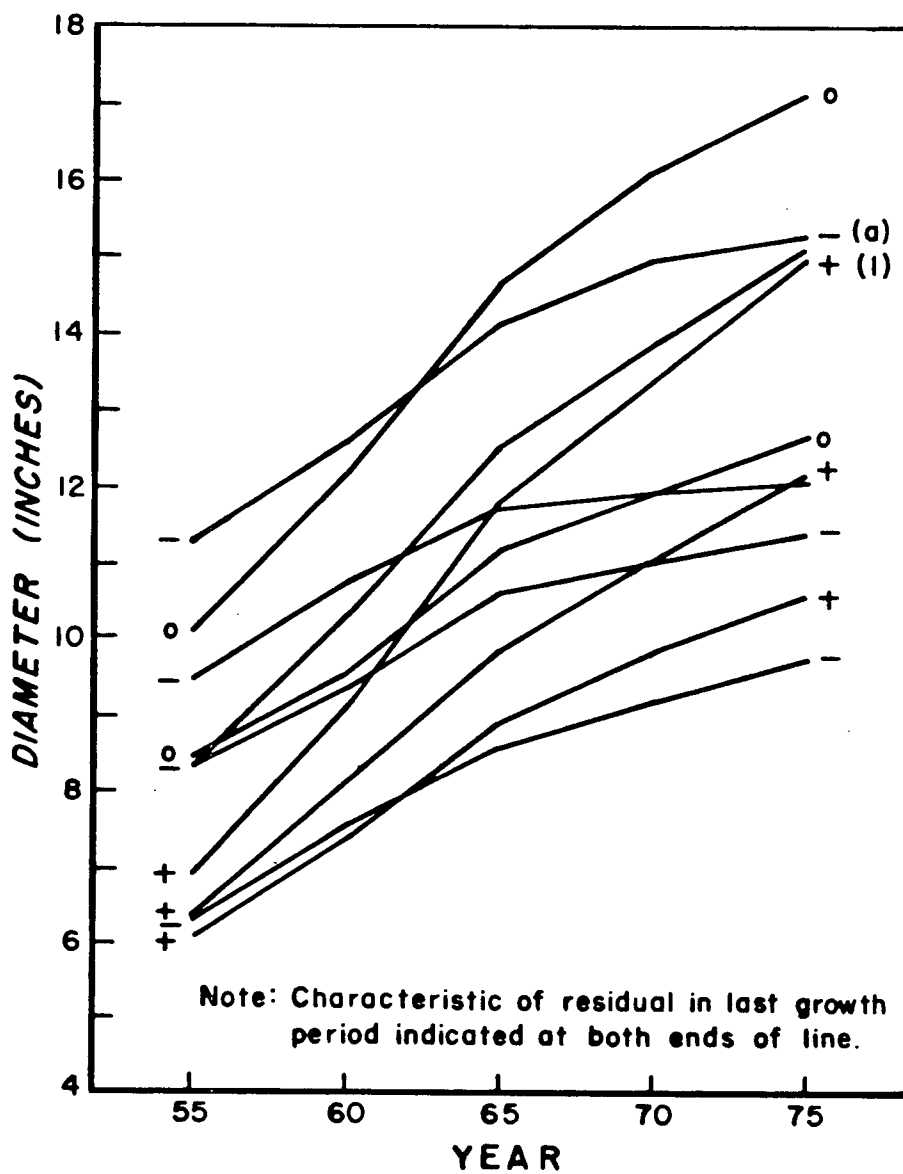
Figure 32. A sample of cumulative diameter histories for Plot #359.

trees from the unthinned plot 356 and heavily thinned plot 359 respec-
tively. It is evident that across the competition spectrum, trees with
positive residuals are continuing to out-perform trees having negative
residuals. Crown selection trees were included in the sample of trees
illustrated purposely. The selected trees are indicated by a paren-
thetical number. The residual indicated by (a) is a phenotypic selec-
tion which had a positive residual. A closer examination of the per-
formance not presented in detail indicated that the size of the residual
correlates well with the current slope of the growth record line. This
analysis serves to allay the suspicion that some trees might represent
sudden, fortuitous release rather than the established competitive
advantage. The results offer encouragement for the use of the proposed
selection method, even though the encouragement is not strictly genetic.
The results also suggest the importance of setting biologically sound
management goals in the establishment of plus tree selection for
western hemlock. There are trees in the stand which continue to grow
better than their neighbors under the influence of intense crowding.
Trees capable of high production under intense competition contribute
more volume per acre than large trees which require disproportionately
large amounts of growing space.

Combining Competition and Crown Parameters

Competition indices reflect the differences in growth due to spatial
patterns on the ground. The ability of crown measures to predict growth
especially as this related to treated stands confirms the importance of
considering the aerial competition in hemlock. The ability of hemlock

crowns to seek openings in the canopy and not directly above the stem distribution at breast height make the crown a possible component in the construction of growth models which have a value in the selection of superior individuals. Figure 33 illustrates a small portion of plots 354 and 355 stem map. The accompanying overlay shows the capability of crowns to shift into more open areas of the canopy. Thus in thinned stands it might be expected that crown parameters would be more apt to predict the growth of the remaining trees than competition index derived from stem maps. Indeed, this is the case for the Turnour Island PSP's. On plots which have been recently thinned, or do not have a completely closed canopy, crown parameters contribute a larger proportion of the reduction in sums of squares than competition indices or in the case of plot 359 a larger proportion than past diameter.

If crown parameters and the competition indices express different qualities in the environment of an individual tree it would be reasonable to combine them in a single growth model. Three of the plots were chosen to represent extremes in condition. Plots 350 and 359 currently have open canopies due to thinnings. Plot 355 is one of the densest and one whose growth was poorly described under tree assumptions of all the previously investigated models. A linear model including crown area projection (CRAR), crown class (CC) as assigned by MacMillan-Bloedel foresters, and Bella's index was fit,

$$BAGR = b_0 + b_1(CRAR) + b_2(CC) + b_3(CRAR) + e.$$

The data were limited to trees which had the index computed (i.e., those
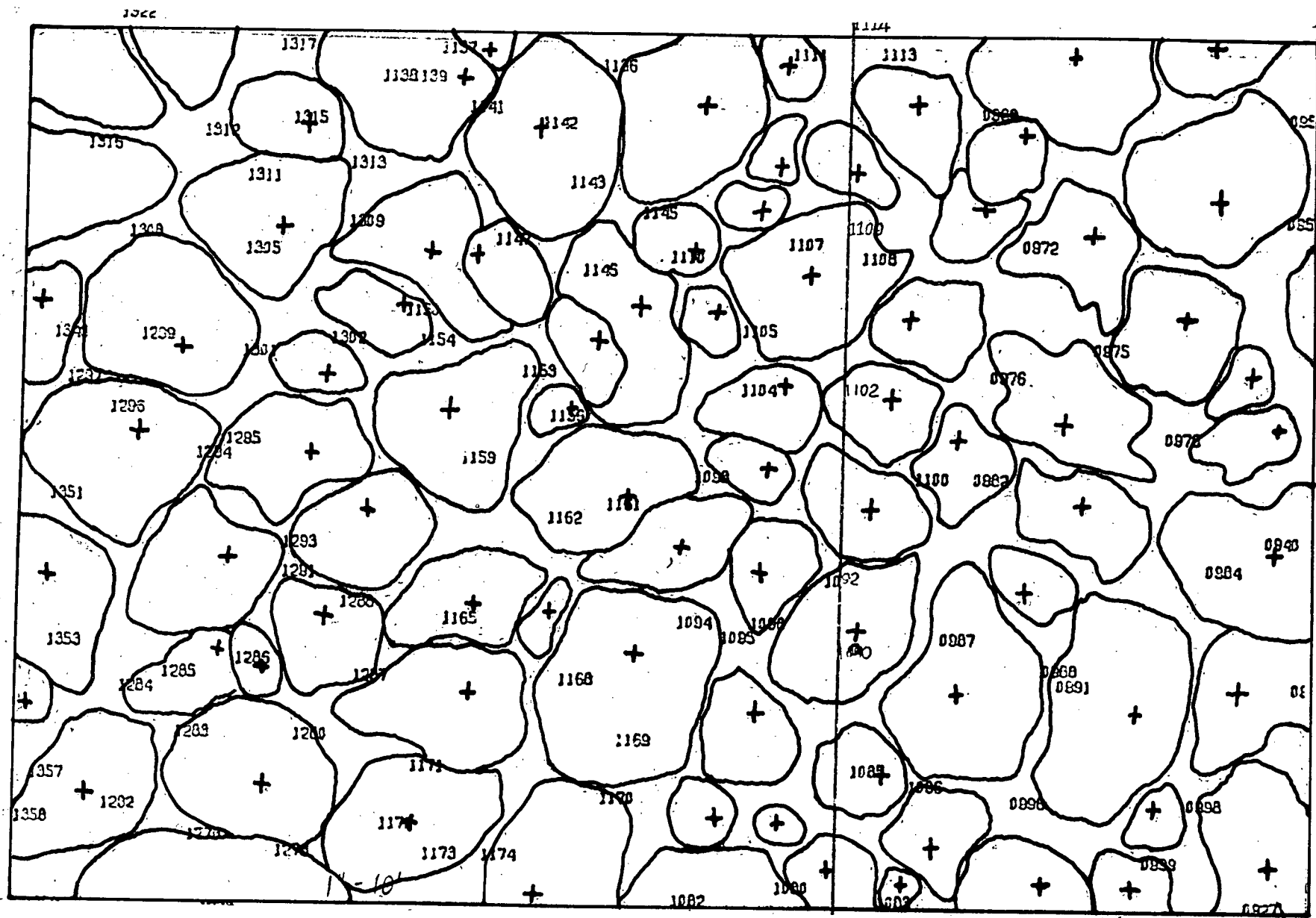
Figure 33.   Stem map of a portion of plots 354 and 355 and Crown Map Overlay.

within the buffered area on the plot) and photographed crowns. In all three cases the R-square value was increased over that obtained using CRAR alone. Plot 350, the most recently thinned, showed the least improvement over regressions involving CRAR alone. Comparison of R-square for multiple variable models and Bella's index alone shows higher values for 355 and 359. Plot 350 has a lower R-square value. These latter comparisons should be interpreted carefully. The R-square value should increase with the addition of predictive values. The coefficients of the added variables are significantly different from zero indicating that they do add to the regression. The comparisons are of logarithmic transformations. Plot 350 has lower quality photographs which should tend to decrease the chance that it would contribute more information to the competition model. The results of the regressions are summarized in Table 31. These models were considered exploratory and no selections were made using this approach. The reduction in standard errors of regression are noticeable, but genetic interpretation is less clear, also the analysis of covariance becomes extremely difficult to interpret. Until some methods of constructing common models becomes available there seems little possibility of constructing models of general application to the problem of selecting superior trees. Coefficients (b_1's) are significantly different even in the closely related plots 355 and 359.

The attempt to combine competition indices and crown information has been discussed briefly and has not been used to select candidate trees.

Application Beyond Permanent Sample Plots

It was an objective of this study to examine the possibility of

TABLE 31. <u>Analysis Combining Crown and Competition Covariates.</u>

SOURCE	DF	SUM SQRS	MEAN SQR	F-STAT	SIGNIF
BETWEEN MEANS	2	3236.5			
COVARIATES	3	14611.	4870.4	158.86	.0000
ERROR	212	6499.6	30.658		
— — — — — — — —					
EQUAL SLOPES	6	1113.7	185.61	7.0993	.0000
ERROR	206	5385.9	26.145		
— — — — — — — —					
EQUAL ADJ MEANS	2	162.79	81.397	2.6550	.0726 NS
ERROR	212	6499.6	30.658		
— — — — — — — —					
TOTAL					

<u>COEFFICIENTS</u>

COVARIATE	COEFF	T-STAT	SIGNIF
CRAR	.71784-1	9.6075	.0000
CC	-2.6372	-4.4644	.0000
Bella	-.15441	-3.4765	.0006

<u>REGRESSIONS</u>

PLOT #	350	355	359
N	72	103	43
CONSTANT	25.348	7.3258	37.042
CRAR	.43834-1	.12856	.33358-1
CC	-2.7501	-1.4685	-5.4105
BELLA	-.27795	-.58770	-.45680
SE OF REGR	6.3058	4.3676	4.5105
R-SQR	.67509	.77471	.81993

developing a field procedure based on the results from the permanent sample plots. Descriptive analysis of individual phenotypic selections were undertaken. First trees selected on the permanent sample plots are described, then characteristics of the wider sample of phenotypic selections are reviewed.

Crown Photographed Areas and Crown Projection

With a view to extending the crown photography results of Turnour Island baseline plots to dispersed, phenotypic selections, stepwise multiple regressions were run on Turnour Island trees which had both crown photographs (CRAR) and crown projectional (CRPRO) measurements. Again, the expression of growth was basal area growth over the last five years.

Several transformations were tried, but simple linear models proved sufficient. The results are indicated in Table 32. It appears that ground measurements of crown area projection in young growth stands are best and that aerial photographs are better in older stands. It is possible that use of an instrument to assure perpendicular viewing of the crown would improve measurements from the ground in the older (taller) stands. In the interim, crown area in stands aged 70 and above can still be predicted from crown projection using the results from Turnour Island trees presented in Table 33.

Table 32. Parameter Selection Based on Turnour Island

$$\underline{\text{Phenotypic Trees}}$$

$$Y = b_0 + b_1 \text{ CRPRO} + b_2 \text{ CRAR} + b_3 \text{ (HT to BLC}^{1/}*) + e$$

Group	n	b_0	b_1	b_2	b_3	R^2	SEE[2/]
I	11	6.155	.08552			.75	6.57
(less than 60 years)							
II	7	6.136		.0760		.75	4.38
(between 60-80 years)							

Table 33. Regression of Crown Area (Aerial) on Crown Projection

$$\text{CRAR} = b_0 + b_1 \text{ CRPRO} + e$$

n	b_0	b_1	R^2	SEE
22	41.17	.4982	.75	48.38

Analysis of Phenotypic Selections and Associated Check Trees

How do the results of the Turnour Island research plots apply to the practical cruising for plus trees? May we apply some of the findings to individual trees? In order to look into these possible applications previously selected hemlock plus trees were visited and nearby check trees established. Because of the ease of obtaining crown data, the crown projection measurements were emphasized for comparison of the performance of the plus and check trees.

1/ BLC = base of live crown.

2/ Standard error of estimate.

A variety of statistical techniques, paired t tests, elimination of outliers and the regression analysis of variance were applied to the data. Basal area growth differences were not significant, height differences approached significant probability levels (0.91). Check trees were significantly smaller in d.b.h. than plus trees, but this difference was expected since we purposely selected a number of codominant and smaller dominants as check trees (Table 34). Otherwise the phenotype and check trees are equivalent in the categories which are of interest to this study.

Table 34.   Summarized Statistics for Phenotypic
             Selections and Check Trees

Phenotypic Trees	n	Minimum	Maximum	Mean	Std Dev	SEE
Diameter (inches)	26	13.0	26.3	19.0	3.5	0.66
Height (feet)	"	90.0	139.0	114.1	13.6	2.53
Ht to BLC* (feet)	"	20.0	85.0	65.3	13.1	2.45
Age (years)	"	38.0	79.0	60.4	13.0	2.30
Diameter growth (inches)	"	.23	1.68	.800	.32	0.059
Check Trees						
Diameter (inches)	29	9.80	24.0	16.9	3.6	0.72
Height (feet)	"	84.0	150.0	110.7	15.1	2.96
Ht to BLC (feet)	"	30.0	85.0	64.2	16.8	3.29
Age (years)	"	38.0	110.0	62.2	16.1	3.07
Diameter growth (inches)	"	.24	1.34	.768	.32	.065

* Height to base of live crown.

Separate regression lines for phenotypic plus and check tree strata were tested against the pooled regression and against each other. They did not differ significantly. The pooled regression (Figure 34) is thus used for both:

$$Y = 16.46 + .3154 \text{ (CRPRO)} \tag{19}$$

The residuals were examined to determine if phenotypic trees having positive residuals were predominant among the best trees. Of the best ten trees, five were check trees and five were phenotypes. This is strong evidence that plus trees selected in the past have not been notably more efficient than their neighbors. If a quantitative improvement in initial selection is to be effected in the future, a baseline selection technique offers the highest probability of success; recall that small differences between nearby trees may be attributed to relationship of the plus phenotype and its nearby neighbors (Ledig, 1974). Rejection of the current plus trees should not be contemplated without establishment of a baseline approach or other genetic analysis. The implied lack of difference between trees merely points out the lack of quantified difference in growth efficiency between trees. It should either be quantified or investment in the current method of selection be reduced.

Periodic Growth Increment and Age

The periodic growth rate of trees is not constant over time. Growth accelerates during juvenile growth stages and begins decelerating before culmination of mean annual increment. The rate of change of the growth function is quite rapid. It is difficult to compare stands or individual trees if growth is not adequately defined in terms of competition and
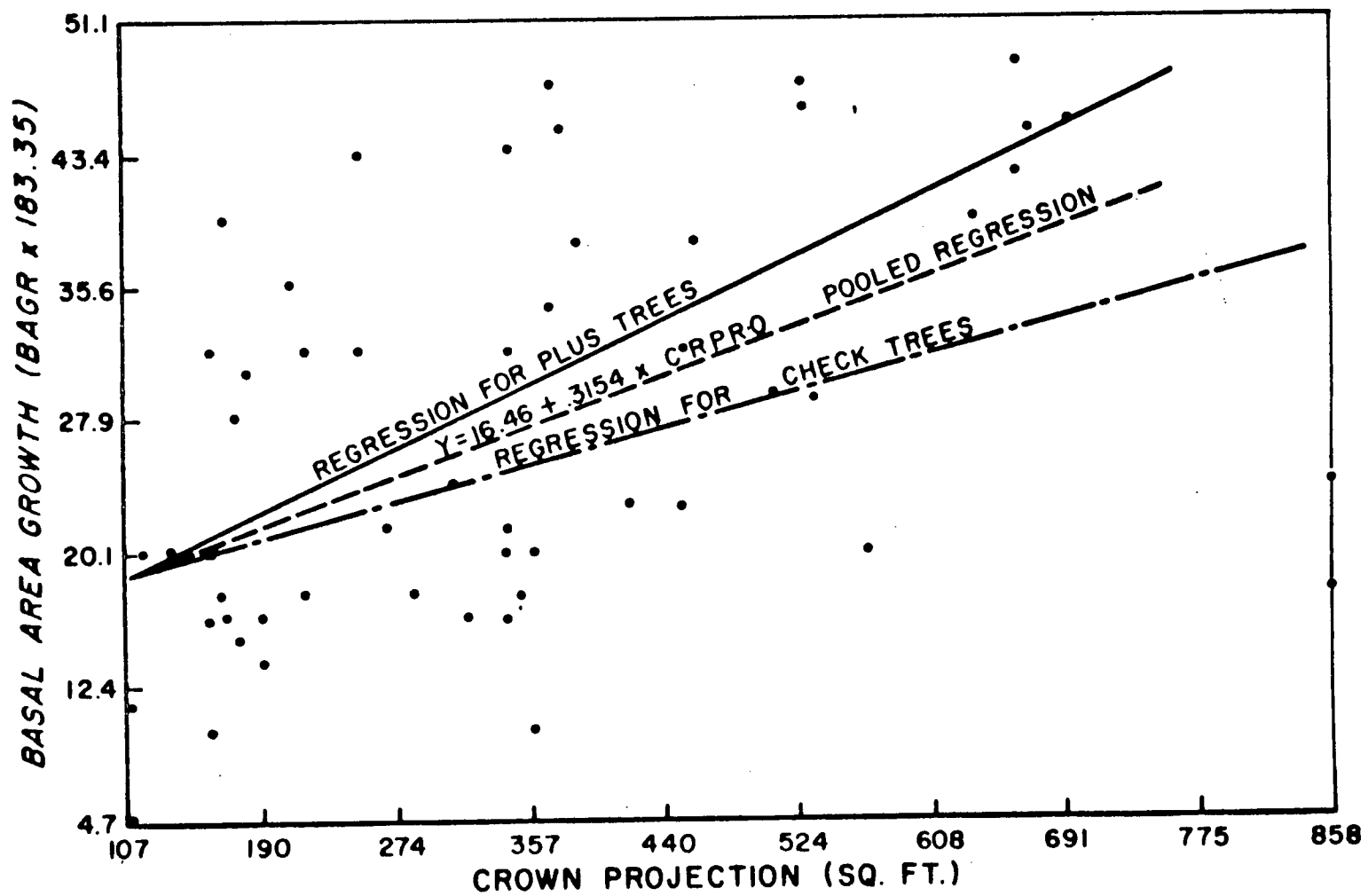
Figure 34. Growth-Crown Projection Regression lines for Phenotypic and Check trees.

age. Because periodic growth rate has been the dependent variable in this study, an examination of age stratified regressions was undertaken.

Age has two roles in the selection of plus trees: 1) relative or differential age and, 2) absolute or stand age. A few years' age advantage for individual trees overshadows potential genetic differences. An analysis of the effect of age for relatively small age differences (1 to 3 years) in the Turnour Island data was not possible. Ages for all, or at least a large majority of trees, would be necessary. Absolute age involves the changes in growth rate associated with the current annual increment. Nonetheless, two indications corroborating the importance of age were noted:

1. Unusually large values for the residual (more than three standard deviations) were positively associated with trees of +7 to +10 years age differential.

2. The difference in regression slope between Groups I and II is probably associated with the age difference between these groups.

There is one drawback to the regression analysis. Each regression is descriptive of a single stand and age. Thus, without comparable stands of several ages, no method is available for calculating the effects of age on selections for growth efficiency. A functional relation has not been discovered which would allow overlaying independently determined age-increment relationships on the competition-growth relationships for individual trees.

Phenotypic Tree Age-Strata

Stratified regression analyses based on age were performed using data from the 54 of the 57 phenotypic trees after removal of one individual with unusually large basal area growth and two trees having

extremely large crowns and consequently, low basal area growth efficiency. Age stratification was based on the pattern obtained on Turnour Island plot Groups I to III. Figure 35 is a histogram of phenotypic age distribution.

Table 35. Phenotypic Tree Age Strata

Strata Age	Number of Trees	True Mean Age	Std. Dev[1]	Range
30-49	16	42.1	2.9	38-47
50-69	21	62.7	5.2	51-68
70-89	17	73.4	3.98	70-84

Stepwise regression analysis indicated that crown dimension was the best predictor of growth in all cases. In the youngest group, CRAR was the only variable that entered the regression; CRAR, height and age, and CRAR and age, entered the 50-69 and 70-80 group regressions respectively. These findings offer some confirmation that our suspicions regarding age are justified.

Table 36.   The Effect of Height, Age and Crown Area on Periodic Growth

$$Y = b_0 + b_1 CRPRO + b_2 Ht + b_3 Age + e$$

Age	n	b_0	b_1	b_2	b_3	R^2	SEE
30-49	16	17.98	.0389	-	-	.24	9.34
50-69	21	9.80	.0386	.4391	-.7178	.46	7.37
70-90	17	-108.67	.0542	-	1.522	.84	6.11

These results also suggest that age and additional crown dimensions (length of live crown or a linear regression combination of height and

---

[1] Sample standard deviation
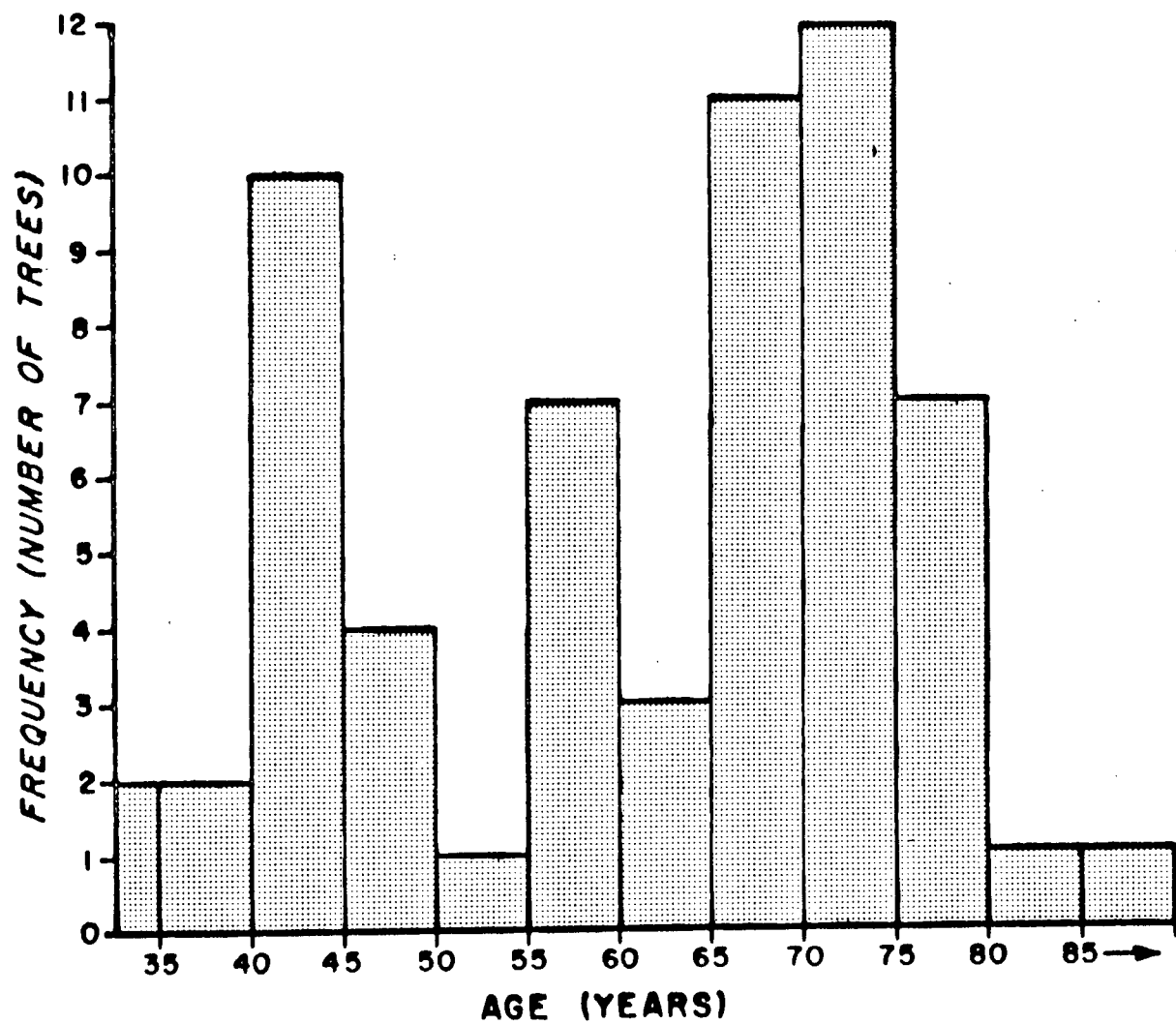
Figure 35. Frequency histogram of age distribution.

height to the base of the live crown) may be of importance in expanding our selection technique from the research plots to field selections.

These analyses are not equivalent to the Turnour Island study. The check trees do not provide a sufficient baseline to define the relationship between CRAR and basal area growth. They are included to illustrate that the concern for age in selection of plus trees is well founded.

A baseline is required which defines the basal area growth-crown relations as well as giving an estimation of the variation in the population. The variability in the population is the factor which determines the size of a standardized residual. A larger number of check trees would be required to establish confidence limits, as in the Turnour Island portion of this study.

CONCLUSION

This study was initiated by MacMillan-Bloedel Ltd., under a scientific subvention of the Canadian Forest Service in an attempt to resolve disparate selection criteria for western hemlock. The current criteria were not uniform for government agencies and forest industries. It was early in the selection phase of an improvement program for western hemlock. The expectation was that increased attention to environmental influences on the growth of individual trees would lead to more valuable genetic material for inclusion in tree breeding programs. The evidence does not lead to unqualified conclusions. Examination of past phenotypic selections and comparisons of them to check trees showed that phenotypes have not been notably more efficient in the last five-year growth period than the check trees. Regression analyses of phenotype-check trees, applied to age-stratified data, suggests that stand age and possibly other characteristics of the stand may bias the criteria used in current selections. Independent regression models applied to each age stratum. Even though some significant differences between phenotypes and check trees were discovered, the lack of clear superiority of past selections confirms the value of investigating the original hypotheses. For increased initial gains in an improvement program a more statistically rigorous selection procedure including some measure of competition is desirable.

Competition Indices

An attempt to rationalize growth, genetics and environment into mathematically and biologically consistent models was made. Periodic growth was predicted from competition. The residual variation in the model was equated with genetic variance and selection was then based on well-defined statistical procedures. Eight competition indices were applied to stem-mapped stands of western hemlock. Four of the indices were eliminated as unsuitable for complete evaluation. Of the four remaining, two indices seemed best, Newnham's and Bella's. It is somewhat disappointing that no clear trend in performance of the indices was discovered. This lack of model superiority plus the relatively low R-square values suggest that current competition expressions do not adequately explain purely environmental relationships between individual trees. For selection of trees other than those on PSP's, competition index alone does not seem to have sufficient predictive precision to be used with confidence in a selection model based on periodic basal area growth on other than permanent sample plots. Nonetheless, there was some encouragement for the analysis. Both Newnham's and Bella's indices reflected the history of thinning on Plots 354-359 and 357-358, where an increased mean value of the index indicated increased density (no thinning). Slopes of regression were similar for these plots, but sufficient ambiguities existed to require a careful analysis of covariance.

The analyses of covariance using competition indices illustrate the possibility of combining information from several of the plots. Newnham's index was used as covariate on Group II Plots, still all

the plots did not have the same slope. The example was extended by
eliminating the plot having significantly different slope. While
it is not necessary to reject combined models which show statisti-
cally different slopes for individual plots at a given probability
level, in practice inclusion of plots having different slopes increases
the variance due to competition-environment. The competition index
approach does not seem to be one which offers immediate application
to selection. Large stand-mapped plots are required along with exten-
sive data processing. The theoretical construction of the indices is
primarily abstract-mathematical. They include both internal and exter-
nal measures of variability, spacing and diameter. These indices
work admirably in the computer simulation environment for which they
were designed. Their shortcoming for this application lies in the
absence of a causal relation to biological and environmental competition.

Crown Efficiency

The second approach to selection utilized low-level aerial photo-
graphs to evaluate trees on the plots and to select candidates with
efficient crowns. Despite problems with flight control and lack of
coordination in the processing of aerial photographs, this approach
seems worthy of further trial. The statistical procedures for selec-
tion seem quite sound even in the shadow of less than reliable data.
Basal area growth/unit crown area is a measure of efficiency of space
utilization. This concept has been successfully employed in southern
pine selection (Brown and Goddard, 1961). An adaptation of this method
should be extensively investigated. It is necessary to reiterate that
the decision variable used in this study was basal area growth and not

tree volume change. To fully validate the approach, volume should be the selection criterion.

This study has demonstrated that use of additional individual tree information and standard statistical procedures can select trees growing better than expected by a given model. Exactly which trees are selected remains a problem for the definition of the manager. It can be argued that selections from among the largest crowned trees, even if they are more "efficient" than other large trees now, had an initial advantage over their neighbors, or that if grown in stands they would result in less wood per acre because of their large area occupancy. Trees grown in closer competition to their neighbors on the other hand might be smaller because they have the same spatial requirement of larger trees and simply have not had access to it during their life. Nonetheless, the results of examining growth patterns of trees at Turnour Island indicate that some smaller trees are still growing at a constant rate compared to the deceleration of trees of similar crown area occupancy. For the managed stand of the future larger numbers of stems capable of sustained growth rate mean increased harvestable wood production per acre.

Studies of both agricultural crops and trees indicate the existence of different physical and physiological growth strategies, (Duncan, 1971, Pienaar, 1965, and Ledig, 1975). Some plants convert the products of photosynthesis into supporting tissues (wood fiber in trees), others reinvest these products in leaf area. It is obvious that juvenile selection would favor plants having the former qualities. Later examination of selections might find that the plants which emphasized production of leaf early had grown more rapidly in the long run and had contri-

buted more to the total volume in a stand. These ideas support the value of crown functional relations in the selection of superior trees.

Crown Area

As with the study of competition indices analyses of covariance for crown area-growth relations were undertaken to determine the generality of this relation among plots. The analyses were consistent with hypotheses predicting differences between plots receiving thinning treatments. The slope of a growth-crown area regression line for plots within groups were statistically consistent. Levels of the lines were correlated to the number of stems or average initial diameter of the plots. These findings suggest the possibility of combining plots of similar age, site and growth type and selecting trees from a single regression baseline. Slope differences between the two groups dictate further research to determine the cause or an appropriate covariate to account for these differences. The limited range in age, location and site prescribes speculation as to the reason for differences at this time.

Both methods of measuring competition's influence on the growth of western hemlock select trees with a statistically interpretable meaning. The standardized residual indicates the probable position of a tree with respect to a model of environmental influences. Many of the trees selected would not have been considered under current field selection procedures. The methods are not as prone to the bias of subjective evaluation as happens with individual cruisers. While individual experience is irreplaceable for some characteristics, automated selection of quantifiable characteristics seems desirable. Both

the competition index and crown efficiency methods attempt to overcome the effect of fortuitous spacing and other undefined advantages on the phenotypic criteria used to select genetically superior parent trees. Simplicity of models and future sample size reductions possible in the application of crown models recommend the value of crown measurements. Direct application of the competition index approach in stem mapping entire stands is impractical. However, some modification of phenotypic selection coupled with stand basal area or competition measurement could prove feasible. Cruisers did pick trees with relatively low levels of competition.

Crown area measurements could easily be added to a selection cruise procedure with little additional time in the field as was done in the analysis of phenotypic selections (see field form, Appendix V). Application of selection criteria, as is practiced in southern pines, (Robinson and van Buijtenen, 1971), would be possible.

In the final analysis, field testing of seedlings or clones is the only certain method for determining the genetic value of the selection. Seed and cuttings of some of the Turnour Island selections were collected in September 1976 and sent to Mr. Dick Piesch of the Canadian Forestry Service for vegetative propagation and progeny testing. Additional collections are needed, however, before halfsib and full-sib and clonal tests can be carried out. Competitive ability should be a primary criterion in evaluation of the families, clones and individual offspring. Variable spaced field tests, e.g., as recommended by Lin and Morse (1975), could assist in making more objective evaluations of present plus trees progency, and in making recurrent selections for advanced generation breeding.

RECOMMENDATIONS

The research initiated here should be consolidated. Results obtained to date should also have interesting implications for allied growth and yield studies.

1. Two approaches which increase objectivity in the selection of plus trees can be suggested, based on the finds of the current project:

    a) Individual baseline construction at each candidate tree, consisting of the sampling of sufficient trees to define the competition or crown efficiency trend line and computation of the residual of the selected trees—similar to present Weyerhaeuser method and also suggested in Ledig (1974).

    b) A method of establishing a multiple regression similar to the one suggested by Robinson and van Buijtenen (1971) using crown dimensions, height, site index and age. In the latter, check trees would be sampled in the initial phases of the program, but gradually phased out as the data bank increased. Eventually, selections would be compared to the appropriate strata regression with few, if any, check trees being selected in the field.

    A baseline regression need not consist of an entire plot of 100 or more trees as in the Turnour Island study. Knowledge of the form and variability of the regression could be used to reduce the sample size to the order of 10-30 trees, each mapped as above. A few trees chosen to represent the extremes of the regression could yield quite adequate estimates of the slope against which to compare a subject tree's performance. These trees would come from the dominant and intermediate crown classes. The subject tree's residual would be compared to the regression line to determine its periodic growth performance. Integration of the growth rate selections with other phenotypic criteria is also being studied.

2. A field form which could be readily adapted to either of these approaches was designed for field work on phenotypically selected trees and is included in Appendix IV crown dimensions and competitor diameters and distances are included. Integration of the forms into the current plus tree cruising procedures should make future application of either of the methods of selection with computer assistance practical.

3. Scion material and open-pollinated seed must be collected from the appropriate Turnour Island selections. The vegetative material should be propagated for subsequent clone bank establishment and breeding work.

4. An expanded, basic study of the relationships between western hemlock crown characteristics and growth rates should be undertaken. Tree height and possible form measurement should be specified as critical if the high correlation between crown area and volume growth rate is verified, the results could warrant further modification of plus tree selection methods as well as supplying relevant information for future physiological, ecological and growth and yield studies of western hemlock.

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APPENDICES

APPENDIX I

A SET OF ALGORITHMS FOR EVALUATING INTER-TREE COMPETITION INDICES

From

F. Hegyi and L.D. Oxtoby

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A SET OF ALGORITHMS FOR EVALUATING
INTER-TREE COMPETITION INDICES

From

F. Hegyi and L. D. Oxtoby

INTRODUCTION

Since 1964, when Newnham (1964) introduced his distance-dependent stand model for Douglas-fir, inter-tree competition indices have played an important role in growth simulation methodology. In fact, the subsequent development of distance-dependent single tree growth simulators stimulated different formulations of inter-tree competition indices (Newnham 1964, Lin 1969, Bella 1970, Arney 1971, Ek and Monserud 1973, Hegyi 1973). While these indices all require data on inter-tree distances, the actual calculations provide some variations which may be explained in terms of crown overlap calculations, angle measures, and d.b.h. ratios of competitors over subject trees.

In recent years, single tree growth modeling picked up considerable momentum in British Columbia (Hegyi 1975, Glew, et al. 1976). However, because the main differences between the various single tree growth simulators appear to be due to the formulations of inter-tree competition, it was considered essential that an evaluation of competition indices be carried out before some of the models are implemented operationally. Therefore, a set of FORTRAN algorithms was developed at the Pacific Forest Research Center which facilitates the calculations of competition indices by Staebler (1951), Newnham (1964), Lin (1969), Bella (1970), Arney (1971), Hegyi (1973), Ek and Monserud (1973), and Quenet (1975). The above indices were selected on the basis of having high potential of application in our operational growth prediction system (Hegyi 1975, Glew, et al. 1976).

ARNEY'S COMPETITIVE STRESS INDEX

$$CSI_i = 100 \times \frac{\left(\sum_{j=1}^{n} ZO_{ij} \right) + ZA_i}{ZA_i}$$

WHERE:

CSI = COMPETITIVE STRESS INDEX
ZO = AREA OF ZONE OVERLAP
ZA = INFLUENCE–ZONE AREA
n = NUMBER OF COMPETITORS
i = SUBJECT TREE
j = COMPETITOR

REQUIRES:

- OPEN–GROWN CROWN RADIUS FUNCTION
- CW = f(DBH)
- X–Y COORDINATES
- DBH

APPLICATION

- SPATIAL PATTERNS (X–Y COORDINATES)
- GENERATE POTENTIAL HEIGHT AND DBH INCREMENTS PER TREE
- CALCULATE CSI FOR EACH TREE
- ADJUST POTENTIAL INCREMENTS BY CSI
- HEIGHT AND DBH REDUCTION: 0–1
- MORTALITY = f(CROWN LENGTH, CSI)
- CALIBRATION: REDUCTION FACTORS
- INCREMENT PERIOD: FIXED (1 YEAR)
- INPUT PARAMETERS: GENERATED OR SUPPLIED

BELLA'S COMPETITIVE INFLUENCE–ZONE OVERLAP INDEX

$$CIO_i = \sum_{j=1}^{n} \left[\frac{ZO_{ij}}{ZA_i} \times \left(\frac{D_j}{D_i} \right)^{EX} \right]$$

WHERE:

CIO = COMPETITIVE INFLUENCE–ZONE OVERLAP INDEX
ZO = AREA OF ZONE OVERLAP
ZA = INFLUENCE–ZONE AREA
D = DBH
EX = EXPONENT
n = NUMBER OF COMPETITORS
i = SUBJECT TREE
j = COMPETITOR

REQUIRES:

— OPEN–GROWN CROWN RADIUS FUNCTION
  CR = f(DBH)
— ADJUSTING FACTOR (FC)
  INFLUENCE = CR x FC
— X–Y COORDINATES
— DBH

APPLICATION:

— SPATIAL PATTERNS (X–Y COORDINATES)
— GENERATE POTENTIAL HEIGHT AND
  DBH INCREMENTS PER TREE
— CALCULATE CIO FOR EACH TREE
— ADJUST POTENTIAL INCREMENTS BY CIO
— HEIGHT AND DBH REDUCTION: 0–1
— MORTALITY = f(CURRENT INCREMENT, CIO, RANDOM)
— CALIBRATION: FC, EX, REDUCTION FACTORS
— INCREMENT PERIOD: VARIABLE
— INPUT PARAMETERS: GENERATED OF SUPPLIED

EK'S COMPETITION INDEX

$$CIU_i = \sum_{j=1}^{n} \left(\frac{ZO_{ij}}{ZA_i} \times \frac{H_j \times CR_j}{H_i \times CR_i} \right)$$

$$CIA_i = CIU_i \times TOL_i$$

WHERE:

CIU = UNADJUSTED COMPETITION INDEX
CIA = ADJUSTED COMPETITION INDEX
ZO = AREA OF ZONE OVERLAP
ZA = INFLUENCE—ZONE AREA
H = HEIGHT
CR = OPEN—GROWN CROWN RADIUS
TOL = SHADE TOLERANCE VALUE
n = NUMBER OF COMPETITORS

REQUIRES:

— OPEN—GROWN CROWN RADIUS FUNCTION
— HEIGHT OR HEIGHT = f(DBH)
— TOL OR SHADE TOLERANCE FUNCTION
— X—Y COORDINATES
— DBH

APPLICATION

— SPATIAL PATTERNS (X—Y COORDINATES)
— GENERATE POTENTIAL HEIGHT AND
  DBH INCREMENTS PER TREE
— CALCULATE CIA FOR EACH TREE
— ADJUST POTENTIAL INCREMENTS BY CIA
— HEIGHT AND DBH REDUCTION: 0—1
— MORTALITY = f(CROWN RATIO, CIU, PERIOD, RANDOM)
— CALIBRATION: TOL, REDUCTION FACTORS
— INCREMENT PERIOD: VARIABLE
— INPUT PARAMETERS: GENERATED OR SUPPLIED

HEGYI'S COMPETITION INDEX

$$CI_i = \sum_{j=1}^{n} \left(\frac{D_j}{D_i} \times \frac{1}{DIS_{ij}} \right)$$

WHERE:

CI = COMPETITION INDEX
D   = DBH
DIS = DISTANCE
n   = NUMBER OF COMPETITORS AS DETERMINED
       BY A 10 BAF ANGLE GAUGE
i   = SUBJECT TREE
j   = COMPETITOR

REQUIRES:

— DBH
— X–Y COORDINATES

APPLICATION:

— SPATIAL PATTERNS (X–Y COORDINATES)
— GENERATE POTENTIAL HEIGHT AND
   DBH INCREMENTS PER TREE
— CALCULATE CI FOR EACH TREE
— ADJUST POTENTIAL INCREMENTS BY CI
— HEIGHT AND DBH REDUCTION: 0–1
— MORTALITY = f(STOCKING OR CAI, CI, RANDOM)
— CALIBRATION: REDUCTION FACTORS
— INCREMENT PERIOD: FIXED (1 YEAR)
— INPUT PARAMETERS: GENERATED OR SUPPLIED

LIN'S GROWING SPACE INDEX

$$GSI_i = \sum_{j=1}^{n} \left(25 - RF \right)$$

$$RF = f(K)$$

$$K = \frac{DIS_{ij}}{D_j} \times \frac{2 \times D_i}{D_i + D_j}$$

WHERE:

GSI = GROWING SPACE INDEX
RF = GSI REDUCTION FACTOR (≤ 25)
   AS OBTAINED FROM A TABLE
K = WEIGHTED K RATIO
DIS = DISTANCE
D = DBH
n = NUMBER OF COMPETITORS AS DETERMINED BY A
   10 BAF (OR LESS) ANGLE GAUGE UP TO A MAXIMUM
   OF 4 (THE LARGEST TREE IN EACH QUADRANT)
i = SUBJECT TREE
j = COMPETITOR

REQUIRES:

— CROWN RADIUS (FOR RF)
— REDUCTION FACTOR TABLE
— X–Y COORDINATES
— DBH

APPLICATION:

— SPATIAL PATTERNS (X–Y COORDINATES)
— GENERATE POTENTIAL HEIGHT AND
   DBH INCREMENTS PER TREE
— CALCULATE GSI FOR EACH TREE
— USE GSI IN GROWTH FUNCTIONS
— MORTALITY = f(PAI, GSI)
— CALIBRATION: RF, K, GROWTH FUNCTIONS
— INCREMENT PERIOD: FIXED (2 YEARS)
— INPUT PARAMETERS: GENERATED OR SUPPLIED

NEWNHAM'S COMPETITION INDEX

$$CI_i = \frac{\displaystyle\sum_{j=1}^{n} \left(\theta_{ij} \times \frac{CW_j}{CW_i} \right)}{2\pi}$$

CI = COMPETITION INDEX
θ = ANGLE FROM THE CENTRE OF SUBJECT TREE CROWN TO THE TWO POINTS OF INTERSECTION WITH THE COMPETITIVE CROWN
CW = OPEN—GROWN CROWN WIDTH
π = 3.141596
n = NUMBER OF COMPETITORS
i = SUBJECT TREE
j = COMPETITOR

REQUIRES:

— OPEN—GROWN CROWN RADIUS FUNCTION
CW = f(DBH)
— X—Y COORDINATES
— DBH

APPLICATION:

— SPATIAL PATTERNS (X—Y COORDINATES)
— GENERATE POTENTIAL DBH INCREMENTS
DBH GROWTH = f(DIAMETER, AGE) BY SITES
— CALCULATE CI FOR EACH TREE
— ADJUST POTENTIAL DBH INCREMENTS BY CI
— DBH REDUCTION: 0—1
— MORTALITY = f(DBH INCREMENT, CI)
— CALIBRATION: REDUCTION FACTORS
— INCREMENT PERIOD: FIXED (5 YEARS)
— INPUT PARAMETERS: GENERATED OR SUPPLIED

QUENET'S COMPETITION INDEX

$$CI_i = \sum_{j=1}^{n} \frac{D_j}{DIS_{ij}}$$

CI = COMPETITION INDEX
D = DBH
DIS = DISTANCE
n = NUMBER OF COMPETITORS AS DETERMINED
       BY A 10 BAF ANGLE GUAGE
i = SUBJECT TREE
j = COMPETITOR

REQUIRES:

— X—Y COORDINATES
— DBH

STAEBLER'S COMPETITION INDEX (MODIFIED)

$$CI_i = \frac{\sum\limits_{j=1}^{n} LO_{ij}}{2R_i}$$

WHERE:

CI = COMPETITION INDEX
LO = LINEAR OVERLAP
R = RADIUS OF COMPETITION CIRCLE
n = NUMBER OF COMPETITORS
i = SUBJECT TREE
j = COMPETITOR

REQUIRES:

- OPEN—GROWN CROWN RADIUS FUNCTION
- CW = f(DBH)
- X—Y COORDINATES
- DBH

FLOWCHART OF THE COMPETITION INDICES PROGRAMS

APPENDIX II

LIN'S GROWING SPACE INDEX

Lin's competition index was included in the proposal for this project as it is specifically designed for western hemlock. The index obviously performs well in the simulation it was designed for. However, several problems developed with its application to the current project. The first was not serious, it is the only index which can assume value zero. This means that calculations which involve division transformations must be replaced by an arbitrary small value. In addition the index is based on competitors found in fixed quadrants around the subject tree. This condition does not seem apropos measurements of individual trees required by consideration of genetic variability. Note the following sketch:
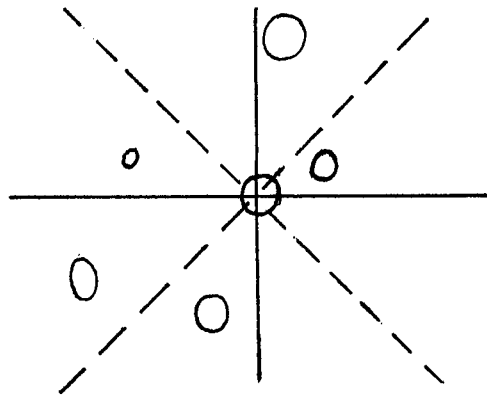
In the figure, because large trees are growing in two quadrants, GSI is reduced to 50%. The upper right quadrant has two large trees, but only one is necessary to reduce the growing space to zero for the quadrant. If the reference axes are rotated to the position indicated by dashed lines, the GSI for three quadrants is reduced to zero; GSI = 25% for the same tree! The dependence of GSI on arbitrary orientation of the field plot axes (XY-axes are not oriented identically on Turnour Island plots) is not equivalent to simulation of stand growth in a computer model. The GSI would be expected to average out over the plot but not reflect perfectly individual tree differences. These observations do not reflect in any way deprecatory to the function of Lin's index in the computer model environment. However, for these reasons GSI was eliminated from the final evaluation at this time.

APPENDIX III

EXAMPLE OF COMPUTER OUTPUT USED TO SELECT CROWN EFFICIENT CANDIDATES

DEP.VAR.	INDEP.VAR.	A(CCNST.)	B(COEFF.)	FRATIO(B)	FPROB(B)	STD.ERR.A	STD.ERR.B	STD.ERR.Y	FSQ
BAGRTH	CA	1.641	0.9243E-01	136.7	0.7633E-16	1.201	0.7848E-02	6.614	0.5860

PLCT CF Y VS X ANC PLCT CF THE REGRESSION LINE.
THE "." AND "*" ARE USED TO PLOT THE REGRESSION LINE; THE "*" IS USED WHEN A PLOT POINT COVERS DATA POINTS

Plot 358
Unthinned Hemlock

Growth

$D75^2 - D70^2$

(square inches)

DISTANCE BETWEEN SLASHES CN THE X-AXIS IS   4.000

Crown   Area   (square feet)

DEP.VAR.	INDEP.VAR.	A(CONST.)	B(COEFF.)	FRATIO(B)	FPROB(B)	STD.ERR.A	STD.ERR.B	STD.ERP.Y	RSQ
BAGR.TH	CA	1.641	0.9243E-01	138.7	0.7633E-16	1.201	0.7846F-02	6.614	0.5860

```
                    YHAT    VERSUS RESICUALS                              CA      VERSUS RESICUALS
  42.0  -         (predicted Y).                         /    380.  -                    .  1                    /
        /                            .                   /          /                       .                   /
        /    Plot 358                .                   /          /                       .                   /
        /                            .                   /          /                    1                      /
        /                          .  1                  /          /                       .                   /
        /                            .                   /          /                       1                   /
        /                            .                   /          /             1                             /
  33.0  -             1            .                      /    300.  -                   .1                      /
        /                            .                    /         /             1     1    1                  /
        /            1    1                               /          /                    .                     /
        /                .1  1                            /          /                       .1                 /
        /            1    1                               /          /                       2                  /
        /                            .                    /          /                                          /
        /                1                                /          /                    1  .                  /
        /                2                                /          /                    1                     /
  24.0  -                .                                /    220.  -                       11    1            /
        /              2                                  /          /                      1 1                 /
        /                  . 1        1                   /          /                    2 1.         1        /
        /                 11 1                            /          /             1         .      2           /
        /                 1.      1                       /          /                    1        1            /
        /               2      1                          /          /                 1  1  .   .             /
        /          1      .       11                      /          /             11   1 .                    /
        /            1                                    /          /                 11 1   1                /
        /         11   1.                                 /          /                 1 1                     /
  15.0  -           1 21                1                 /    140.  -             11  12. 1                   /
        /         2   11.                                 /          /                 1        1   1          /
        /        .11  1   11                              /          /                 1  1 1                  /
        /             1 1 1                               /          /                                         /
        /          1  1.    1           .    1            /          /             1    11   1            1    /
        /         111                                     /          /                 1                       /
        /        1 111111                                 /          /             1 1  11                     /
        /        1 1    111      1                         /          /            1 1  111     1              /
        /          211 1                                  /          /             1 1 . 111                  /
        /          1 1  1                                 /          /                211 1                    /
  6.00  -          112.                                   /    60.0  -             1 1.                        /
        /          131                                     /         /             11  1                       /
        /          2311                                    /         /                12.                      /
        /          11  1     1                             /         /                31    1                  /
        /            .1                                    /         /                2311                     /
        /                                                 /          /                11  1                    /
        /            .                                    /          /                  .1    1               /
  -3.00 -            .                                     /   -20.0 -                   .                      /
       /////////////|////////////|////////////|//////////|          /////////////|////////////|//////////|//////////|
          -45.0    -27.0    -9.00    9.00    27.0    45.0            -45.0    -27.0   -9.00    9.00    27.0
                         DISTANCE BETWEEN SLASHES ON THE X-AXES IS  0.9000
```

DEP.VAR.	INDEP.VAR.	A(CONST.)	B(COEFF.)	FRATIO(B)	FPROB(B)	STD.ERR.A	STD.ERR.B	STD.ERR.Y	RSQ
BAGRTH	CA	1.641	0.9243E-01	138.7	0.7633E-16	1.201	0.7843E-02	6.614	0.5860

PROBABILITY OF RESIDUALS VS RESIDUALS
(PLOT TO VERIFY THE NORMALITY OF THE DIST OF RESIDUALS)

Plot 358

Probability of Residuals

```
  2.600   -                                                              1        2.600
                                                                                  2.490
                                                                                  2.380
                                                          *                       2.270
                                                                                  2.160
                                                      .1                          2.050
                                                    .1                            1.940
                                                  . 1                             1.830
                                                 . 1                              1.720
                                               . 1                                1.610
  1.500   -                                   . 1                                 1.500
                                            * 1                                    1.390
                                           **                                      1.280
                                         1*                                        1.170
                                        1*.                                        1.060
                                       2*.                                         0.9500
                                      12.                                          0.8400
                                      3.                                           0.7300
                                     13.                                           0.6200
                                     12..                                          0.5100
  0.4000  -                          5 .                                           0.4000
                                    22..                                           0.2900
                                    22.                                            0.1800
                                    4 .                                            0.7000E-01
                                   5..                                            -0.4000E-01
                                   *.                                             -0.1500
                                   4.                                             -0.2600
                                   .                                              -0.3700
                                  .4                                              -0.4600
                                  ..1                                             -0.5500
 -0.7000  -                       .3                                              -0.7000
                                  .31                                             -0.8100
                                  .11                                             -0.9200
                                 .2                                               -1.030
                                 .11                                              -1.140
                                .. 2                                              -1.250
                                . 2                                               -1.360
                               .11                                                -1.470
                               . 1                                                -1.560
                               . 1                                                -1.690
 -1.600   -                   . 1                                                 -1.800
                              1                                                   -1.910
                                                                                  -2.020
                             .                                                    -2.130
                             1                                                    -2.240
                            .                                                     -2.350
                                                                                  -2.460
                           1                                                      -2.570
                                                                                  -2.680
                                                                                  -2.790
 -2.900   -                                                                       -2.900
```

CISTANCE BETWEEN SLASHES ON THE X-AXIS IS 0.1361

-6.804   -4.082   -1.361   1.361   4.082   6.804

APPENDIX IV

LIST OF "PLUS" TREES SELECTED BY FOUR COMPETITION MODELS,
CROWN AREA MODEL AND ON BASIS OF PHENOTYPE

Number	Number	Number	Bella	Ek-Monserud	Hegyi	Newnham	Competition	Phenotypes	Comments
I	350	29	2.4	2.8	2.5	2.6	2.66		
		53	1.5	1.8	1.7	-	-		
		64	2.8	3.4	3.2	2.0	4.86*		
		31	- .10					X	Inside plot
		85	-1.43					X	Inside plot
	351	238	-	1.7	-	1.6			
		254		1.5	1.4				
		304			1.5				
		370				2.0			
		220					4.54*		
		317					1.63		Phenotype #'s ?
	352	437	1.14		1.18		3.20		
		442		1.81	1.65	1.13			
		476	1.79	2.63	2.63				
		488	1.43	1.74		1.52			
		613		2.18	1.74	1.08	3.00		Seed & scions
		519						X	In buffer
		583						X	In buffer
	357	1873	2.1	2.8	2.0	1.4			
		1906	1.7	1.6	1.7	1.2			
		1959		1.8	1.2				
		1826					3.01		
		1915					2.49		
		1806						X	In buffer
		1894						X	In buffer
	358	2054				1.16			
		2093		1.81	1.68				
		2110	2.54	1.93	2.44		4.32*		
		2212	1.31		1.65		2.06		
		2220	1.74						
		2346				1.43			
		2294					2.09		
		2258						X	In buffer
		2239						X	In buffer
II	354	883	2.7	2.7	3.5	3.0			
		896		2.1					
		992	1.4						
		1012			1.4				
		1016	1.6				2.52		
		1027		1.6			1.99		
		922			1.8				
		1033					2.12		
		904	.58					X	Inside plot
		954	1.63					X	Inside plot
	355	1039	1.8	1.8		1.3	3.52*	X	Inside
		1219	1.3	1.9			4.85*		
		1165						X	Buffer
	356	1574	2.4	2.6	2.2	1.7			
		1592	1.3	1.9	1.4	2.3			
		1639		1.9	1.2	1.9			
		1742	1.2*						
		1411					2.49		
		1590					4.43		
		1431						X	In buffer
		1697						X	In buffer
		1725						X	In buffer
		1745						X	In buffer

* Tree mismeasured or older.

Group Number	Plot Number	Tree Number	Bella	Ek-Monserud	Hegyi	Newnham	Crown Competition	Phenotypes	Comments
	359	2147	1.24	1.69	1.10	1.55	(- .23)	X	Inside, scions
		2193	1.69	1.43	1.30	1.37	2.07		
		2212		1.10	1.27	1.02			
		2204					3.85*		
		2160	.37					X	Inside
		2165	.44					X	Inside
		2176						X	Buffer
III	353	670		1.6				X	Inside
		683	1.2		1.5				
		723	1.2	1.4		1.4			
		749	1.8	1.8	1.6	1.3			Seed & scions
		750				1.2	1.83	X	Seed & scions
		693					4.53*		
	400	116	1.3		1.27				
		119		1.14	1.80				
		199	1.9				1.75		
		206	1.7	1.64	1.42			X	Inside
		295		1.56					
		323					1.74		
		159						X	Buffer
	401	69	1.6	1.5					
		97	2.2		1.9	1.9	2.86		
		106	2.0	1.5	2.1	2.1			
		152	1.9		2.1	1.7			
		265	(1.43)	2.0		1.9		X	Inside
		268	(1.31)	2.2		1.8		X	Inside
		12					3.02		

APPENDIX V

COMPETITION INDEX - PLUS TREE SELECTION FORM

Location: *KELSEY Louise Arm*
≐ MILE 1
HELLMOREID

TREE	0	6	1	0		DBH	1	8	4		HT.	1	2	2
	1	2	3	4								27	28	29

BLC Bose Live Crown	0	8	0		AGE	0	6	6		CORE#	2 0 4 7	GG
	30	31	32			34	35	36			1 9 7 9	. 6 5

Crown Dimensions

	N		NE		E		SE		S		SW		W		NW	
		9		9	1	4		6		5	1	5		3		9	
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60

CC: 1 — Dom   CC: 5 — Dead   Sp.: 1 — Hemlock   Sp.: 5 — Spruce
2 — Codom   6 — Cut   2 — Fir   6 — Other Conif.
3 — Inter   3 — Bolsom   7 — Maple
4 — Sup   4 — Cedar   8 — Alder   9 — Other Decid

Competitors:

Tree No.	Distance	Bearing	Diameter	Species	Crown Class	Observations *=Plus Tree—Enter tree# after *
0 0	0 0 . 0	0 0 0	1 8 . 4	1	1	
0 1	1 6 .	1 3	1 2 .	1	2	
0 2	2 4 .	3 0	1 8 . -	1	2	≠ 0611 *
0 3	1 3 . 5	5 2	9 .	1	3	
0 4	1 6 . 5	1 1 4	1 1 .	1	2	
0 5	1 7 .	1 4 4	1 5 .	1	2	
0 6	1 3 . 5	1 5 4	9 .	1	3	
0 7	1 0 .	1 7 6	1 3 .	1	2	
0 8	2 0 . 6	1 8 2	2 0 .	1	1	
0 9	1 6 . 5	2 1 0	8 .	1	3	
1 0	2 9 . 5	2 3 0	2 8 .	2	1	
1 1	1 9 . 5	2 7 0	2 0 .	1	1	
1 2	1 5 . 5	2 8 8	9 .	1	3	
1 3	1 6 .	3 4 4	1 2 .	1	2	
1 4	.		.			
1 5	.		.			
1 6	.		.			
1 7	.		.			
1 8	.		.			
1 9	.		.			
2 0	.		.			
2 1	.		.			
2 2	.		.			
2 3	.		.			
2 4	.		.			
2 5	.		.			

5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

Time: 12/8/76
Signature: CT
TAT