ANALYSIS OF BIOMASS, BIOMASS SAMPLING METHODS, AND WEIGHT SCALING OF LODGEPOLE PINE

by

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ABSTRACT

Tree and tree component weights of 63 forest-grown lodgepole pine trees were investigated. Data were collected from one tenth-acre plot located in south western Alberta. Both graphical and multiple regression techniques were used. Of the independent variables tested, tree basal area was most closely related to the component weights, with the exceptions of bole bark weight and total stem dry weight. The fresh and dry weights of bole bark were most closely associated with tree height, and total stem dry weight was most closely associated with dbh. Very reliable estimates of tree and tree component weights were obtained using regression techniques and the independent variables previously mentioned.

The proportions of the component weights of the total tree weights were determined. The proportions were highly variable and widely dispersed about the mean. The tree characteristic most closely associated with the various proportions varied for the component being analysed. The proportion of the total tree weight contained in the stem, slash, bark and bole wood decreased with increasing tree size. The proportion represented by the needles, branches, merchantable stem, and crown increased with tree size.

The crown and needle characteristics of lodgepole pine were investigated. Tree size, whether measured as stem weight in pounds or cubic foot stem volume (ob), was most closely correlated with dry needle weight (in pounds). The number of needles per cubic foot of stem volume increased with increasing tree size. The needle characteristics of lodgepole pine are highly variable. Needle length was significantly related to needle width. Needle length was not significantly related to any tree characteristics.

The need to develop reliable sampling methods for biomass and fire control studies was discussed. Double sampling with regression appeared to offer accurate estimates with a minimum of weight measurement. The number of trees required to obtain a sample mean within plus or minus 10 per cent of the population mean at the 95 per cent confidence level is too large to be practical for most biomass and fire control studies. A higher standard error of estimate is probably more desirable, thus allowing a greater number of conditions to be sampled in order to increase the representativeness of the study.

The mutual relationship between tree weight and tree volume was investigated. Tree volume was highly correlated with tree weight. Reliable estimates of tree weight were obtained from tree volume. Variation in moisture content and specific gravity, within and between trees was analyzed. These variables were surprisingly uniform and appear to pose only minor problems in weight scaling, for lodgepole pine.

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INTRODUCTION

In an attempt to obtain meaningful data for the assessment of the productivity of forest trees, the component weights of 63 lodgepole pine trees (*Pinus contorta* Dougl. var. *latifolia* Engelm.) were gathered. No data were obtained for the subterranean parts of the trees. In addition, information was gathered on the moisture contents and specific gravities of the trees. The field work was conducted during the summer of 1966.

According to Ovington (1962) biomass can be defined as "the total quantity of organic matter present in the ecosystem at a stated time and may be related to particular organisms or groups of organisms." Biomass, therefore, is a measure of net basic or primary productivity of an ecosystem which can be restated as the amount of energy in the form of photosynthate stored by the producer organisms, which in the case of forest communities are primarily the trees. It should be noted that the term net productivity is used which refers to the energy produced by the plant in excess of the amount of organic matter contained in those organs shed or removed from the tree and losses through respiration, and thus is stored by the plant. This might also be termed apparent photosynthesis or net assimilation.

Odum (1959) in his discussion of the fundamentals of ecology suggested six possible methods of measuring productivity. These included:

1. The harvest method whereby the amount of organic matter was measured.
2. The oxygen method in which the amount of oxygen produced is measured.
3. The carbon dioxide method involving the measurement of the amount of carbon dioxide taken in by the plant.
4. The radioactive materials method where in marked materials were measured.
5. The raw materials method whereby the raw materials taken in by the plant were measured.
6. The chlorophyll method in which the amount of chlorophyll present was measured.

Biomass analysis is, of course, a form of the first method mentioned. This method appears to be the most practical due to the massive and complex nature of forest ecosystems. Thus it attempts to measure productivity, although not necessarily the yield to man of forest trees, which is governed by the availability of raw materials, solar energy, and other environmental influences including man.

In the past, forest management was characterized by a more or less 'laissez-faire' attitude because of the self-sustaining nature of the resource and therefore forest research was not considered vital. Productivity was generally considered as yield to man and as such was measured on a volume basis. However, as pointed out by Ovington (1962), due to population pressure, the need to convert more forested land to agricultural use, and the increased value of forest products, multiple and more intensive use of forested land is inevitable. This point of view is shared by Young (1964) resulting in his proposal of the complete tree concept, and it prompted Woods (1960) to put forward his concept of energy flow silviculture.

Coincident with intensification of forestry practices there will undoubtedly be an increased demand for knowledge of such factors as forest organic matter, energy, water, and factors of the environment including soil, climate, and the influence of man. Biomass analysis affords an opportunity to measure some of these factors. It will provide quantitative information, which was previously often unavailable, basic to a more complete understanding of productivity and related processes.

In silviculture it offers an opportunity to measure the photosynthetic machine and the effects of stand improvement on the ecosystem. It can be used to analyse fertilizer trials, the flow of nutrients, and the amount of nutrients removed from the site by various harvesting methods. Biomass measures are useful in watershed research in determining the amount of forest cover which influences the interception, evaporation, infiltration, and transpiration of a forested area. Biomass estimates can greatly assist mensurationists concerned with understanding tree and stand growth, and with weight scaling. Fire control specialists can use biomass data in their endeavors to assess fire dangers and fire effects on habitat, by aiding them in measuring quantities of fuels before and after logging. Finally, the measurement of biomass gives an indication of the food supply available to insects, fungi, and wild life.

The author hopes that the results presented in this thesis will assist foresters in the management of lodgepole pine, a species which is becoming increasingly important in the western portions of Canada and the United States. It is also hoped that it will illustrate some of the problems associated with biomass sampling for this species.

DATA COLLECTION

All of the data used in this study were gathered on the Kananaskis Forest Experiment Station near Seebe, which is located approximately fifty miles due west of Calgary, Alberta. The station is located in the SE1 section of the Subalpine Forest Region (Rowe, 1959).

One square tenth-acre plot was selected for this study. The species composition of the plot was predominantly lodgepole pine, with some western white spruce (Picea glanca (Moench) Voss var. albertiana (S. Brown) Sarg.) in the understory. The pine trees were of a similar age (approximately 100 years old), and since the trees grew within such a small area it can be assumed that any differences occuring in the resulting analysis can not be attributed to the influence of climate, or geographic location.

Past plot records indicate that in 1938 the stand contained 3005 stems per acre with a basal area of 195.6 square feet per acre. The present (1966) plot data indicate that the stand now contains 1020 stems per acre with a basal area of 227.7 square feet per acre. The mean tree dbh was 6.12 inches. Lodgepole pine contributes 5, 147 cubic feet (calculated from volume formulae prepared by Smith and

Munro (1965)) of the total volume per acre (5, 624 cu. ft.) found in the stand.

Prior to felling, the plot boundaries were located and each tree was tagged. Measurements of diameter at breast height (dbh), average crown width (the average of two measurements taken at right angles at the widest part of the live crown) total tree height, and live crown length (the length from the tip to the lowest whorl of live branches), were made. In addition, a stem map showing the exact location of each tree and its crown was prepared.

The plot was then felled. An attempt was made to maintain a fairly constant stump height at 1 foot above ground level. A dial scale with a capacity of 500 pounds was used to weigh the trees. The first weight obtained was that of the entire tree above stump height (including branches and foliage). The entire stem (the total tree less branches and foliage) was then weighed and finally the merchantable stem weight to a 4.0 inch top diameter outside bark was obtained.

The foliage was then clipped from the larger branch parts and placed in burlap sacks. These sacks were then placed in the shade to minimize drying. Discs, approximately one inch in thickness were then sawn from the stem. These discs were sawn at stump height, breast height, eight feet above stump height, and at eight foot lengths thereafter to the top of the tree.

Following cutting, the diameter outside bark of each disc was measured and recorded on a stem analysis sheet. These discs were placed in polyethylene bags which were sealed to prevent drying.

The bagged samples were subsequently transported to the drying and weighing facilities. This was carried out as frequently as possible so that the samples were rarely allowed to dry in the woods for more than four hours before reweighing.

Upon arrival at these facilities each bag of foliage plus twigs was weighed and this weight was recorded according to tree and bag number. The bags were then placed in a drying shed where the temperature was maintained at approximately 85°C. Each disc was weighed and then placed in a gas drying oven in which a temperature of 100°C was maintained.

Upon completion of the necessary drying period (usually 24 hours in the case of the discs and several weeks for the foliage bags) the discs and foliage were removed from the drying facilities, re-weighed, and their dry weights recorded according to the appropriate tree and bag or disc number coinciding with the fresh weights. Thus it was possible to obtain the moisture contents of the discs, expressed in terms of per cent as:

$$\text{MC } (\%) = \frac{\text{Fresh weight (gm)} - \text{Dry weight (gm)}}{\text{Fresh weight (gm)}} \times 100\ \%$$

Radial growth was then measured on each disc. Since considerable shrinkage had resulted from the drying all the radial growth measurements made on the dried discs were carried out along an average diameter line equal to the average diameter measured and recorded immediately after the tree sections were cut in the woods. The actual fresh volume inside and outside bark was determined from Reineke charts.

Since specific gravity measurements were not incorporated in the original study plans, all measurements of volume for specific gravity calculations are on an oven dry wood basis. No attempt was made to break the sections into early wood or late wood, or into sapwood or heartwood and thus all measurements are based only upon cross-section measurements. The volume measurements were obtained by immersing a pie-shaped section (sector), cut from each disc, into water and measuring the volume of water displaced. The specific gravity at various heights within each tree was obtained from the ratio of the oven-dry weight of each sector to its displaced volume. The specific gravities, oven-dry volume basis, can be converted to green volume basis using the formula from the Forestry Handbook (S. A. F., 1961):

$$Po = \frac{Pg}{1.0 - 0.28\ Pg}$$

thus: $$Pg = \frac{Po}{1.0 + 0.28Po}$$

where: Pg = specific gravity green volume basis

Po = specific gravity oven-dry volume basis.

The laborious and tedious task of removing all of the needles from twigs and other extraneous matter gathered from the crowns of the trees proved to be the most time consuming phase of the entire project. By trial and error it was found that the only acceptable method to accomplish this was to pluck, by hand, each fascicle of pine needles (which, unlike the spruce needles were held tenaciously to the twigs). The cleaned needles (without fascicles) were then replaced in the bags and reweighed.

A handful of needles was then withdrawn from one of the bags of needles collected for each tree. Three of the longest and shortest needles contained in each handful were measured for length and width. In addition, fifteen needles were randomly drawn from the remainder of those in each handful and these were measured for length only. Finally, the number of needles in one-half gram of oven-dry needles was counted.

As mentioned previously only the dry weights of the needles on each tree were obtained. Using data on needle moisture content, provided by Kiil (1967), it was also possible to calculate the fresh needle weights of each tree. The weight of green branches for each tree was obtained by subtracting the weight of green needles from the fresh weight of crown materials (needles plus branches). The dry branch weight per tree was then obtained by multiplying the fresh branch weights times the moisture content of branch wood, obtained from Kiil (1967).

Since the volumes, inside and outside bark, of each tree were known, it was possible to calculate the dry weight of the bark of each tree by multiplying the bark volume by the specific gravity of bark obtained from Wahlgren (1967). Since no data appears to be available on the moisture content of lodgepole pine bark, the value reported for jack pine (Pinus banksiana Lamb.) by Besley (1967), was used to convert dry bark weights to green bark weights.

The proportions of each component (needles, branches, boles and bark) of the total above ground weight were obtained. This was accomplished by obtaining the percentage that the weight of each component contributed to the weight of the total tree weight.

Upon completion of the data collection it was found that complete data on only 63 pine trees were available. Consequently, the results presented in this thesis, are based on data collected from these 63 trees only.

A DISCUSSION OF BIOMASS

Factors Affecting Organic Matter Production

Conifers are generally more productive than deciduous trees, although there is a tendency for the latter to occupy better sites. Ovington (1956) reported that conifers proved to be the more productive when the two occurred under similar conditions. These results were confirmed by Whittaker (1966). Tadaki (1966) suggested a reasonable range for the leaf biomass of deciduous broad leaved forests to be only 2.0 to 3.0 oven-dry tons per hectare while that for evergreen coniferous forests would be 9.0 to 15.0 oven-dry tons per hectare.

Environmental factors are very important determinants of organic matter production and generally the amount of matter produced annually decreases from the equator towards the poles. Bazilevic and Rodin (1966), and Rodin and Bazilevic (1966) reported that the amount of organic matter contained in tropic and subtropic communities greatly exceeds that produced by temperate communities. These results tend to suggest that organic production increases with increasing temperature and length of growing season, although exceptions to this may occur with Pseudotsuga menziesii (Mirb.) Franco, Sequoia spp., and *Eucalyptus spp.* Comprehensive compilations of the results of many studies on organic matter have been prepared by Scott (1955), Ovington (1962), Bray and Gorham (1964), Tadaki (1966), Bazilevic and Rodin (1966), and Rodin and Bazilevic (1966).

Environmental factors such as light, temperature, moisture, mineral nutrition, the physical and chemical properties of the soil, atmospheric carbon dioxide, toxicindustrial gases, and such agents as insects and fungii will greatly influence the productivity of a forest complex. Odum (1959) noted that the rate of production of an ecosystem is in equilibrium (inflows balance outflows of materials and energy) with the supply or the rate of inflow of the minimum limiting constituent ("Law of the Minimum").

Results reported by Mar:Moller (1947), Kittredge (1948), Scott (1955), La Mois (1958), Brown (1963 and 1965) Vaidya (1963), Bray and Gorham (1964), Ando (1965), and Tadaki (1966) indicate that the amount of organic matter per unit area contained in the crowns of trees decreases with reduced site quality. Hatiya *et al.* (1966) reported that site quality did not significantly influence seasonal variations in leaf and leaf-fall amounts. Whittaker (1966) concluded from his investigations that biomass decreased from mesic to xeric sites and from low to high elevations. According to Witkamp (1966) the total organic mass weight (including trees, vegetation, litter and humus, and soil organic matter) decreased with decreasing soil moisture.

Witkamp's results indicated that the total weight of ground vegetation, litter, and humus on top of mineral soil decreased less than corresponding tree volume, as the water holding capacity of the soil decreased.

There are two schools of thought concerning the influence of stand density on the amount of canopy matter contained in a stand. Mar:Moller (1947) found that in closed stands thinning had little influence on the amount of foliage present. This was supported by Ovington (1956), Weetman and Harland (1964), Williston (1965), Tadaki (1966), and Katiya et al. (1966). These results suggest that trees attempt to maximize light utilization, i. e. the leaf biomass per tree increased as the light intensity increased and stand density decreased.

Members of the opposing school include Molchanov (1949), Scott (1955), Dimock (1958), LaMois (1958), Stiell (1962), Dieterich (1963), Reukema (1964), Baskerville (1965 b), Metz and Wells (1965), and Boyer and Fahnestock (1966), who reported that thinning considerably reduced the amount of litterfall per unit area, and thus suggesting a decrease in the amount of crown material present. Reukema (1966) reported that the growth and yield of regularly spaced planted trees decreased initially as density decreased. However as the stand grows older, the faster growth rate per tree of the trees in less dense stands may be great enough to offset the fact that there are fewer trees than in the dense stands and thus the total production of the low density stands may eventually exceed that of high density stands.

Baskerville (1965 b) suggested that Mar: Moller's findings may be true for intolerant species but not for tolerant species. Tadaki (1966) carried out a comprehensive summary of much of the research reported on leaf biomass and concluded that there were large similarities in the amount of foliage produced not only for the same and related species but also for deciduous, evergreen, broadleaved, and needle forest formations. Certainly one would expect that as the density of the over-story increased the biomass of the understory vegetation would decrease. This is supported by the results of Baskerville (1966).

It would also be logical to expect the biomass of fully stocked stands to increase directly with stand density up to the point at which heavy irregular mortality occurs. In dense stands at full stocking (Smith, 1966 a), one can expect that biomass will increase directly with the depth of live crown which decreases with basal area per acre (Smith, Ker, and Csizmazia, 1961).

The influence of stand density on stand development has been discussed by Dahms (1966), and Stiell (1966). Growth-density relationships were discussed by Reukema (1966), and Berg (1966). Smith (1966 b) discussed the financial implications of stocking control.

The total amount of foliage displayed by a tree is related to such factors as tree size, competition, and site conditions. It appears that those conditions that favor increased tree growth will result in increases in the amount of foliage supported by a tree. A number of investigations, too numerous to summarize, here were abstracted by Johnstone (1967 a) and the results of these investigations unanimously indicate that the weight of foliage per tree increases with increases in tree dbh and basal area per tree. Hall (1965) reported that a strong relationship existed between the amount of stem growth at any point in the tree and the amount of foliage present above that point. Similar results are reported by Tadaki (1966).

Strong relationships between the weight of foliage and branches, and height growth have been reported by Ovington (1956), Vaidya (1963), Weetman and Harland (1964), and Tadaki and Kawasaki (1966). According to Ovington (1956) the weight of the canopy increases as tree age increases. Ovington (1962) suggested that the productivity of young trees increases rapidly up to approximately 35 years of age, levels off for a short period and then declines. Tadaki (1966) reported that there was a rapid increase in leaf biomass during the pole stage of development reaching a maximum when the canopy closed then a decline occurred. Molchanov (1949) reported the needle weight of pine trees to be directly proportional to volume increment regardless of tree age.

In addition to Molchanov (1949) several other researchers including Kittredge (1948), Poljakova-Mincenko (1961), Tadaki *et al.*(1962), Satto (1962), and Zyrjcev (1964) have observed high correlations between changes in foliage amount and growth increments. Siminov (1961) reported linear relationships between leaf and stem weights, stem and branch weights, and branch and leaf weights.

The amount of organic matter contained in branches increases with tree size. If this amount is subdivided into the amounts comprised of dead and living matter it can be seen that there is very little branch matter of a dead nature until crown closure occurs. After this time the dead branch component increases as a result of the lower branches dying due to shading. Ovington (1957) reported that the weights of living and dead branches may be approximately equal in older trees. Baskerville (1965 b) reported that the amount of live branches increased and the amount of dead branches decreased as stand density decreased. La Mois (1958) reported that the weight of dead branches is strongly influenced by site and that good site qualities hasten the appearance of dead branches and speed the dying of branches. Some of the factors effecting natural pruning and its related factors were intensively analyzed by Smith, Ker, and Csizmazia (1961), and by Bailey (1964).

The amount of bole material constitutes the greatest weight of any component in a tree. The proportion of the total tree weight contained in the bole increases with tree size, and it appears from Ovington's (1957) work with Scots pine (Pinus sylvestris L.) that this proportion increases with age. Ovington reported that the ratio of oven-dry bole weight to oven-dry canopy weight and to canopy area increases as tree size increases. It appears, therefore, that although the weights of tree components increase with tree size the proportion of these components to total tree weight decreases with the exception of the bole component. Baskerville (1965 b) reported that although the amount of wood produced is unaffected by stand density the amount of bole wood is. Baskerville's data suggested that in small trees more total growth goes into stem wood and less into foliage than in large trees. Similar results to Baskerville's were reported by Satoo and Senda (1966). Baskerville's results therefore appear to be in direct opposition to Ovington's. This contradiction may have resulted because the small diameter trees measured by Baskerville were probably suppressed trees having cylindrical formed boles and sparse crowns. Results presented by Baskerville on bark proportion are not in agreement with those presented by Smith and Kozak (1967) for most of the commercial tree species of British Columbia. Certainly one would expect to observe a situation similar to the one presented by Ovington (1957).

Stand Fuels

Of the many factors which govern the behaviour of fire, the quantity of fuel available is the most constant and easily measured variable. By using weight measurement it is possible to obtain an indication of the quantity of fuel and thus the potential energy release. In forestry the most important fuel is slash or the residue left following the harvesting of an area. It is important for the forester to be able to accurately estimate the quantity of slash in order to establish the size and cost of the disposal job or protection requirement. The quantity of slash will also greatly influence the silvicultural treatment necessary to create conditions favorable for regenerating new stands.

Following logging any attempt to estimate the quantity of slash is almost impossible because of the irregular and interlaced nature of the slash on the ground. Consequently, the best method, in terms of ease and accuracy, appears to be a pre-harvest estimate. By using an appropriate equation or slash quantity table in conjunction with a stand table it is possible to obtain an estimate of future expected slash disposal requirements.

Slash weight tables have been constructed by several researchers including Bruce (1951), and Chandler (1960). Equations to be used for slash weight prediction have been developed by Fahnestock (1960) for western conifers, by Brown (1963 and 1965), and Dieterich (1963) for red pine (*Pinus resinosa* Ait.), and by Kiil (1965), and Muraro (1964 and 1966) for lodgepole pine. In addition, many of the methods used for the estimation of biomass or foliage quantities, mentioned in preceding parts of this report, can be applied. Many of the methods and results reported previously have failed to establish the size distribution of the various slash components, which greatly influence the potential fire hazard, and rate of spread. However, these results should not be considered meaningless and as Fahnestock (1960) pointed out, any objective method of estimation is vastly superior to guesswork.

A summary of previous research on biomass foliage and slash is presented in Appendix I.

Method of Analysis

The data were analysed using multiple regression techniques The regression program described by Kozak and Smith (1965) and the University of British Columbia's I. B. M. 7040 electronic computer were used for the analysis. Tree component weights, and the proportions of the weights of the component to the total tree weight were used as dependent variables with the independent variables diameter at breast height in inches (dbh), tree height in feet (Ht.) crown length in feet (CL), crown width in feet (CW), height to live crown in feet (Ht. LC), and tree basal area in square feet (BA). The independent and dependent variable analysed were always in the units previously mentioned.

The following were used as dependent variables in the regression analyses of tree and component weights:

a) Total Tree Weight - The weight of all of the components (including needles, branches, cones, bole wood, and bark) above a one foot stump. The fresh weights were measured in the field and the dry weights were obtained by the addition of the dry needle weight plus the dry stem weight plus the dry branch weight.

b) Total Stem Weight - The weight of the total stem (the total tree less the sum of the branches plus needles plus cones). The fresh weight was obtained by field measurements and these were converted to a dry weight basis using the average of the moisture content measurements for each tree.

c) Needle Weight - The weight of the cleaned and dried needles was obtained by actual measurement. The fresh weight of the needles was calculated using needle moisture content data provided by Kiil (1967).

d) Branch Weight - Neither the fresh nor dry branch weights were measured directly. The fresh branch weight was determined by subtracting the sum of the fresh stem and fresh needle weights from the total tree fresh weight. The dry weight of branches was calculated by reducing the fresh branch weight by branch moisture content data provided by Kiil (1967).

e) Bole Bark Weight - Neither the fresh nor dry bark weights were measured. The volume of bark was obtained from Reineke charts and this volume was converted to dry weight using bark specific gravity data provided by Wahlgren (1967). Because of the unavailability of bark moisture content data for lodgepole pine; moisture content data for jack pine bark (Besley, 1967) was used.

f) Bole Wood Weight - The bole wood weight was calculated by reducing the total stem weight by the weight of bark.

g) Crown Weight - Crown weight excludes the weight of the main bole within the crown and is the weight of the branches plus needles. The fresh crown weight was measured in the field. The dry crown weight was calculated by adding the dry weight of the branches plus the dry weight of the needles.

h) Slash Weight - Slash weight is the weight of the needles plus the weight of the branches plus the non-merchantable top weight. Fresh slash weights were obtained in the field. The weights of dry slash were determined from the sum of the dry weight of needles and branches plus the difference between the total stem and the merchantable stem weights adjusted for a moisture content determination taken from a part of the stem located within the crown.

i) Merchantable Stem Weight - The merchantable stem is the weight of the stem between a one foot stump and a four inch top. The fresh weight was determined by direct measurement and this weight was reduced by the average moisture content of each tree to obtain the dry weight of the merchantable bole.

The proportions of the weight of each of the components, discussed previously, to the weight of the total tree were related to the independent variables dbh, height, crown length, crown width, height to live crown, and tree basal area using multiple regression techniques.

An additional analysis was carried out to relate tree characteristics to crown and needle characteristics. For purposes of this analysis it was assumed that the geometric form of lodgepole pine crowns is that of a parabola. The formulae for the volume and surface area of a parabola are:

$$\text{Crown Volume (Cr. Vol.)} = \frac{\pi R^2 CL}{2}$$

$$\text{Crown Surface Area (Cr. S.A.)} = \frac{\pi R}{6 CL^2} \quad (R^2 + 4 CL^2)^{3/2} - R^3$$

where: $\pi = 3.1416$

R = crown radius = (crown width / 2)

CL = crown length

The number of needles per tree was calculated by multiplying the number of needles per half gram times the weight of needles per tree in grams. Needle characteristics were studied and the relationship of needle length on needle width established using a simple linear regression. In addition, needle characteristics were also related to tree characteristics using regression analysis.

Using regression techniques, the crown characteristics: crown volume, crown surface area, dry needle weight, and number of needles per tree were related to tree stem volume (ob) in cubic feet and to total tree weight in pounds. A multiple regression of the number of needles per cubic foot of volume (ob) on dbh, height, and basal area (bh) was used to study the productive efficiency of the different sized trees. Using regression analysis, the same three independent variables were related to the dry needle weight and number of needles per cubic foot of crown volume and per square foot of crown surface area.

Results of Analysis

Tree and component weight relationships.

Table 1 presents the means, standard deviations, and minimum and maximum values of the independent variables used in the analyses.

Table 1. Mean, Standard Deviation, Minimum and Maximum Values of the Tree Characteristics used as Independent Variables for 63 Lodgepole Pine Trees.

Independent Variables	Mean	Standard Deviation	Minimum Value	Maximum Value
DBH (in)	6.48	1.668	4.30	10.90
Height (ft)	58.46	6.444	45.00	72.00
CL (ft)	17.24	5.940	8.00	32.00
CW(ft)	4.79	1.321	2.50	8.80
Ht. LC (ft)	41.22	5.070	25.10	50.80
BA (sq. ft.)	0.24	0.131	0.10	0.65

It should be noted in the preceding table that the size range of the trees from which the data were collected is very narrow. No attempt should be made to apply the formulas developed in this thesis beyond the dimension range of these trees.

The means, standard deviations, minimum values, and maximum values of the dependent variables are presented in Table 2.

Table 2. Mean, Standard Deviation, Minimum and Maximum Weights in Pounds for the Tree Characteristics used as Dependent Variables, for 63 Lodgepole Pine Trees

Dependent Variable		Mean	Standard Deviation	Minimum Value	Maximum Value
Total Tree:	Fresh	437.95	278.71	126.00	1,183.00
	Dry	234.92	141.78	78.16	640.13
Total Stem:	Fresh	387.59	238.38	107.00	1,049.00
	Dry	208.55	120.68	72.01	530.03
Needle:	Fresh	21.60	16.79	1.95	73.95
	Dry	11.05	8.59	1.00	37.84
Branch:	Fresh	28.76	28.64	2.04	153.56
	Dry	15.31	15.24	1.09	81.74
Bole Bark:	Fresh	30.68	24.32	7.75	121.35
	Dry	21.17	16.78	5.35	83.73
Bole Wood:	Fresh	369.50	228.01	99.16	989.04
	Dry	196.08	113.59	66.60	495.02
Crown:	Fresh	50.37	42.94	4.00	209.00
	Dry	26.36	22.54	2.09	110.11
Slash:	Fresh	108.54	36.85	62.00	233.00
	Dry	57.03	20.34	25.31	122.11

Simple correlation coefficients (r) between the dependent and independent variables are shown in Table 3.

Table 3. The Simple Correlation Coefficients Between Tree and Component Weights and Some Tree Characteristics for 63 Lodgepole Pine Trees.

Dependent Variables		Independent Variables					
		DBH	HT	CL	CW	Ht.LC	BA
Total Tree:	Fresh	0.982**	0.886**	0.732**	0.821**	0.268*	0.986**
	Dry	0.980**	0.889**	0.716**	0.799**	0.290*	0.982**
Total Stem:	Fresh	0.979**	0.894**	0.781**	0.808**	0.280*	0.980**
	Dry	0.977**	0.898**	0.712**	0.781**	0.307*	0.974**
Needle:	Fresh	0.907**	0.773**	0.724**	0.815**	0.133ns	0.908**
	Dry	0.907**	0.773**	0.724**	0.815**	0.133ns	0.908**
Branch:	Fresh	0.879**	0.723**	0.619**	0.792**	0.196ns	0.908**
	Dry	0.879**	0.725**	0.619**	0.792**	0.196ns	0.908**
Bole Bark:	Fresh	0.839**	0.819**	0.680**	0.674**	0.245ns	0.848**
	Dry	0.839**	0.819**	0.680**	0.674**	0.245ns	0.848**
Bolewood:	Fresh	0.979**	0.890**	0.728**	0.808**	0.278*	0.981**
	Dry	0.975**	0.891**	0.706**	0.779**	0.306*	0.983**
Crown:	Fresh	0.941**	0.786**	0.696**	0.847**	0.183ns	0.961**
	Dry	0.940**	0.785**	0.695**	0.846**	0.184ns	0.960**
Slash:	Fresh	0.770**	0.623**	0.549**	0.678**	0.149ns	0.802**
	Dry	0.782**	0.641**	0.538**	0.725**	0.184ns	0.809**

**significant at the 0.01 probability level

*significant at the 0.05 probability level
ns not significant at the 0.05 probability level

(Note: These notations will be used, as defined above, throughout the remainder of this thesis).

It can be seen from the results in Table 3 that in all cases, with the exceptions of total stem dry weight, basal area per tree is most closely associated with the weight variables. Dbh is second only to basal area except for total stem dry weight where the situation is reversed. Height to live crown in all cases is poorly correlated with tree and component weights. The positive values of all the coefficients show that the weights of the trees and tree components increase with increasing tree size.

The regression relationships presented in the following sections for tree and component weight and for the proportion of the component to the total tree weight are of a linear form. Generally, the formulae presented in the literature have been of a logarithmic transformation form. Transformed variables are not presented in the following section because it is felt that the narrow range of the data and high accuracy of the linear form do not require the transformation. Logarithmic regressions equations are presented in Appendix II.

The regression techniques used result in the best possible fit of the regression line or surface. The techniques do not, however, condition the regression relationships and consequently, the equations may be in error for very small trees.

In the following results the standard error of estimate is expressed both in absolute units and as a per cent of the mean, the latter is isolated by brackets and is presented in the discussions of the results only. These percentages are included to facilitate comparisons of the relative variability.

a. total tree weight (lb)

Tables 4 and 5 present the independent variable eliminations from the multiple regression analyses of total tree fresh weight and total tree dry weight. In addition, the simple linear regression equations of total tree fresh and dry weight on dbh are presented in the appropriate tables.

i) fresh weight basis

Table 4. Regression Equations Illustrating the Relationship of Total Tree Fresh Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

Intercept	Independent Variables						R^2	SE_E
	BA	Ht. LC	CL	CW	DBH	Ht		
-305.51	1892.3**	22.170	23.322	11.152	-10.167	-17.480	0.976**	45.58
-305.52	1892.3**	4.690*	5.842*	11.152	-10.164		0.976**	45.18
-320.46	1782.2**	4.290*	5.489*	10.838			0.976**	44.82
-277.52	1888.7**	4.063*	5.043*				0.975**	45.21
-105.85	2087.7**	0.829					0.973**	46.72
- 73.71	2095.9						0.976**	46.52
-625.64					164.07		0.964**	53.24

As can be seen from the preceding results 97.6 per cent of the variation in the fresh weight of the total tree above the ground can be accounted for by the independent variable, tree basal area, with a standard error of 46.52 lb. (10.6%). Dbh accounted for 96.4 per cent of the variation and had a standard error of estimate of 53.20 lb. (12.1%).

As can be seen from Table 4 dbh, crown width, and tree height do not significantly contribute to the multiple regression equation and it appears that there is very little advantage in using a multiple regression instead of a simple linear regression of total tree fresh weight on tree dbh or basal area. The relationship between total tree fresh weight and tree basal area is presented in Figure 1.

ii) dry weight basis

Table 5. Regression Equations Illustrating the Relationship of Total Tree Dry Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

Intercept	Independent Variables						R^2	SE_E
	BA	Ht. LC	CL	DBH	CW	Ht		
-163.79	865.4**	4.431	4.247	8.545	-1.077	-2.030	0.968**	26.68
-163.79	865.4**	2.401	2.217	8.546	-1.077		0.968**	26.44
-166.93	862.7**	2.451	2.285	7.838			0.968**	26.22
-154.45	949.9**	2.755*	2.547				0.968**	26.03
- 67.73	1050.4**	1.121					0.966**	26.66
- 24.25	1061.6						0.964**	27.01
-305.05				83.296			0.960**	28.49

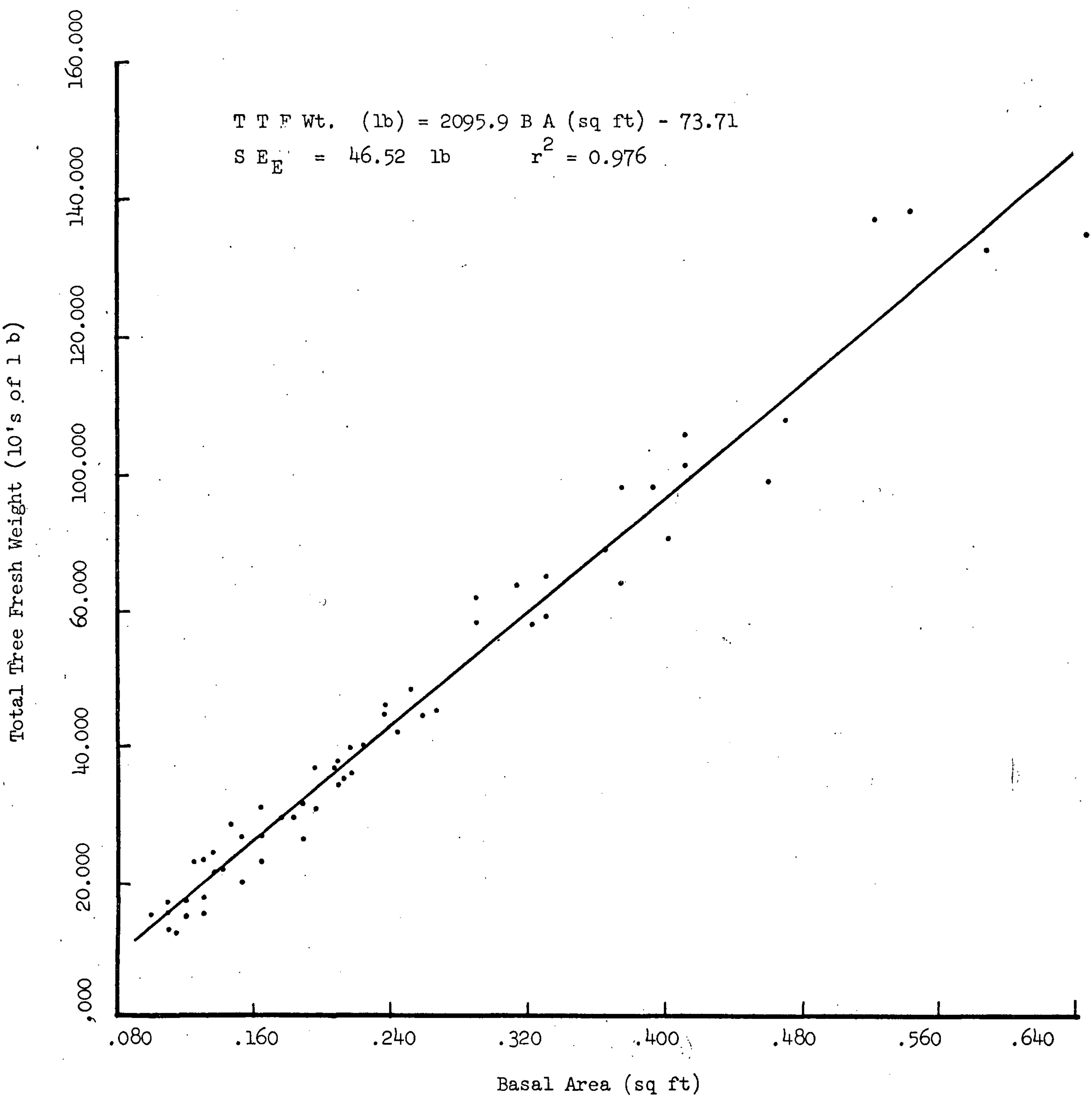


Figure 1. The Relationship Between Total Tree Fresh Weight (lb) and Tree Basal Area (sq ft) at Breast Height.

Basal area was the best single variable for accounting for the variation in total tree dry weight. Basal area accounted for 96.4 per cent of the total variation with a standard error of estimate of 27.01 lb (11.5%). The second best variable was dbh which accounted for 96.0 per cent of the variation and had a standard error of estimate of 28.49 lb (12.1%). The use of a multiple regression did not improve the relationship and therefore, it appears that a simple linear regression of total tree dry weight on basal area or dbh is most satisfactory. The relationship between total tree dry weight and tree basal area is presented in Figure 2.

b. total stem weight (lb)

i) fresh weight basis

Total stem weight is the weight of the bole wood plus bark above a one foot stump. The elimination of the independent variables for the dependent variables total stem fresh and dry weight are presented in Tables 6 and 7, respectively.

Table 6. Regression Equations Illustrating the Relationship of Total Stem Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

Intercept	Independent Variables						R^2	SE_E
	BA	Ht. LC	CL	CW	DBH	Ht		
-355.63	1398.1^{**}	16.430	17.520	5.274	5.139	-10.88	0.967^{**}	45.77
-355.64	1398.1^{**}	5.552^{*}	6.641^{*}	5.274	5.141		0.967^{**}	45.37
-348.08	1453.8^{**}	5.755^{**}	6.819^{**}	5.433			0.967^{**}	44.98
-326.55	1507.1^{**}	5.641^{**}	6.596^{**}				0.966^{**}	44.79
-102.03	1767.4^{**}	1.411					0.961^{**}	47.64
- 47.30	1781.4						0.961^{**}	47.76
-518.95					139.840		0.957^{**}	49.55

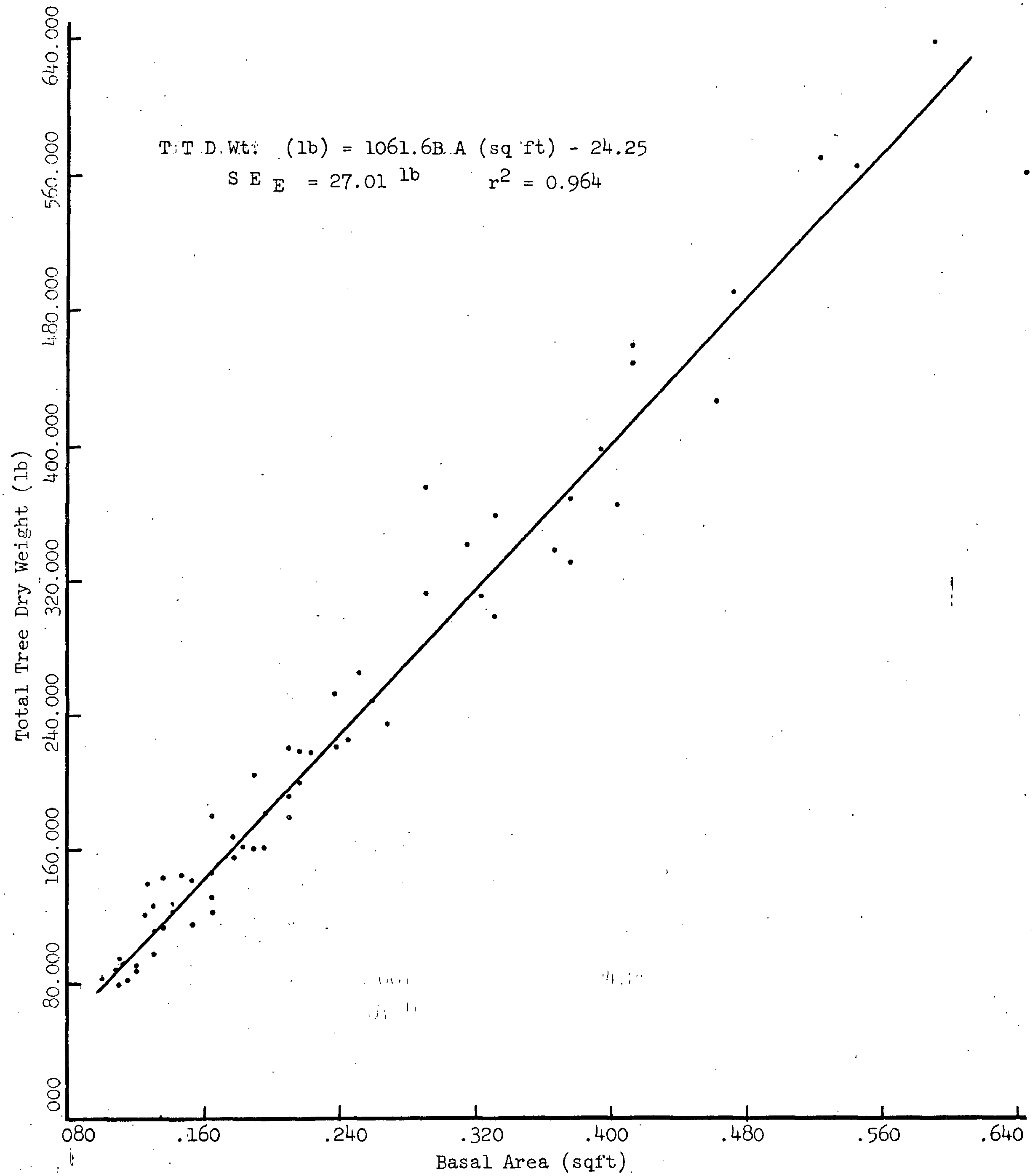


Figure 2. The Relationship Between Total Tree Dry Weight (lb) and Tree Basal Area (sqft) at Breast Height.

As can be seen by the results presented in Table 6, 96.1 per cent of the variation in total stem weight is accounted for by the independent variable basal area with a standard error of estimate of 47.76 lb (12.3%). Using dbh as the independent variable accounts for 95.7 percent of the variation with a standard error of estimate of 49.55 lb (12.8%). As was the case with total tree weight, it appears that there is little to be gained from using a multiple regression instead of a simple linear regression of stem weight on basal area or dbh. The relationship between total stem fresh weight and tree basal area is presented in Figure 3.

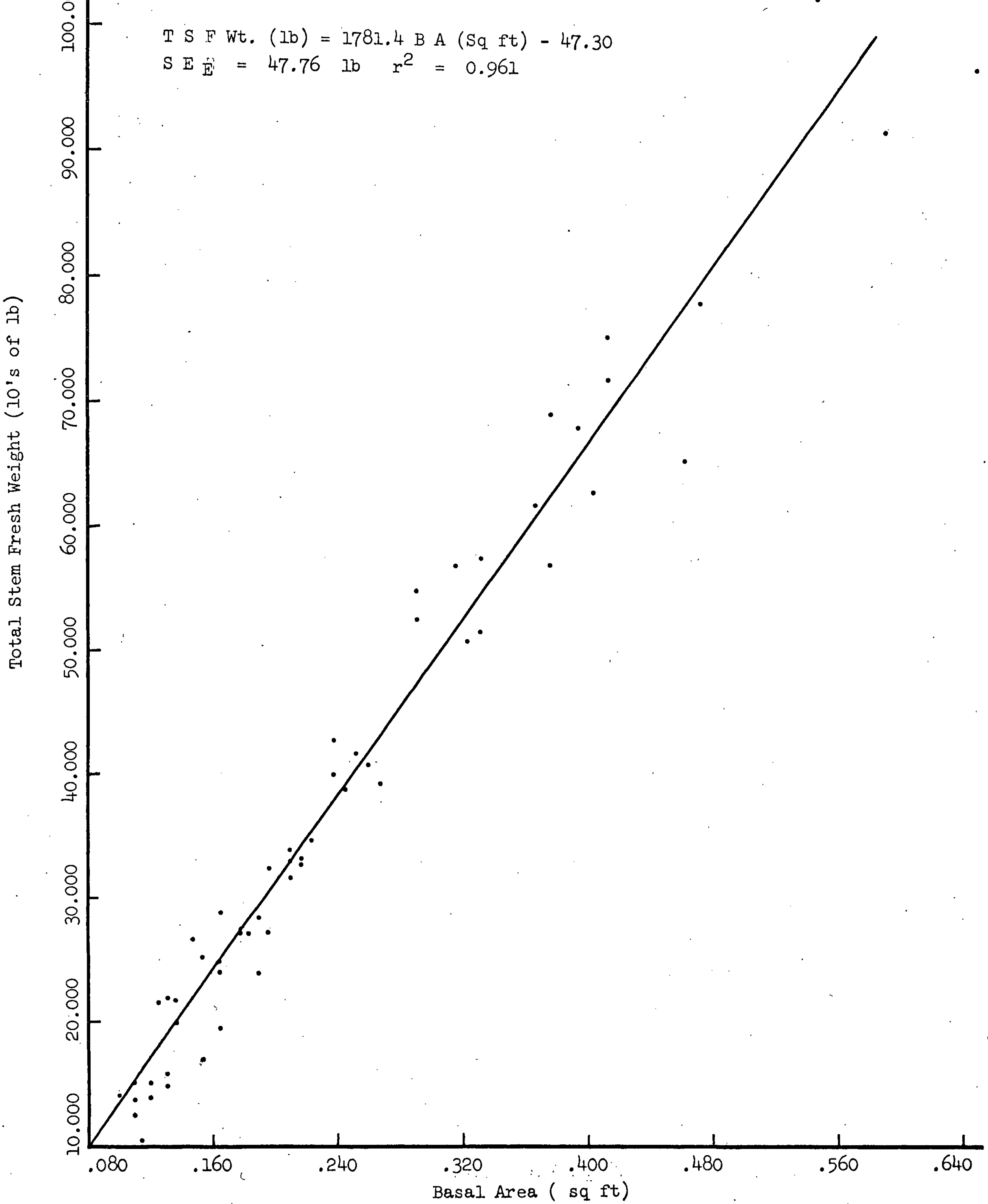
ii) dry weight basis

Table 7. Regression Equations Illustrating the Relationship of Total Stem Dry Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

Intercept	Independent Variables						R^2	SE_E
	BA	Ht. LC	CL	CW	DBH	Ht		
-190.89	602.157*	4.686	4.479	-4.152	16.874	-1.838	0.959**	25.77
-190.89	602.152*	2.848*	2.641	-4.152	16.874		-0.959**	25.54
-166.08	784.887**	3.513**	3.226*	-3.630			0.958**	25.47
-180.46	749.232**	3.589**	3.376**				0.958**	25.41
- 65.55	882.415**	1.424**					0.953**	26.70
- 10.33	896.592						0.949**	27.39
-249.04					70.588		0.952**	26.70

The best single independent variable for predicting total stem dry weight was dbh which accounted for 95.2 per cent of the variation in the

Figure 3. The Relationship Between Total Stem Fresh Weight (lb) and Tree Basal Area (sq ft) at Breast Height.



dependent variable and had a standard error of estimate of 26.70 lb. (12.8%). Basal area alone accounted for 94.9 per cent of the variation in the dry weight of the total stem with a standard error of estimate of 27.39 lb. (13.1%). The small gain in standard error does not warrant the use of a multiple regression equation. The relationship between total stem dry weight and dbh is presented in Figure 4.

c. bole wood weight (lb.)

Bole wood weight can be defined as the weight of the total stem minus the weight of the bark. Table 8 presents the elimination of the independent variables from the multiple regression for bole wood fresh weight, and in Table 9 the elimination of the independent variables from the multiple regression for bole wood dry weight are presented.

i) fresh weight basis

Table 8. Regression Equations Illustrating the Relationship of Bole Wood Fresh Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

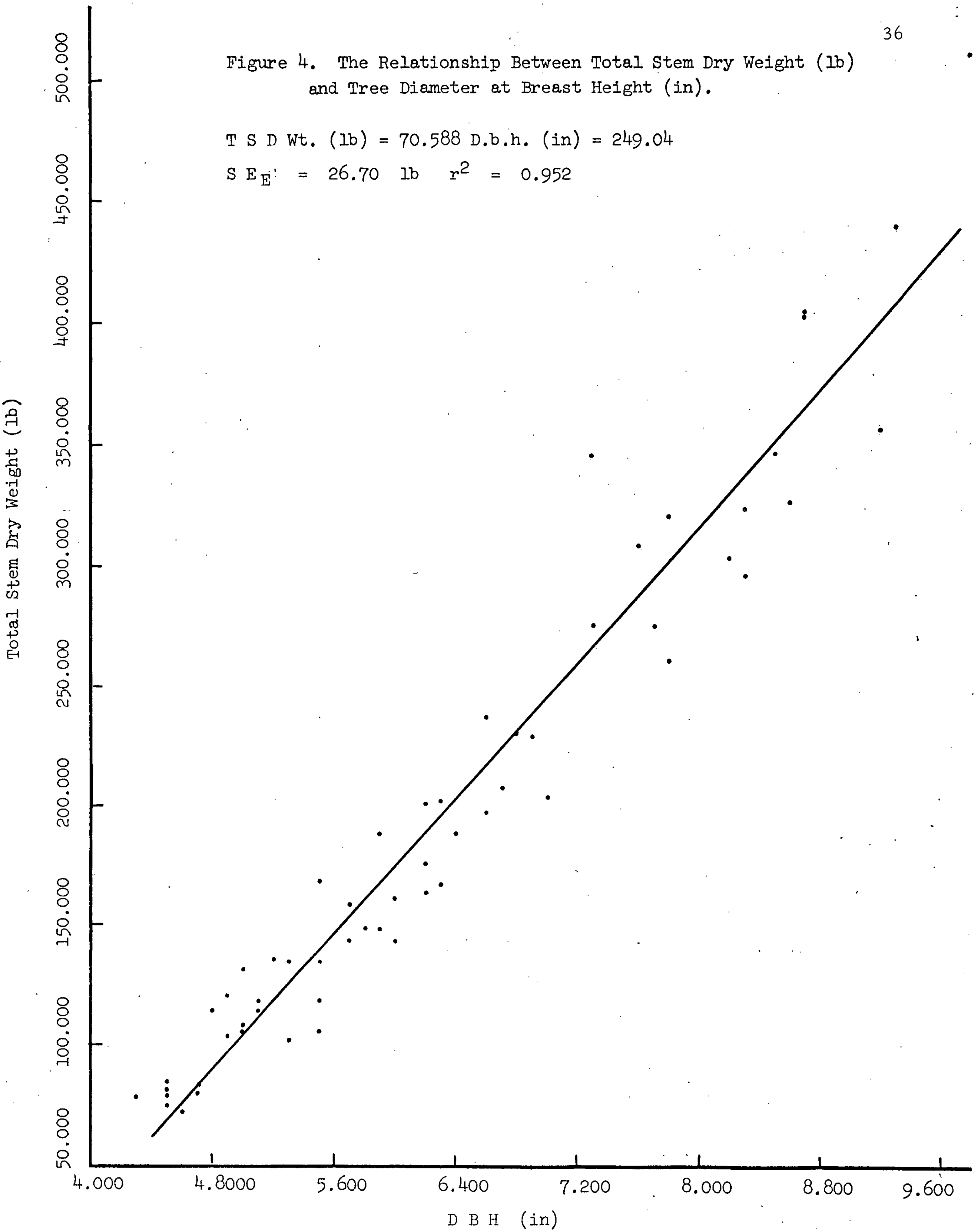
Intercept	Independent Variables						R^2	SE_E
	BA	Ht. LC	CL	CW	DBH	Ht		
-301.86	1361.3**	6.670	7.432	3.934	7.726	-2.273	0.967**	43.66
-301.86	1361.3**	4.396*	5.159*	3.934	7.726		0.967**	43.28
-290.50	1444.9**	4.700*	5.427*	4.173			0.967**	42.92
-273.97	1485.9**	4.613*	5.255*				0.967**	42.68
- 95.08	1693.3**	1.242					0.963**	44.49
- 46.89	1705.7						0.962**	44.55
-497.97					133.816		0.958**	46.96

Basal area proved to be the best single independent variable. Basal area accounted for 96.2 per cent of the variation with a standard

Figure 4. The Relationship Between Total Stem Dry Weight (lb) and Tree Diameter at Breast Height (in).

T S D Wt. (lb) = 70.588 D.b.h. (in) = 249.04

S E_E = 26.70 lb r^2 = 0.952



error of 46.96 lb. (12.7%). No advantage can be gained from using a multiple regression as opposed to a simple regression of bole wood fresh weight on basal area or dbh. The relationship between bole wood fresh weight and tree basal area is presented in Figure 5.

ii) dry weight basis

Table 9. Regression Equations Illustrating the Relationship of Bole Wood Dry Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

Intercept	Independent Variables						R^2	SE_E
	BA	Ht. LC	CL	CW	DBH	Ht		
-153.78	576.8^{*}	6.632	6.199	-5.076	18.654	-4.581	0.958^{**}	24.49
-153.78	576.8^{*}	2.051	1.618	-5.076	18.655		0.958^{**}	24.27
-126.35	778.8^{**}	2.785^{**}	2.266^{*}	-4.499			0.957^{**}	24.26
-144.18	734.6^{**}	2.879^{**}	2.451^{*}				0.956^{**}	24.30
- 60.75	831.3^{**}	1.307^{*}					0.953^{**}	24.93
- 10.05	844.3						0.950^{**}	25.56
-234.56					66.430		0.951^{**}	25.23

The best independent variable proved to be dbh which accounted for 95.1 per cent of the variation in dry bole wood weight with a standard error of estimate of 25.23 lb. (12.9%). This was slightly better than basal area which accounted for 95.0 per cent of the variation and had a standard error of 25.23 lb. (12.9%). The results suggest that there is very little to be gained from using a multiple regression. The relationship between bole wood dry weight and dbh is presented in Figure 6.

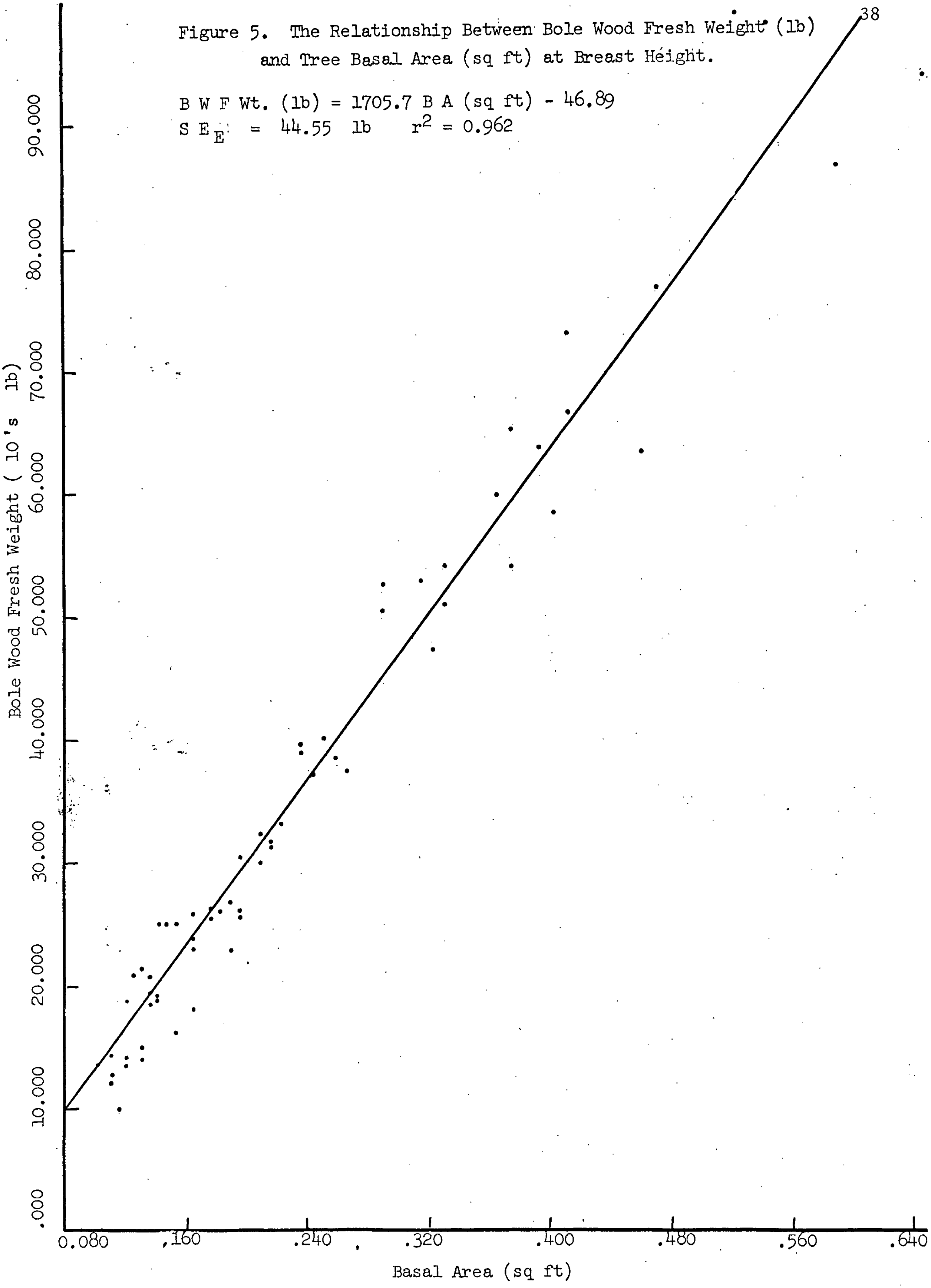


Figure 5. The Relationship Between Bole Wood Fresh Weight (lb) and Tree Basal Area (sq ft) at Breast Height.

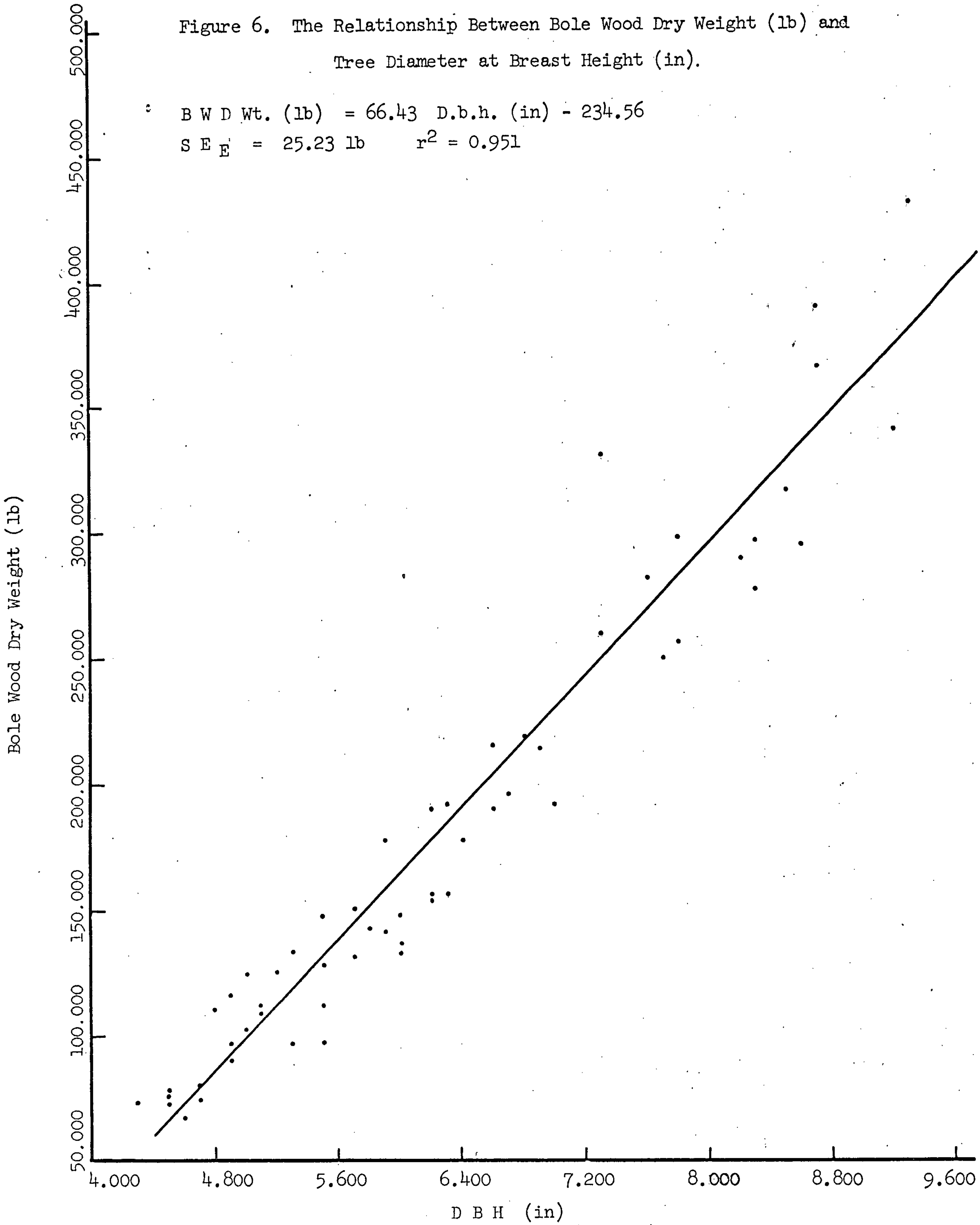


Figure 6. The Relationship Between Bole Wood Dry Weight (lb) and
Tree Diameter at Breast Height (in).
B W D Wt. (lb) = 66.43 D.b.h. (in) - 234.56
S E E = 25.23 lb   r2 = 0.951
Bole Wood Dry Weight (lb)
500.000
450.000
400.000
350.000
300.000
250.000
200.000
150.000
100.000
50.000
4.000
4.800
5.600
6.400
7.200
8.000
8.800
9.600
D B H (in)

d. bole bark weight (lb)

The eliminations of the regression coefficients from the multiple linear regressions of the weight of fresh and dry bole bark are presented in Tables 10 and 11, respectively.

i) fresh weight basis

Table 10. Regression Equations Ellustrating the Relationship of Bole Bark Fresh Weight (lb) on Several Independent Variables, for 63 Lodgepole Pine Trees.

Intercept	Independent Variables						R^2	SE_E
	BA	Ht.LC	CL	DBH	Ht	CW		
-37.13	315.459**	17.938	18.286	-20.294*	-15.964	0.201	0.769**	12.29
-36.54	315.985**	17.847	18.191	-20.164*	-15.882		0.769**	12.18
-35.88	321.146**	19.849**	23.268**	-20.634*			0.770**	12.07
-68.69	91.444**	1.185**	1.636*				0.751**	12.45
-13.00	155.980**	0.136					0.721**	13.07
- 7.73	157.333						0.720**	12.98
-48.61				12.231			0.704**	13.34
-150.07					3.092		0.671**	14.06

Tree basal area accounted for the most variation (72.0 per cent) of fresh bole bark weight with a standard error of estimate of 12.98 lb. (42.3%). The second best variable was dbh. Dbh accounted for 70.4 per cent of the variation and had a standard error of estimate of 13.34 lb. (43.5%). As demonstrated by the results in Table 10 the use of a multiple regression improved the relationship because the contribution to the explained variation by the other variables was significant. The relationship between bole bark fresh weight and tree height is presented in Figure 7.

ii) dry weight basis

Table 11. Regression Equations Illustrating Relationship of Bole Bark Dry Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

Intercept	Independent Variables						R^2	SE_E
	BA	Ht.LC	CL	DBH	Ht.	CW		
-25.63	217.767**	12.174	12.414	-14.014*	-10.812	0.139	0.769**	8.48
-25.22	218.131**	12.110	12.348	-13.924*	-10.754		0.769**	8.40
-24.77	221.626**	1.370**	1.606**	-14.243*			0.770**	8.33
-47.42	63.077**	0.818*	1.129**				0.751**	8.59
- 8.98	107.623**	0.094					0.721**	9.02
- 5.33	108.558						0.720**	8.95
-33.54				8.439			0.704**	9.21
-103.55					2.133		0.671**	9.70

A multiple linear regression of bole bark dry weight on the combination of tree basal area, crown length, height to live crown and diameter at breast height was the most reliable estimate. These four variables combined accounted for 77.0 per cent of the variation with a standard error of estimate of 8.33 lb(39.4%). The elimination of diameter at breast height from the multiple regression did not result in a large increase in the standard error or a large decrease in the amount of the variation accounted for. Tree basal area was the best single independent variable accounting for 72.0 per cent of the variation with a standard error of estimate of

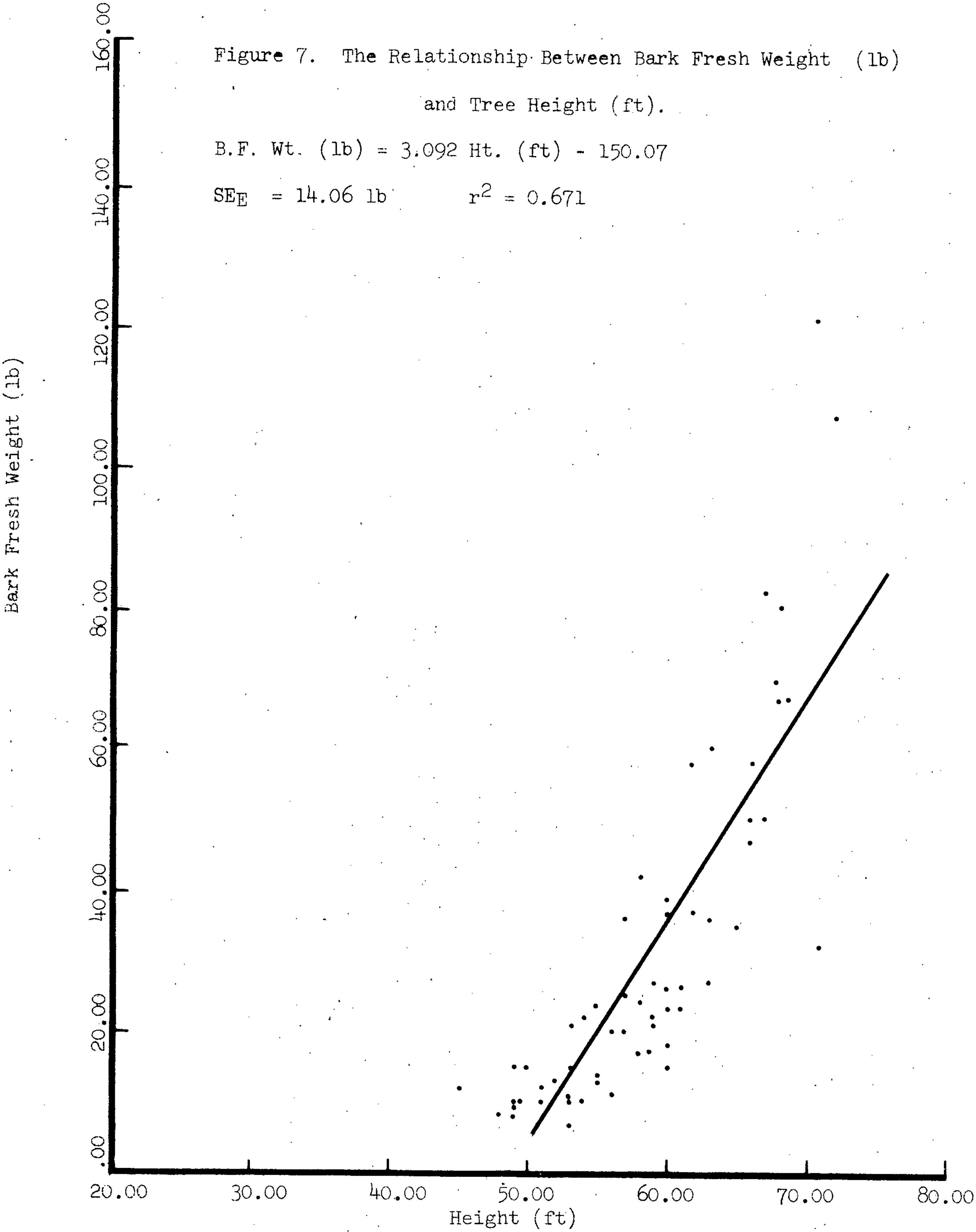


Figure 7. The Relationship Between Bark Fresh Weight (lb) and Tree Height (ft).

B.F. Wt. (lb) = 3.092 Ht. (ft) - 150.07

SE_E = 14.06 lb $r^2 = 0.671$

8.95 lb.(42.2%). The relationship between bole bark dry weight and tree height is presented in Figure 8.

e. needle weight (lb)

Table 12 presents the elimination of the regression coefficients from the relationship of fresh needle weight on several independent variables. The elimination of the regression coefficients from the multiple regression of dry needle weight on the same independent variables is presented in Table 13.

i) fresh weight basis

Table 12. Regression Equations Illustrating Relationship of Fresh Needle Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

Intercept	Independent Variables						R^2	SE_E
	DBH	Ht.LC	CW	CL	BA	Ht.		
-21.05	9.068	-0.572	2.640*	-0.081	-10.760	-0.020	0.860**	6.60
-21.05	9.068	-0.592	2.640*	-0.101	-10.760		0.860**	6.55
-19.14	8.168**	-0.566	2.630*	-0.084			0.860**	6.49
-21.31	7.862**	-0.507**	2.685*				0.860**	6.44
-19.22	9.615**	-0.522**					0.845**	6.71
-37.596	9.132						0.823**	7.13
-6.79					116.279		0.825**	7.09

There appears to be very little difference between the relationships of fresh needle weight on tree basal area and dbh. Basal area accounted for 82.5 per cent of the variation in fresh needle weight, with a standard error of estimate of 7.09 lb (32.8%). The independent variable of dbh

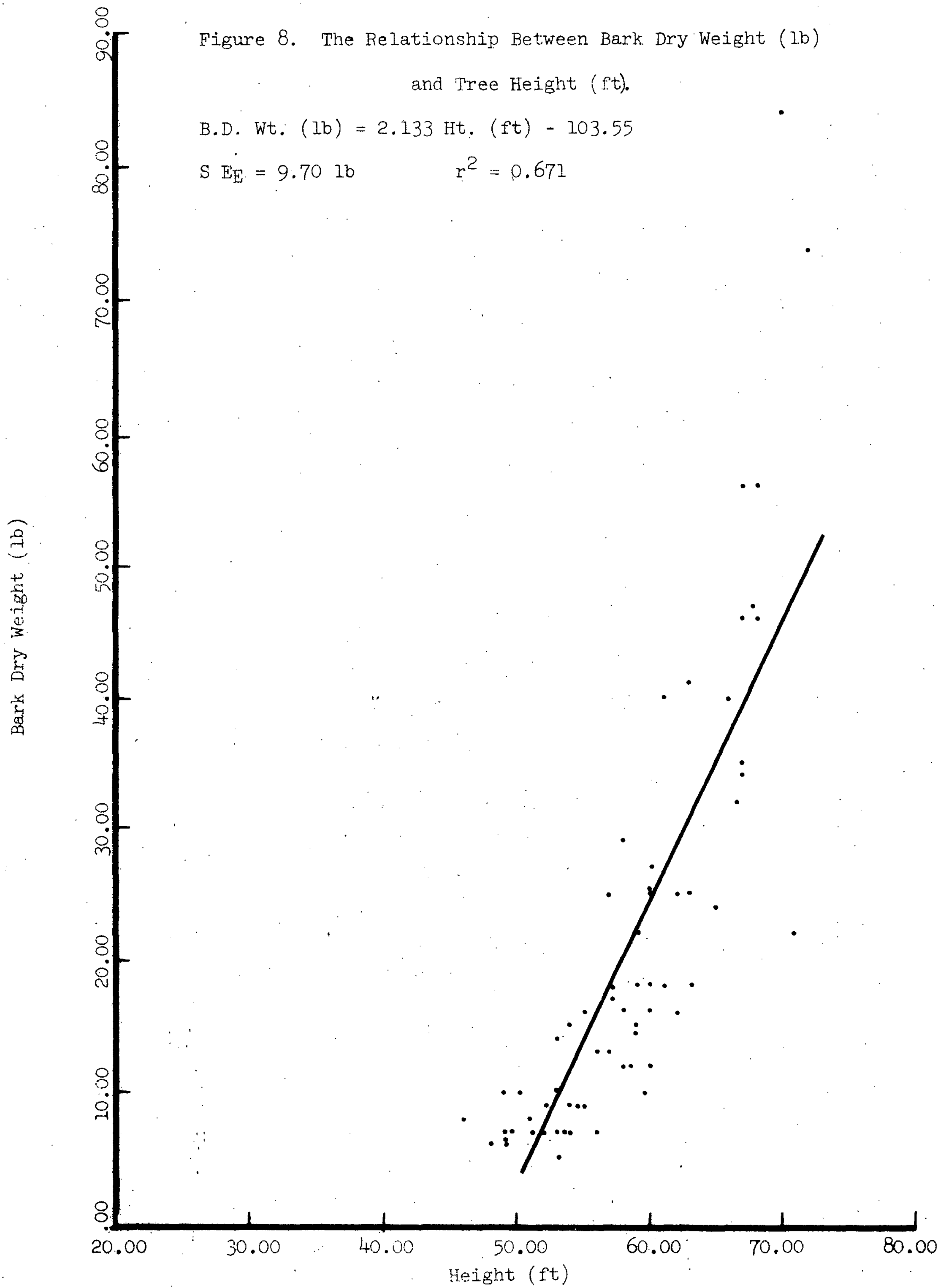


Figure 8. The Relationship Between Bark Dry Weight (lb) and Tree Height (ft).

B.D. Wt. (lb) = 2.133 Ht. (ft) - 103.55

$S\ E_E = 9.70$ lb $\qquad r^2 = 0.671$

accounted for 82.3 per cent of the variation and had a standard error of estimate of 7.13 lb (33.0%) A multiple regression did not offer a large improvement and reduced the standard error of estimate by only 0.38 lb (1.8%) compared to the standard error obtained using basal area. The relationship between needle fresh weight and tree basal area is presented in Figure 9.

ii) dry weight basis

Table 13. Regression Equations Illustrating the Relationship of Dry Needle Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

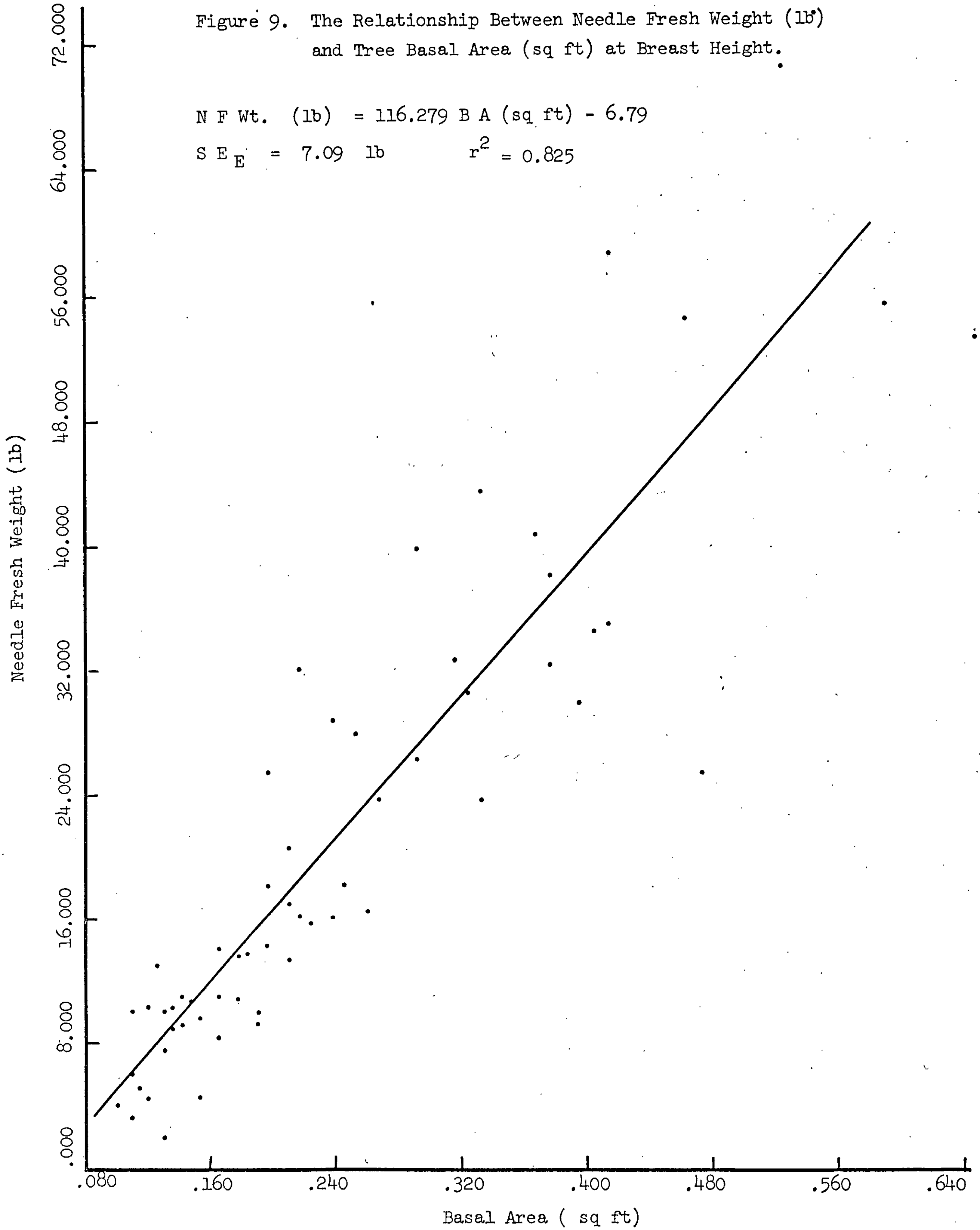
Intercept	DBH	Ht. LC	CW	Ht	BA	CL	R^2	SE_E
-10.77	4.640	-0.148	1.351*	-0.155	-5.506	0.103	0.860**	3.35
-10.77	4.640	-0.251*	1.351*	-0.052	-5.506		0.860**	3.35
- 9.79	4.179**	-0.247*	1.346*	-0.043			0.860**	3.32
-10.90	4.023**	-0.260**	1.374*				0.860**	3.29
- 9.84	4.920**	-0.267**					0.845**	3.43
-19.24	4.673						0.823**	3.65
- 3.47					59.499		0.825**	3.63

There appears to be no advantage to be gained by using a multiple regression for predicting dry needle weight. The independent variables dbh and basal area accounted for 82.3 and 82.5 per cent of the variation respectively. The standard error of estimate using dbh is 3.65 lb (33.0%), and using the independent variable basal area 3.63 lb (32.9%). By virtue of its easier estimation, dbh is preferable

Figure 9. The Relationship Between Needle Fresh Weight (lb) and Tree Basal Area (sq ft) at Breast Height.

N F Wt. (lb) = 116.279 B A (sq ft) - 6.79

$S\,E_E$ = 7.09 lb r^2 = 0.825



to basal area. The relationship between needle dry weight and tree basal area is presented in Figure 10.

f. branch weight (lb)

Tables 14 and 15 present the independent variable eliminations from the multiple regressions of fresh and dry branch weight, respectively, on several independent variables.

i) fresh weight basis

Table 14. Regression Equations Illustrating the Relationship of Fresh Branch Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

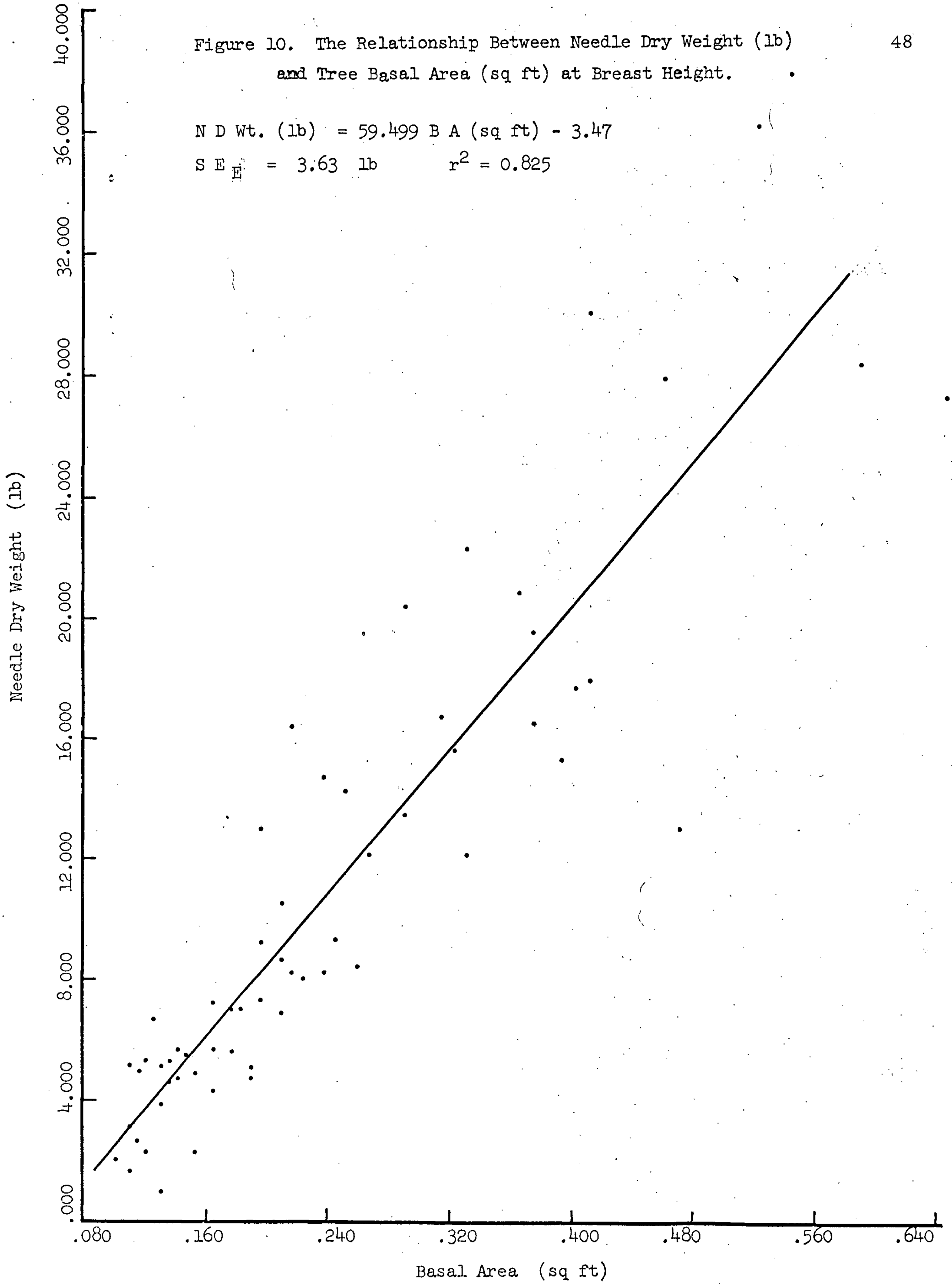
Intercept	BA	DBH	CW	Ht. LC	Ht.	CL	R^2	SE_E
71.17	504.934**	24.370**	3.238	2.148	-2.419	1.721	0.870**	10.86
71.17	504.927**	-24.369**	3.238	0.427	-0.698		0.870**	10.77
59.09	532.092**	-29.026**	3.637**	0.255			0.867**	10.79
60.20	502.005**	-26.448**	3.648*				0.866**	10.76
67.12	520.277**	-25.510**					0.856**	11.04
-19.63	198.220						0.824**	12.12
-69.09		15.094					0.773**	13.76

The best single independent variable is basal area with accounts for 82.4 per cent of the variation with a standard error of estimate of 12.12 lb (42.1%). The relationship appears to be a multiple regression of fresh branch weight on the independent variables basal area and dbh. This relationship removes 85.6 per cent of the variation and has a

Figure 10. The Relationship Between Needle Dry Weight (lb) and Tree Basal Area (sq ft) at Breast Height.

N D Wt. (lb) = 59.499 B A (sq ft) - 3.47

S E_E = 3.63 lb $r^2 = 0.825$



standard error of 11.04 lb (58.3%). The relationship between branch fresh weight and tree basal area is presented in Figure 11.

ii) dry weight basis

Table 15. Regression Equations Illustrating the Relationship of Dry Branch Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

Intercept	Independent Variables						R^2	SE_E
	BA	DBH	CW	Ht-LC	Ht.	CL		
37.88	268.767**	-12.972**	1.724	1.190	-1.334	0.962	0.870**	5.78
37.88	268.764**	-12.971**	1.724	0.227	-0.372		0.870**	5.73
31.45	283.223**	-15.450**	1.936*	0.136			0.867**	5.74
32.04	267.208**	-14.078**	1.942*				0.866**	5.73
35.73	276.934**	-13.579**					0.856**	5.87
-10.45	105.509						0.824**	6.45
-36.77		8.034					0.773**	7.33

The best independent variable for predicting dry branch weight is basal area. This variable accounted for 82.4 per cent of the variation with a standard error of estimate of 6.45 lb (42.1%). Dbh attributed 77.3 per cent of the variation with a standard error of estimate of 7.33 lb (47.9%). The best multiple regression for predicting dry branch weight used basal area and dbh, accounting for 85.6 per cent of the variation, and had a standard error of estimate of 5.87 lb (38.3%). The relationship between branch dry weight and tree basal area is presented in Figure 12.

g. crown weight (lb)

Crown weight can be defined as the weight of the branches plus

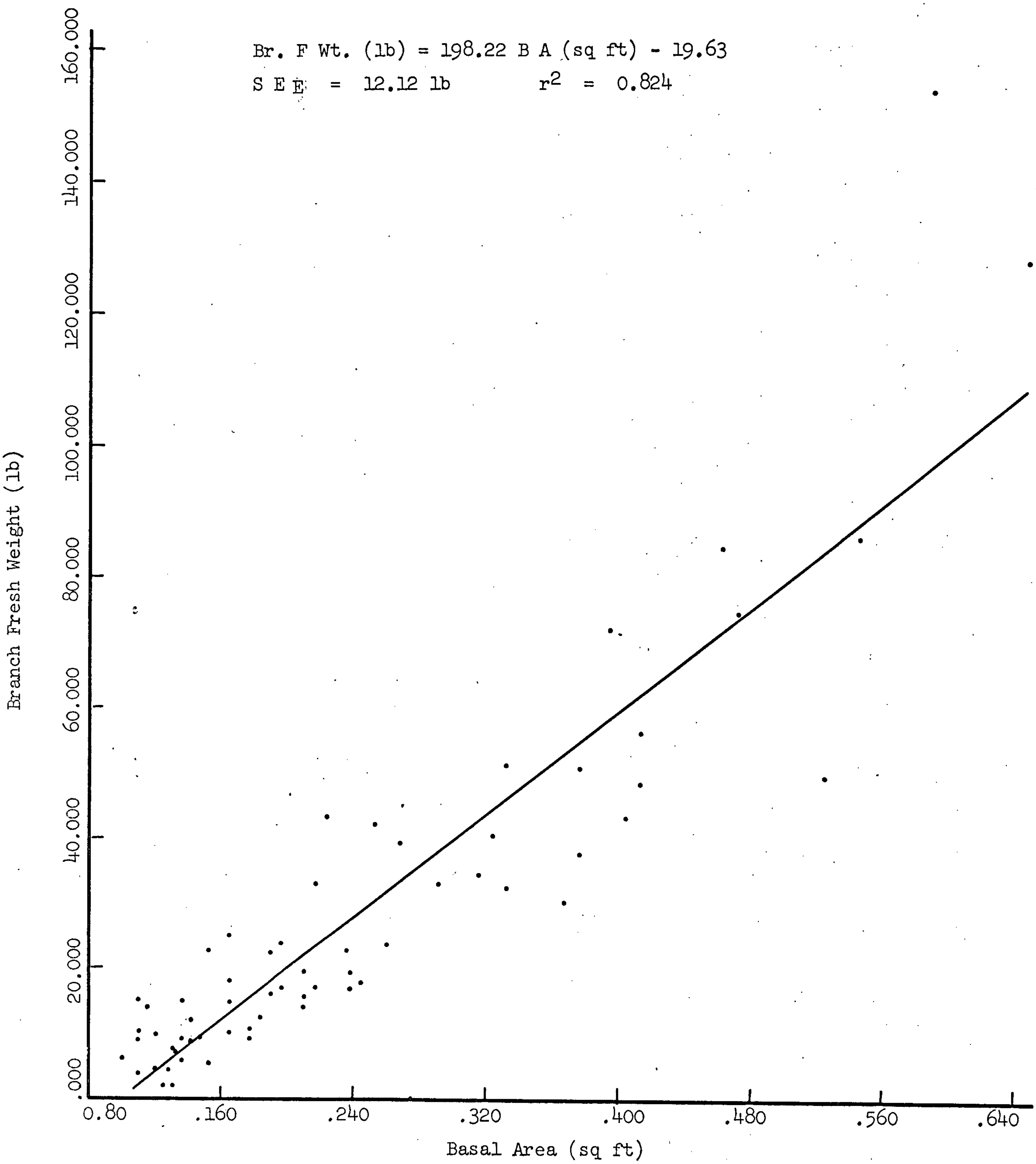


Figure 11. The Relationship Between Branch Fresh Weight (lb) and Tree Basal Area (sq ft) at Breast Height.

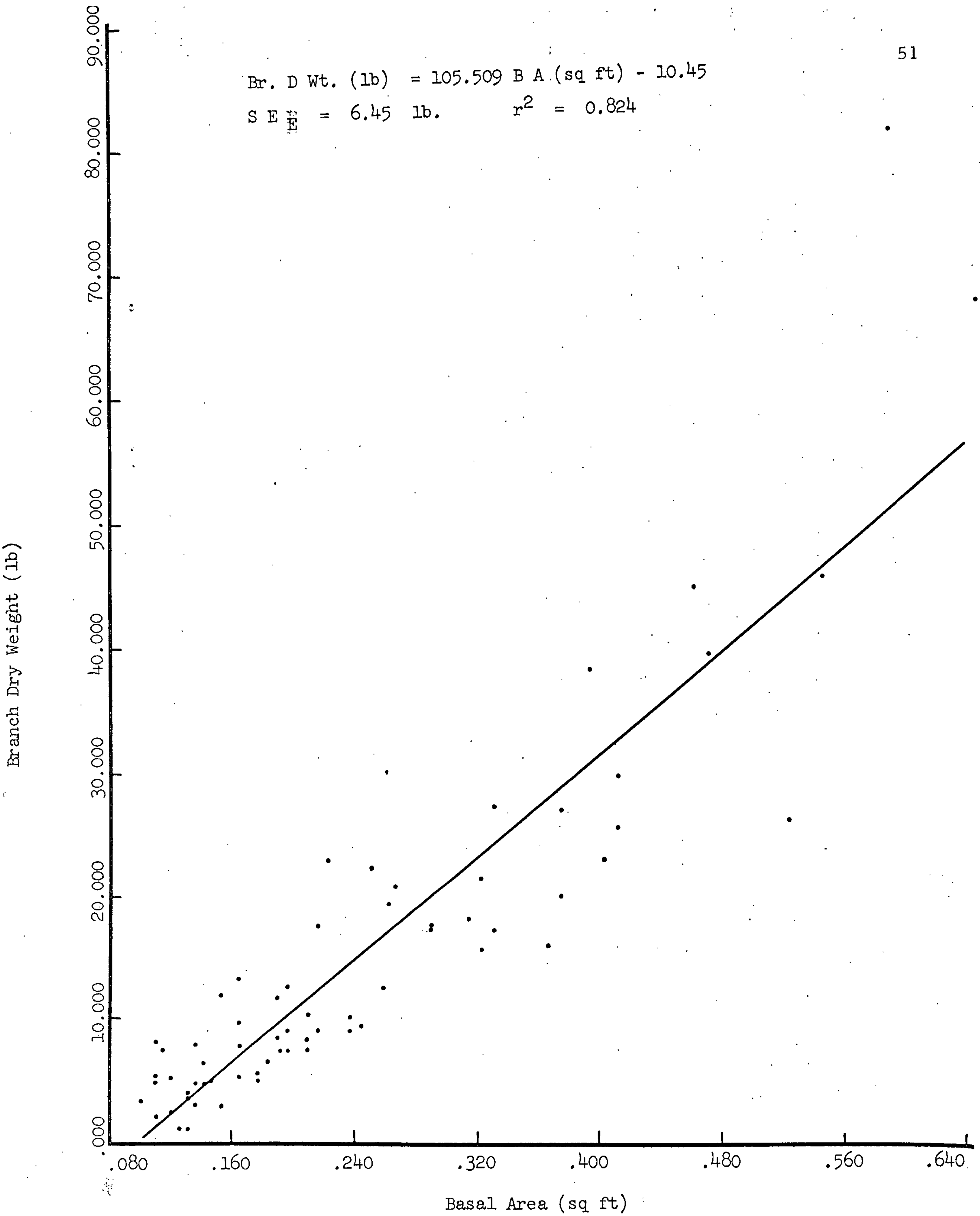


Figure 12. The Relationship Between Branch Dry Weight (lb) and Tree Basal Area (sq ft) at Breast Height.

needles. The eliminations of regression coefficients from the multiple regressions of fresh crown weight and dry crown weight on several independent variables are presented in Tables 16 and 17, respectively.

i) fresh weight basis

Table 16. Regression Equations Illustrating the Relationship of Fresh Crown Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

Intercept	Independent Variables						R^2	SE_E
	BA	CW	DBH	Ht.	CL	Ht.CL		
50.12	494.19**	5.878**	-15.303	-4.116	3.317	3.253	0.948**	10.31
50.11	494.17**	5.879**	-15.302	-0.863	0.064		0.948**	10.22
50.76	498.26**	5.848**	-15.484	-0.849			0.948**	10.14
35.17	556.02**	6.324**	-23.266**				0.945**	10.28
-42.76	265.83**	5.896**					0.933**	11.26
26.41	314.50						0.923**	12.04
-106.68			24.226				0.886**	14.64

The best independent variable is basal area which accounted for 92.3 per cent of the variation with a standard error of estimate of 12.04 lb (24.0%). A more reliable estimate can be obtained by using a multiple regression of fresh crown weight on the independent variables basal area, crown width and dbh. This relationship accounted for 94.5 per cent of the variation with a standard error of estimate of 10.28 lb (20.4%). The relationship between crown fresh weight and tree basal area is presented in Figure 13.

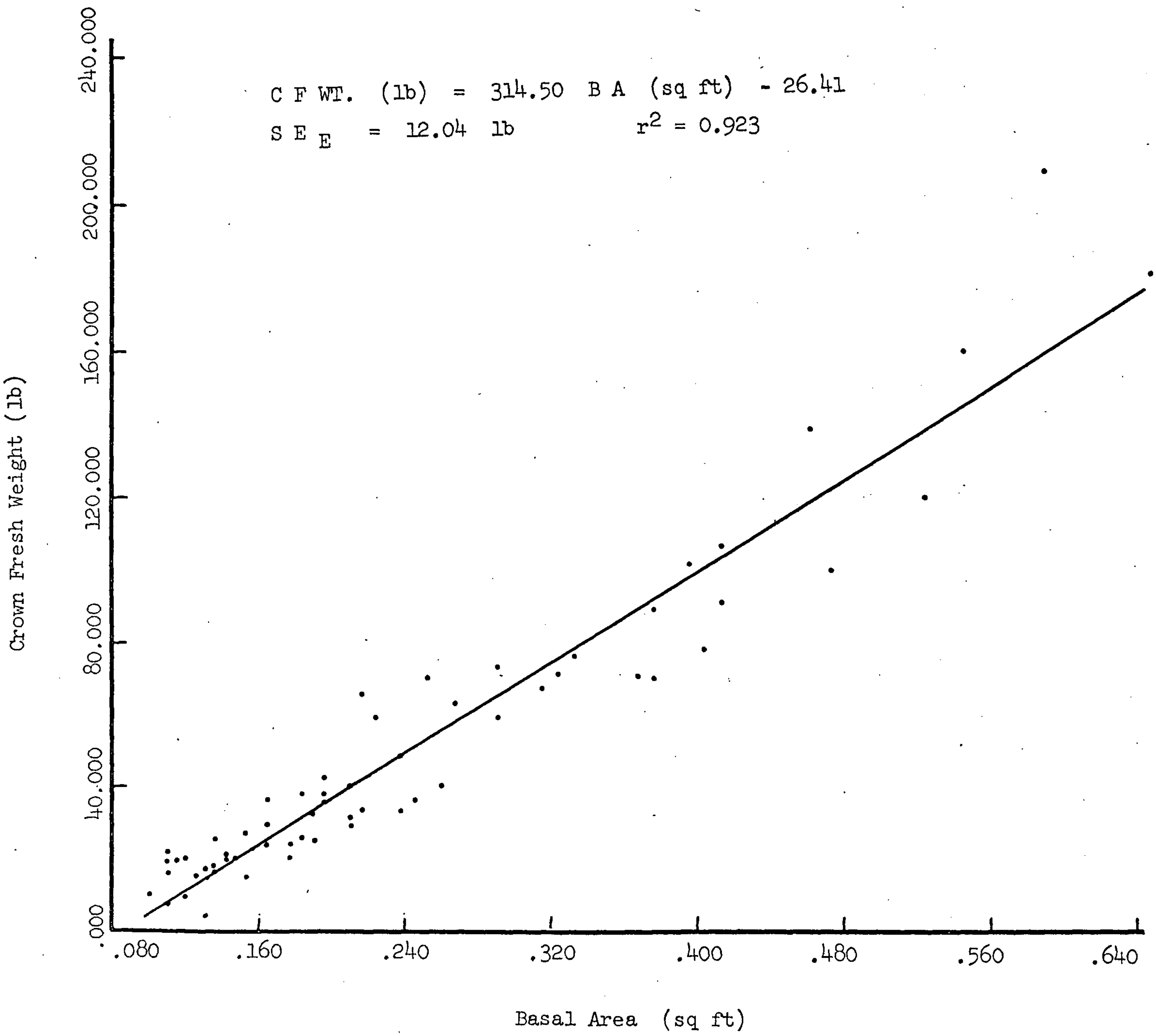


Figure 13. The Relationship Between Crown Fresh Weight (lb) and Tree Basal Area (sq ft) at Breast Height.

ii) dry weight basis

Table 17. Regression Equations Illustrating the Relationship of Dry Crown Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

Intercept	Independent Variables						R^2	SE_E
	BA	CW	DBH	Ht.	CL	Ht. LC		
27.11	263.265**	3.075**	-8.332	-1.988	1.565	1.541	0.947**	5.46
27.11	263.258**	3.075**	-8.331	-0.447	0.024		0.947**	5.41
27.35	264.785**	3.063**	-8.399	-0.442			0.947**	5.37
19.24	294.845**	3.311**	-12.449**				0.945**	5.44
-22.46	139.568**	3.082**					0.932**	5.97
-13.92	165.008						0.921**	6.37
-56.01			12.707				0.884**	7.74

The best independent variable was basal area which accounted for 92.1 per cent of total variation with a standard error of estimate of 6.37 lb (24.2%). Dbh alone accounted for 88.4 per cent of the variation with a standard error of estimate of 7.74 lb (29.4%). The variables height, crown length and height to have crown did not significantly improve the multiple linear relationship. The relationship between crown dry weight and tree basal area is presented in Figure 14.

h. slash weight (lb)

Slash weight is the weight of the needles, and branches plus the unmerchantable top (less than 4 inches dob). The results of the elimination procedure for fresh slash weight on several independent variables is presented in Table 18. Results for the elimination of independent variables from the relationship of dry slash weight on

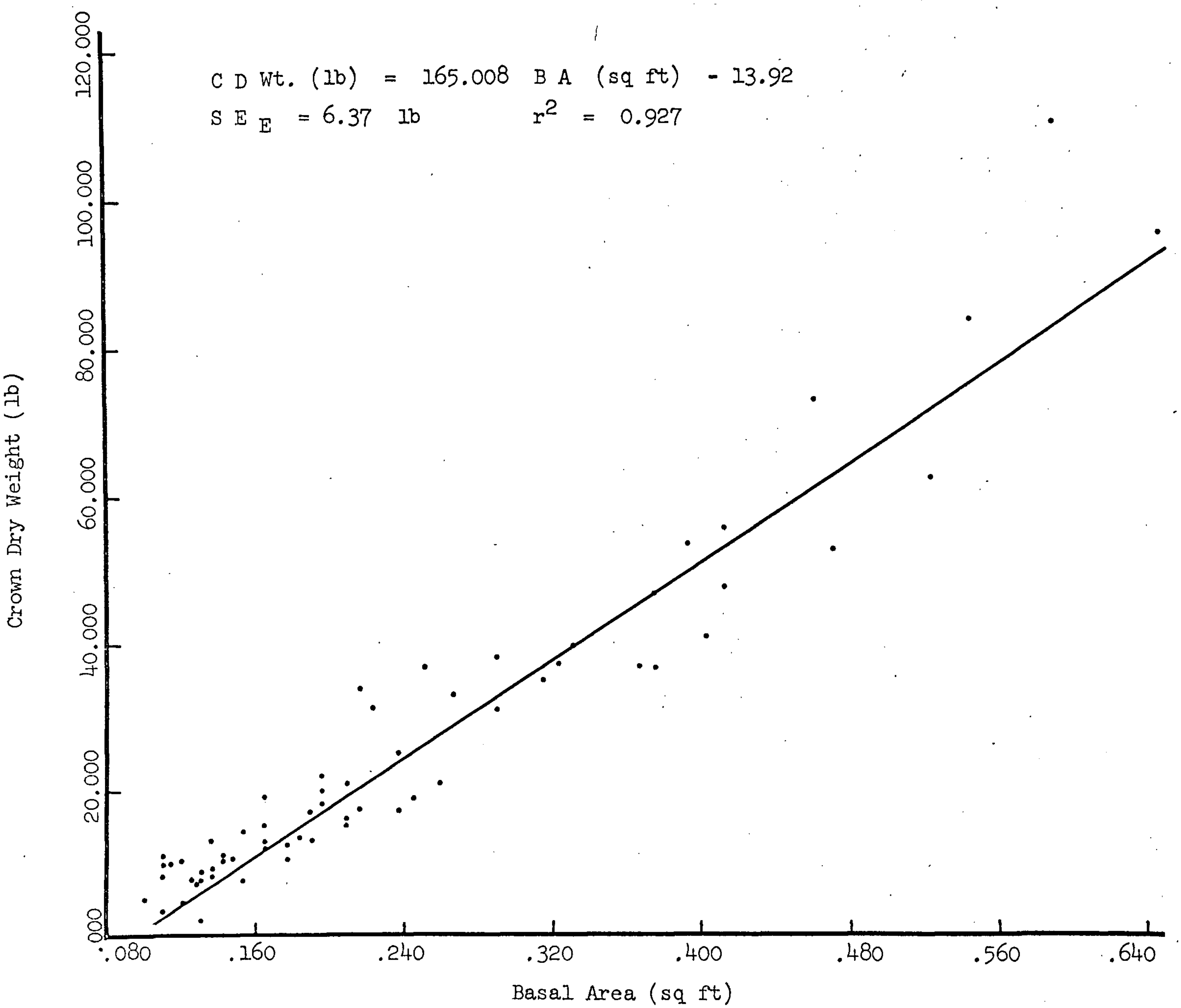


Figure 14. The Relationship Between Crown Dry Weight (lb) and Tree Basal Area (sq ft) at Breast Height.

several independent variables is presented in Table 19.

i) fresh weight basis

Table 18. Regression Equations Illustrating the Relationship of Fresh Slash Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

Intercept	Independent Variables						R^2	SE_E
	BA	DBH	Ht. LC	Ht.	CW	CL		
199.41	713.293**	-37.108*	6.490	-6.913	1.920	5.972	0.698**	21.30
199.41	713.271**	-37.106*	0.518	-0.941	1.920		0.698**	21.11
205.00	718.091**	-35.845*	0.548	-1.062			0.697**	20.98
187.79	762.528**	-42.778**	0.289				0.692**	20.95
189.07	728.554**	39.859**					0.691**	20.81
53.52	225.357						0.643**	22.19
-1.67		17.001					0.592**	23.72

As shown in Table 18, the best single independent variable is basal area, which accounts for 64.3 per cent of the variation with a standard error of 22.19 lb (20.4%). Height to live crown, height, crown width, and crown length do not improve the regression. A multiple regression combining the independent variables basal area and dbh accounted for 69.1 per cent of the total variation in fresh slash weight and had a standard error of estimate of 20.81 lb (19.2%). The relationship between slash fresh weight and tree basal area is presented in Figure 15.

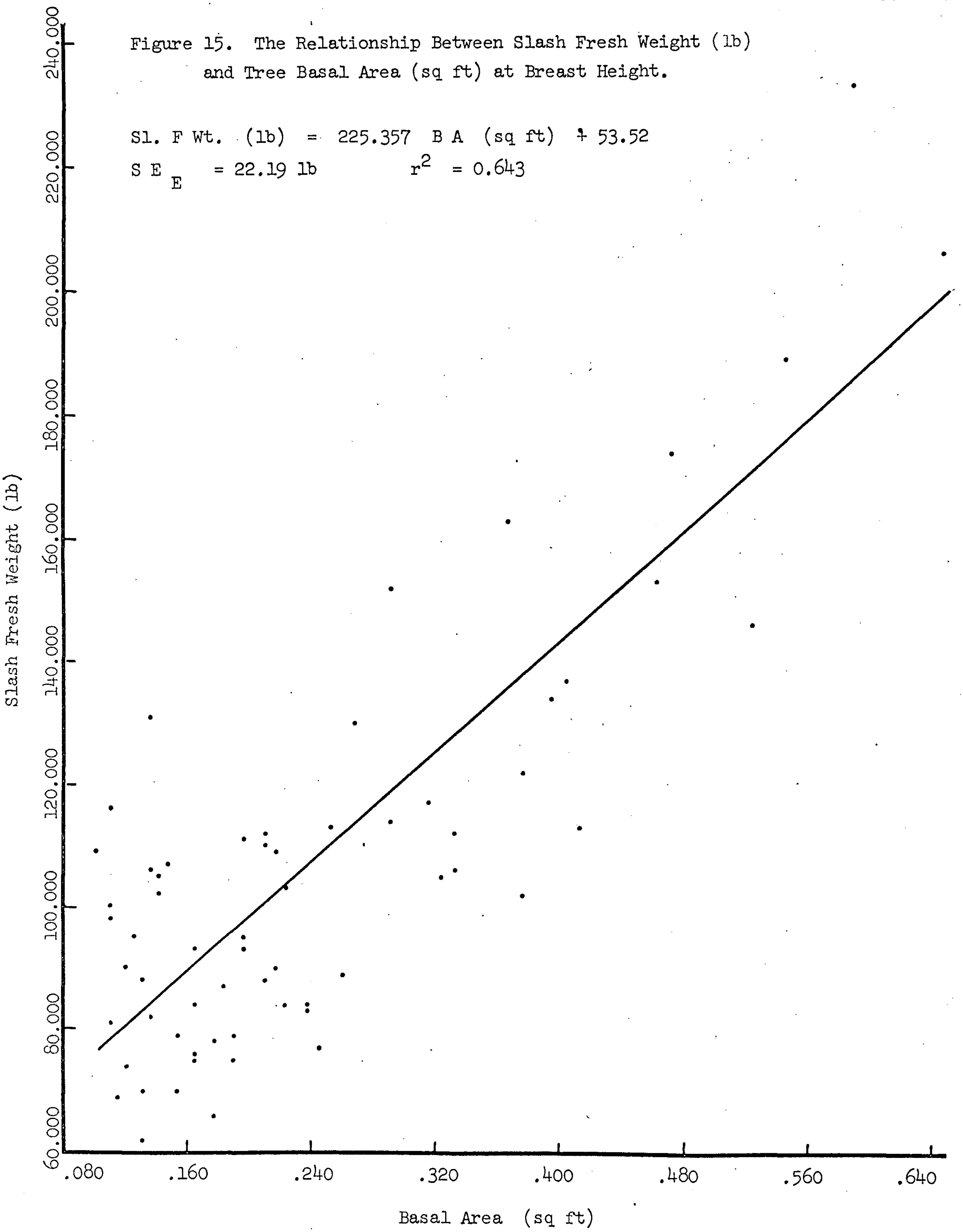


Figure 15. The Relationship Between Slash Fresh Weight (lb) and Tree Basal Area (sq ft) at Breast Height.
Sl. F Wt. (lb) = 225.357 B A (sq ft) + 53.52
S E E = 22.19 lb r2 = 0.643
Slash Fresh Weight (lb)
240.000
220.000
200.000
180.000
160.000
140.000
120.000
100.000
80.000
60.000
.080
.160
.240
.320
.400
.480
.560
.640
Basal Area (sq ft)

ii) dry weight basis

Table 19. Regression Equations Illustrating the Relationship of Dry Slash Weight (lb) with Several Independent Variables, for 63 Lodgepole Pine Trees.

Intercept	Independent Variables						R^2	SE_E
	BA	CW	DBH	Ht. LC	Ht.	CL		
86.35	331.204**	2.951	-16.726	0.606	-0.773	0.250	0.703**	11.66
86.35	331.203**	2.951	-16.726	0.356	-0.523		0.703**	11.56
77.32	351.542**	3.250	-20.212*	0.227			0.700**	11.52
78.30	324.767**	3.259	-17.918*				0.698**	11.45
18.28	101.275**	2.930					0.666**	11.95
26.40	125.457						0.654**	12.06
-4.81			9.540				0.612**	12.78

The singularly best independent variable is basal area which accounted for 65.4 per cent of the total variation in dry slash weight with a standard error of estimate of 12.06 lb (21.1%). Dbh accounted for 61.2 per cent of the variation with a standard error of 12.78 lb (22.4%). The relationshipsbetween slash dry weight and tree basal area are presented in Figure 16.

Proportion of component to total tree relationships

The means, standard deviations, minimum values and maximum values of the proportion of the tree components' weight to the total weight of the tree, expressed as percentages, are presented in Table 20.

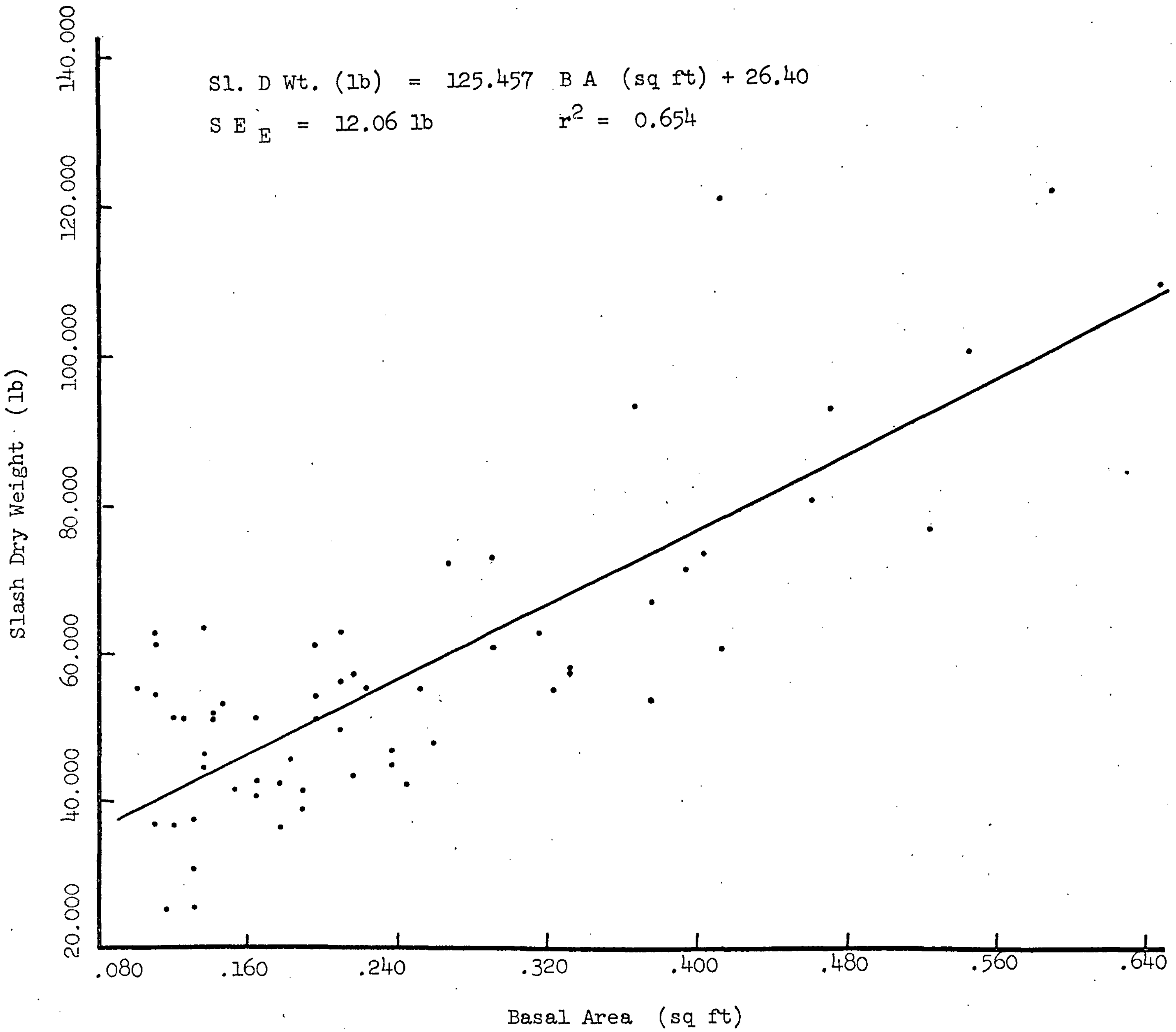


Figure 16. The Relationship Between Slash Dry Weight (lb) and Tree Basal Area (sq ft) at Breast Height.

Table 20. Mean, Standard Deviation, Minimum and Maximum Values of the Proportion (as a per cent) of the Component Weight to the Total Tree Weight, for 63 Lodgepole Pine Trees.

Component		Mean	Standard Deviation	Minimum Value	Maximum Value
Total Stem:	Fresh	89.46	3.10	81.44	97.39
	Dry	89.83	3.22	82.80	97.87
Merchantable Stem:	Fresh	68.70	14.70	28.30	87.51
	Dry	68.93	14.58	28.36	86.88
Bole wood:	Fresh	85.21	3.39	76.93	93.86
	Dry	84.48	3.74	77.33	93.85
Bark:	Fresh	4.25	1.60	0.52	9.31
	Dry	5.35	2.00	0.67	11.10
Needle:	Fresh	4.63	1.32	1.28	8.08
	Dry	4.40	1.43	1.10	8.18
Branch:	Fresh	5.91	2.67	8.88	13.64
	Dry	5.78	2.62	8.94	12.77
Crown:	Fresh	10.54	3.10	2.61	18.56
	Dry	10.17	3.22	2.13	17.20
Slash:	Fresh	31.30	14.70	12.49	71.71
	Dry	29.49	13.35	13.46	69.45

The correlations between the independent variables (dbh, height, crown length, crown width, height to live crown, and basal area), and the dependent variables (the component weight to total tree weight ratios) are presented in Table 21.

Table 21. Simple Correlation Coefficients Between the Proportion of Component Weight to Total Tree Weight and Several Tree Characteristics, for 63 Lodgepole Pine Trees.

Component		Tree Characteristics					
		DBH	Ht.	CL	CW	Ht. LC	BA
Total Stem:	Fresh	-0.531**	-0.372**	-0.414**	-0.564**	0.012ns	-0.533**
	Dry	-0.598**	-0.446**	-0.461**	-0.646**	-0.026ns	-0.599**
Merchantable stem :	Fresh	0.766**	0.806**	0.475**	0.637**	0.468**	0.702**
	Dry	0.760**	0.802**	0.469**	0.628**	0.470**	0.696**
Bole Wood:	Fresh	-0.423**	-0.334**	-0.396**	-0.462**	0.039ns	0.422**
	Dry	-0.491**	-0.430**	-0.453**	-0.551	-0.016ns	0.487**
Bole Bark:	Fresh	-0.132ns	-0.012ns	-0.037ns	-0.112ns	-0.058ns	0.137ns
	Dry	-0.044ns	-0.086ns	0.104ns	-0.010ns	-0.013ns	-0.054ns
Needle:	Fresh	0.355**	0.270*	0.456**	0.437**	-0.192ns	0.331**
	Dry	0.404**	0.323*	0.467**	0.493**	-0.137ns	0.381**
Branch:	Fresh	0.439**	0.298*	0.254*	0.437**	0.081ns	0.455**
	Dry	0.513**	0.371**	0.311*	0.523**	0.107ns	0.527**
Crown:	Fresh	0.531**	0.372**	0.414**	0.564**	-0.012ns	0.533**
	Dry	0.598**	0.446**	0.461**	0.646**	0.026ns	0.599**
Slash:	Fresh	-0.766**	-0.806**	-0.475**	-0.637**	-0.468**	-0.702**
	Dry	-0.696**	-0.718**	-0.451**	-0.500**	-0.384**	-0.638**

The results presented in Table 21 suggest that the proportions of organic matter contained in the total stem (fresh and dry), the bole wood content (fresh and dry), and the crown (fresh and dry) are most closely associated with crown width. The proportions of total tree weight contained in the merchantable bole (fresh and dry), and in the slash (fresh and dry) were most highly correlated with total tree height. Basal area was the variable most closely correlated with the proportion of the total tree weight contained in the bole bark (fresh basis), and the branches (fresh and dry). The proportions contained in the bole bark (dry basis), and in the needles (fresh and dry) were most closely associated with crown length.

The results indicate that the proportions of the total stem, bole wood, bole bark and slash materials to the total tree decrease with increasing tree size. This is indicated by the negative correlation coefficients. It is apparent that as tree size increases the proportions of the total tree contained in the merchantable stem, branches, needles, and crown also increase.

Multiple regression elimination procedures, similar to those used to establish the relationships of tree component weights on several independent variables, were used to relate the per cent of total tree weight ascribable to each component to dbh, height, crown length, crown width, height to live crown, and basal area of each tree. The results of these percentage relationships are presented in subsequent sections; however, unlike the weight relationships, only those regression equations containing significant regression coefficients are presented. In all cases, the six independent variables were tested and it can be assumed that those variables not appearing in the reported equations did not improve the relationships by removing a significant amount of the residual variation.

a. total stem per cent (%)

i) fresh weight basis

The results of the analysis indicated that a multiple regression did not improve the estimation the fresh total stem per cent (FTSP). The two best simple linear regressions are:

$$\text{FTSP (\%)} = 95.789 - 1.322\ \text{CW}$$

$$SE_E = 2.58\ \% \qquad r^2 = 0.318^{**}$$

$$\text{FTSP (\%)} = 92.535 - 1.259\ \text{BA}$$

$$SE_E = 2.64\% \quad r^2 = 0.284^{**}$$

Crown width accounted for 31.8 per cent of the variation and basal area accounted for 28.4 per cent of the variation with standard errors of estimate of 2.58% (2.9%) and 2.64% (3.0%), respectively. The relationship of FTSP on CW is presented in Appendix III-1.

ii) dry weight basis

The two best independent variables for relating the dry total stem per cent (DTSP) to tree characteristics were crown width and basal area. The simple linear regressions of dry total stem per cent on crown width and basal area are:

$$DTSP\ (\%) = 97.363 - 1.574\ CW$$

$$SE_E = 2.48\% \qquad r^2 = 0.417^{**}$$

$$DTSP\ (\%) = 93.418 - 14.707\ BA$$

$$SE_E = 2.60\% \qquad r^2 = 0.359^{**}$$

Crown width accounted for 41.7 per cent of the variation with a standard error of estimate of 2.48% (28%). The second best independent variable BA accounted for 35.9 per cent of the variation and had a standard error of estimate of 2.60% (2.9%). The relationship of DTSP in CW is presented in Appendix III-2.

b. merchantable stem per cent (%)

i) fresh weight basis

The independent variables crown width, height, crown length, and height to live crown did not account for a significant amount of the variation when combined in a multiple regression with basal area and dbh. The multiple linear regression of the fresh merchantable stem per cent (FMSP) on basal area and dbh is:

$$FMSP\ (\%) = 41.339\ DBH - 443.226\ BA - 91.084$$

$$SE_E = 6.40\% \qquad R^2 = 0.817^{**}$$

This multiple regression accounted for 81.7 per cent of the variation with a standard error of estimate of 6.40% (9.3%).

The two best independent variables for simple linear relationships are height and dbh. The simple linear regressions of fresh merchantable stem per cent on height and dbh are:

$$\text{FMSP}\ (\%) = 1.839\ \text{Ht.} - 38.802$$

$$SE_E = 8.77\% \qquad r^2 = 0.650^{**}$$

$$\text{FMSP}\ (\%) = 24.952 + 6.748\ \text{DBH}$$

$$SE_E = 9.53\% \qquad r^2 = 0.586^{**}$$

Of the total variation in fresh merchantable stem proportion, 65.0 per cent was attributable to height, which had a standard error of estimate of 8.77% (12.8%). Dbh accounted for 58.6 per cent of the variation with a standard error of estimate of 9.53% (13.9%). The relationship of DMSP on dbh is presented in Appendix III-3.

ii) dry weight basis

Of the six independent variables in the multiple regression only dbh and basal area contributed significant amounts to the variation accounted for. The multiple regression of dry merchantable stem per cent (DMSP) on dbh and basal area is:

$$\text{DMSP}\ (\%) = 41.473\ \text{DBH} - 446.259\ \text{BA} - 90.972$$

$$SE_E = 6.37\% \qquad R^2 - 0.815^{*}$$

The multiple regression combining dbh and basal area accounted for

81.5 per cent of the variation. The standard error of this multiple regression was 6.37% (9.2%).

Height was the best single independent variable accounting for 64.4 per cent of the variation with a standard error of estimate of 8.77% (12.7%). The second best independent variable, dbh accounted for 57.8 per cent of the total variation with a standard error of 9.55% (13.9%). The simple linear regressions of DMSP on height and dbh are:

$$\text{DMSP } (\%) = 1.815 \text{ Ht.} - 37.154$$

$$SE_E = 8.77\% \qquad r^2 = 0.644^{**}$$

$$\text{DMSP } (\%) = 25.857 + 6.645 \text{ DBH}$$

$$SE_E = 9.55\% \qquad r^2 = 0.578^{**}$$

The relationship of DMSP on dbh is presented in Appendix III-4.

c. bole wood per cent (%)

i) fresh weight basis

The most satisfactory independent variables for accounting for the variation associated with fresh bole wood per cent (FBWP) were crown width and dbh. The use of a multiple regression did not account for a significant amount of additional variation. The simple linear regressions of fresh bole wood per cent on crown width and dbh are:

$$\text{FBWP}\ (\%) = 90.889 - 1.186\ \text{CW}$$

$$SE_E = 3.03\% \qquad r^2 = 0.914^{**}$$

$$\text{FBWP}\ (\%) = 90.779 - 0.859\ \text{DBH}$$

$$SE_E = 3.10\% \qquad r^2 = 0.179^{**}$$

Crown width accounted for 21.4 per cent of the variation and 17.9 per cent of the variation was attributable to dbh, with standard errors of estimate of 3.03% (3.6%) and 3.10% (3.6%), respectively. The relationship of FBWP on dbh is presented in Appendix III-5.

ii) dry weight basis

Similar results to those obtained for the fresh bole wood per cent were obtained for the dry bole wood per cent (DBWP). The use of a multiple linear regression did not improve the relationship of dry bole wood per cent to tree characteristics and the best simple linear independent variables were crown width and dbh. The simple regressions of dry bole wood per cent on crown width and dbh are:

$$\text{DBWP}\ (\%) = 91.936 - 1.559\ \text{CW}$$

$$SE_E = 3.15\% \qquad r^2 = 0.303^{**}$$

$$\text{DBWP}\ (\%) = 91.614 - 1.101\ \text{DBH}$$

$$SE_E = 3.28\% \qquad r^2 = 0.241^{**}$$

Crown width accounted for 30.3 per cent of the variation with a standard error of estimate of 3.15% (3.7%). Dbh accounted for 24.1 per cent of the total variation and had a standard error of estimate of 3.28% (3.9%). The relationship of DBWP on dbh is presented in Appendix III-6.

d. bole bark per cent (%)

i) fresh weight basis

No significant regression equation could be found to relate the fresh bark weight per cent to the tree characteristics dbh, height, crown length, crown width, height to live crown, and basal area.

ii) dry weight basis

None of the independent variables tested, either individually or in combination, provide a relationship which accounted for a significant amount of the total variation of the dry bark per cent.

e. needle per cent (%)

i. fresh weight basis

The independent variables dbh, crown width, height to live crown, and basal area contributed significantly to the variation accounted for when combined in a multiple linear regression for relating the fresh needle per cent (FNP) to several tree characteristics. The multiple linear relationship of FNP on these independent variables is:

$$\text{FNP } (\%) = 2.591 \text{ DBH} + 0.487 \text{ CW} - 0.125 \text{Ht.LC} - 32.151 \text{BA} - 1.505$$

$$SE_E = 1.05\ \% \qquad R^2 = 0.411^{**}$$

The preceding multiple regression removed 41.1 per cent of the variation and had a standard error of estimate of 1.05% (22.6%).

The best simple linear regression was the fresh needle per cent on crown length.

$$FNP\ (\%) = 2.883 + 0.102\ CL$$

$$SE_E = 1.19\% \qquad r^2 = 0.208^{**}$$

This relationship accounted for 20.8 per cent of the variation and offered a standard error of estimate of 1.19% (25.7%).

Dbh alone accounted for only 12.6 per cent of the variation with a 1.25% (26.9%) standard error of estimate. The relationship of FNP on CL is presented in Appendix III=7.

ii) dry weight basis

Similar results to those obtained for the fresh needle per cent were obtained for the dry needle per cent (DNP). The multiple regression of dry needle per cent on dbh, crown width, height to live crown and basal area accounted for 41.9 per cent of the variation and had a standard error of estimate of 1.13% (23.7%). The equation of this multiple regression is:

$$DNP\ (\%) = 2.586\ DBH + 0.578\ CW - 0.119\ Ht.LC - 32.080\ BA$$

$$SE_E = 1.13\% \qquad R^2 = 0.419^{**}$$

Crown width was the best independent variable for relating dry needle per cent to a single independent variable by means of a simple linear regression. The simple linear relationship of dry needle per cent on crown length is:

$$DNP\ (\%) = 1.833 + 0.536\ CW$$

$$SE_E = 1.26\% \qquad r^2 = 0.243^{**}$$

Crown width accounted for 24.3 per cent of the variation and had a standard error of estimate of 1.26% (28.6%). The relationship of DNP on CW is presented in Appendix III-8.

f. branch per cent (%)

i) fresh weight basis

The results of the analysis indicated that the use of a multiple regression of the fresh branch per cent (FBP) on dbh, height, crown length, crown width, height to live crown did not account for significantly more variation than the simple linear regression of fresh branch per cent on basal area alone. The second best simple linear relationship was fresh branch per cent on dbh. The equations of the two simple linear regressions are:

$$FBP\ (\%) = 3.646 + 9.258\ BA$$

$$SE_E = 2.40\% \qquad r^2 = 0.207^{**}$$

$$FBP\ (\%) = 1.344 + 0.704\ DBH$$

$$SE_E = 2.42\% \qquad r^2 = 0.193^{**}$$

Basal area and dbh accounted for 20.7 and 19.3 per cent of the variation, respectively. The standard errors of estimate using basal area was 2.40% (40.6%) and using dbh was 2.42% (40.9%). The relationship of FBP on BA is presented in Appendix III-9.

ii) dry weight basis

As was the case with fresh branch per cent there is apparently no advantage to be gained by using a multiple regression to relate dry branch per cent (DBP) to tree size. The two best simple linear regressions were based on the independent variables basal area and crown width. These equations are:

$$DBP\ (\%) = 3.202 + 10.541\ BA$$

$$SE_E = 2.25\% \qquad r^2 = 0.278^{**}$$

$$DBP\ (\%) = 0.804 + 1.039\ CW$$

$$SE_E = 2.25\% \qquad r^2 = 0.274^{**}$$

The independent variable basal area accounted for 27.8 per cent of the variation and had a standard error of 2.25% (38.9%). Crown width accounted for 27.4 per cent of the variation with a standard error of 2.25% (38.9%). The relationship of DBP on CW is presented in Appendix III-10.

j. crown per cent (%)

i) fresh weight basis

There is no advantage to using a multiple linear regression relationship because the independent variables dbh, height, crown length, height to live crown, and basal area do not contribute significantly to the relationship once fresh crown per cent (FCP) has been adjusted for crown width. The basal area is the second best independent variable. The simple linear regressions of fresh crown per cent on crown width and basal area are:

$$FCP\ (\%) = 4.211 + 1.322\ CW$$

$$SE_E = 2.58\% \qquad r^2 = 0.318^{**}$$

$$FCP\ (\%) = 7.465 + 12.591\ BA$$

$$SE_E = 2.64\% \qquad r^2 = 0.284^{**}$$

The regression of fresh crown per cent on crown width accounts for 31.8 per cent of the variation and had a standard error of estimate of 2.58% (24.5%). Basal area accounted for 28.4 per cent of the variation with a standard error of estimate of 2.64% (25.0%). The relationship of FCP on CW is presented in Appendix III-11.

ii) dry weight basis

As with fresh crown weight, crown width and basal area were the two independent variables most closely associated with dry crown per cent (DCP). Nothing was gained from using a multiple regression. The regression equations of dry ratio on crown width and basal area are:

$$DCP\ (\%) = 2.637 + 1.574\ CW$$

$$SE_E = 2.48\% \qquad r^2 = 0.418^{**}$$

$$DCP\ (\%) = 6.582 + 14.708\ BA$$

$$SE_E = 2.60\% \qquad r^2 = 0.359^{**}$$

The variation accounted for by crown width amounted to 41.8 per cent of the total variation. Crown width offered a standard error of estimate of 2.48% (24.4%). Basal area accounted for 35.9 per cent of the variation with a standard error of estimate of 2.60% (25.6%). The relationship of DCP on CW is presented in Appendix III-12.

h. slash per cent (%)

i) fresh weight basis

The best relationship for describing the fresh slash per cent (FSP) was a multiple regression of fresh slash per cent on dbh and basal area. The addition of the other independent variables did not significantly improve this relationship. The multiple regression equation is:

$$FSP\ (\%) = 191.082 - 41.339\ DBH + 443.222\ BA$$

$$SE_E = 6.40\% \qquad r^2 = 0.817^{**}$$

The two variables combined accounted for 81.7 per cent of the variation with a standard error of estimate of 6.40% (20.4%).

The best simple linear relationship is:

$$FSP\ (\%) = 138.801 - 1.839\ Ht.$$

$$SE_E = 8.77\% \qquad r^2 = 0.650^{**}$$

Height alone accounted for 69.0 per cent of the total variation with a standard error of estimate of 8.77% (28.0%). The relationship of FSP on Ht. is presented in Appendix III-13.

ii) dry weight basis

The addition of the independent variables height, crown width, crown length, and height to live crown did not contribute significantly to the accounted for variation in dry slash per cent (DSP) after it has been adjusted for dbh and basal area. The multiple regression of dry slash per cent on dbh and basal area accounted for 61.2 per cent of the variation with a standard error of estimate of 7.78% (26.4%). The multiple linear regression equation is:

$$DSP\ (\%) = 160.681 - 33.913\ DBH + 363.137\ BA$$

$$SE_E = 7.78\% \qquad r^2 = 0.672^{**}$$

The best simple linear regression is that of dry slash per cent on height. The simple linear equation is:

$$DSP\ (\%) = 116.443 - 1.487\ Ht.$$

$$SE_E = 9.37\% \qquad r^2 = 0.515^{**}$$

Height accounted for 51.5 per cent of the variation and had a standard error of estimate of 9.37%. (31.8%). The relationship of DSP on Ht. is presented in Appendix III-14.

Some crown and related characteristics of lodgepole pine.

Table 22 presents the means, standard deviations, and maximum and minimum values obtained for the crown characteristics analysed.

Table 22. Mean Standard Deviation, Maximum, and Minimum Values of Several Crown Characteristics, for 63 Lodgepole Pine Trees.

Crown Characteristics	Mean	Standard Deviation	Maximum	Minimum
Dry Needle Weight (lb)	11.05	8.59	37.84	1.00
Number of Needles	245 .878	197.362	892,, 525	34, 473
Height to Live Crown(ft)	41.22	5.07	50.80	25.10
Crown length (ft)	17.24	5.94	32.00	8.00
Crown width (ft)	4.79	1.32	8.80	2.50
Crown volume (cu. ft.)	388.94	390.48	2,067.93	120.26
Crown surface area (sq. ft.)	598.68	218.40	1,255.21	256.63

The crown characteristics of lodgepole pine are highly variable in nature as pointed out by the data presented in Table 22. Height to live crown appears to be the most constant of the variables measured and the number of needles per tree exhibited the widest range (having a coefficient of variation of 80.27 per cent).

Correlation coefficients (r) between the crown characteristics and several tree characteristics are shown in Table 23.

Table 23. Simple Correlation Coefficients Between Several Tree and Crown Characteristics, for 63 Lodgepole Pine Trees.

Crown Characteristic	Tree Characteristic					
	DBH	Ht.	CL	CW	Ht. LC	BA
Dry needle weight	0.907**	0.773**	0.724**	0.815**	0.133ns	0.982**
Number of needles	0.867**	0.729**	0.680**	0.788**	0.130ns	0.908**
Height to live crown	0.305*	0.489**	-0.323*	0.231	1.000	0.691**
Crown length	0.720**	0.668**	1.000**	0.553**	-0.323*	0.730**
Crown width	0.818**	0.691**	0.553**	1.000**	0.231ns	0.820**
Crown volume	0.870**	0.728**	0.610**	0.975**	0.211ns	0.885**
Crown surface area	0.951**	0.903**	0.718**	0.804**	0.289*	0.963**

As can be seen from the correlations presented in Table 23, the crown characteristics studied were most closely associated with basal area and dbh, with the exception of crown volume which is most strongly correlated with crown width. The preceding results indicate that size of the various crown characteristicsincreases as tree size increases with the exception of crown length which decreases as the height to live crown increases. The following simple linear regression equations are the best simple linear relationships for relating crown size to tree size both statistically and practically.

a. Dry needle weight:

D. N. Wt. (lb) = 59.499 BA - 3.47

SE_E = 3.63 lb (32.9%) $r^2 = 0.825^{**}$

b. Number of needles:

NN = 102.595 DBH - 419.194

SE_E = 99.131 (41.31%) $r^2 = 0.752^{**}$

c. Height to live crown:

Ht. LC (ft) = 35.21 + 0.926 Dbh (in)

SE_E = 4.83 ft (12%) $r^2 = 0.093^{*}$

d. Crown length:

CL (ft) = 9.827 + 33.066 BA

SE_E = 4.09 (23.72%) $r^2 = 0.533^{**}$

e. Crown width:

CW (ft) = 0.587 + 0.648 DBH

SE_E = 0.765 (16.0%) $r^2 = 0.670^{**}$

f. Crown volume:

Cr. vol. (cu. ft.) = 2,635.58 BA - 54.47

SE_E = 185.15 (31.2%) $r^2 = 0.784^{**}$

g. Crown surface area:

$$CR.S.A.\ (sq.\,ft.) = 1{,}511.49\ BA + 229.68$$

$$SE_E = 92.45\ (15.4\%) \qquad r^2 = 0.824^{**}$$

Table 24 presents the simple correlation coefficients between several crown characteristics and tree volume in cubic feet (ob), and total tree weight in pounds.

Table 24. Simple Correlation Coefficients Between Tree Volume and Weight, and Crown Volume, Crown Surface Area, Dry Needle Weight, and Number of Needles, for 63 Lodgepole Pine Trees.

Crown Characteristic	Tree Volume (ob)	Total Tree Weight
Dry needle weight	0.911^{**}	0.935^{**}
Crown surface area	0.903^{**}	0.909^{**}
Number of needles	0.873^{**}	0.904^{**}
Crown volume	0.866^{**}	0.882^{**}

From the preceding correlation coefficients (Table 24) it can be concluded that there is a strong association between the size of a tree and the size of that tree's crown. Both tree volume and total tree weight are most closely correlated with dry needle weight. Simple linear regression techniques revealed that dry needle weight accounted for 83 and 87 per cent of the total variation for tree volume and total tree weight respectively.

The following simple linear regression equation was obtained for relating the number of needles supported by one cubic foot of tree volume (ob) to tree dbh.

$$NN/cu.\ ft.\ vol. = 15{,}626 + 1{,}930.8\ DBH$$

$$SE_E = 9{,}891\ needles/cu.\ ft.\ (35.1\%) \qquad r^2 = 0.098*$$

This relationship suggested that the number of needles per cubic foot volume increases as tree size increases, thus it appears that larger trees have a greater capacity for future photosynthate production than small trees. However the standard error of the relationship was very high and the regression only accounted for 9.8 per cent of the total variation.

Results of the analysis of number of needles and dry needle weight per square foot of crown surface area, and per cubic foot of crown volume indicated that these dependent variables were most closely associated with tree dbh. The relationships involving crown volume were poorly correlated with dbh and it accounted for only 9.0 per cent of the total variation in number of needles per cubic foot crown volume and 12.0 per cent of the variation in pounds per cubic foot crown volume. Dbh did, however, account for 58.9 per cent of the variation in dry needle weight per square foot crown surface area and 51.0 per cent of the variation in number of needles per square foot crown surface area. The simple linear regressions involving crown surface area are:

D. N. Wt/sq. ft. = 0.00374 dbh - 76.26

SE_E = 0.00525 (32%) $r^2 = 0.589^{**}$

NN/sq. ft. = 80.55 dbh - 151.18

SE_E = 132.85 (36%) $r^2 = 0.510^{**}$

There appears to be very little relationship between average needle length and tree size whether expressed in terms of tree height or dbh, and with crown size expressed as dry needle weight. A multiple regression of average needle length on dbh, height, and dry needle weight accounted for only 7.8 per cent of the variation. Tree height the best independent variable, accounted for 7.3 per cent for the variation. The results indicated that needle length increased with tree height.

A simple linear regression of needle length on needle width accounted for 68.3 per cent of the variation with a standard error of estimate of 14.6 mm (31%). The regression equation derived was:

Needle length (mm) = 71.87 Needle width (mm) - 37.85

SE_E = 14.57 mm (27.3%) $r^2 = 0.683^{**}$

The average needle length measured in this study was 47.2 mm (1.86 inches) and the average needle width was 1.18 mm (0.05 inches).

Table 25 presents the means, standard deviations, and minimums and maximum values obtained for average needle length (mm) and the number of needles per half gram (dry weight) of the 63 trees analyzed.

Table 25. Mean, Standard Deviation, Minimum and Maximum Values Obtained for Average Needle Length (mm) and Number of Needles per Half Gram (Dry Weight), for 63 Lodgepole Pine Trees.

Needle Characteristic	Mean	Standard Deviation	Minimum Value	Maximum Value
Average Length (mm)	53.39	5.64	39.6	66.5
Number per Half Gram	25.08	5.08	16.0	38.0

Summary

Most tree and component weights are closely associated with tree basal area and dbh. All of the weight variables analyzed increased with increasing tree size. The best simple linear relationships between tree or component weight and an independent variable are presented in Table 26.

Table 26. A Summary of the Best Simple Linear Relationships Between Tree and Component Weight (lb) and the Independent Variables Measured, for 63 Lodgepole Pine Trees.

Dependent Variable	Intercept	Regression Coefficient	Independent Variable	r^2	SE_E
TTFWt.	- 73.71	2,095.90	BA	0.976^{**}	46.52
TTDWt.	- 24.25	1,061.60	BA	0.964^{**}	27.01
TSFWt.	- 47.30	1,781.40	BA	0.961^{**}	47.76
TSDWt.	-249.04	70.59	Dbh	0.952^{**}	26.70
BWFWt.	- 46.89	1,705.70	BA	0.962^{**}	44.55
BWDWt.	-234.56	66.43	Dbh	0.951^{**}	25.23
BFWt.	- 75.33	1.598	Ht.	0.604^{**}	8.41
BDWt.	- 51.97	1.103	Ht.	0.604^{**}	5.80
NFWt.	- 6.79	116.279	BA	0.825^{**}	7.09
NDWt.	- 3.47	59.499	BA	0.825^{**}	3.63
Br. F Wt.	- 19.63	198.22	BA	0.824^{**}	12.12
Br. D. Wt.	- 10.45	105.509	BA	0.824^{**}	6.45
C F Wt.	- 26.41	314.50	BA	0.923^{**}	12.04
CD Wt.	- 13.92	165.008	BA	0.921^{**}	6.37
Sl. F. Wt.	53.52	225.357	BA	0.643^{**}	22.19
Sl. D. Wt.	26.40	125.457	BA	0.654^{**}	12.06

Although the weights of the components increase with tree size the proportion of the total tree weight which each component contributes varies with tree size. As tree size increases the proportion of the total tree consisting of the merchantable bole, needles and branches increases, and the proportion consisting of bolewood, bole bark, and slash decreases. The reason for the increasing proportions contained in the needles and branches with increasing tree size is not clear but may be explained by the fact that although crown length increases with tree size, height to live crown is relatively constant regardless of tree size. The independent variable most closely associated with each proportion varied with the component studied.

An analysis of the crown characteristics suggested that the height to live crown is relatively constant for the trees investigated. Crown size increased with increasing tree size with the exception of height to live crown. Dry needle weight is very closely associated with tree size both in terms of volume and weight. These results emphasize the close association between the growth of a tree and the capacity of the tree to produce photosynthate. An increase in the number of needles per cubic foot volume of trees with increasing tree size suggests that large trees have a greater capacity for future growth than small trees. The results also suggested that there is a closer association between crown surface area and tree size than between crown volume and tree size.

The needle characteristics of lodgepole pine are highly variable and appear to be unrelated to tree characteristics. There is not a high degree of association between needle length and width.

SAMPLING FOR BIOMASS

Introduction

Although there have been numerous studies carried out involving measurements of biomass and the weights of tree components, too little attention has been given to the suitability or reliability of the methods used or the results obtained.

It is obvious that any attempt to measure all of the trees present in an area is impractical and a formidable task. The massive nature of the trees presents technical problems in both handling and weighing the trees. Consequently, it appears that the only suitable alternative is to resort to a method of sampling to reduce the time and effort spent on data collection.

Two general methods have been used in the past to estimate the amount of organic matter. The first method involves the development of a functional relationship between the component weights and an independent variable such as dbh. Then using a stand table in conjunction with the formula the weight of the component per unit area is calculated. This method was pioneered by Kittredge (1944 and 1948), and has since been used by Cable (1958), Ovington and Madgwick (1959), Fahnestock (1960), Muraro (1966), Kiil (1966), and Satoo and Senda (1966).

The second method is based on the component weights of a tree of mean dimension. The mean tree may be established on the basis of basal area or dbh (Tadaki et al. (1961, 1962, and 1963), Attiwill (1966), and Satto and Senda (1966), or on the basis of mean tree size (Molchanov (1949), Ovington (1956, 1957 and 1962), and Ovington and Madgwick (1959)). The component weight per unit area can then be obtained by multiplying the mean tree component weight by the number of trees present per unit area.

There are errors inherent in both methods. The first method assumes that the relationship developed from trees in one stand remains constant and thus can be applied to other stands. According to Kittredge (1944) and Cable (1958) the relationship of leaf weight on dbh is applicable to different sizes, densities, crown classes, and ages up to the age of culmination of growth and beyond that age for tolerant species in all-aged stands. However, Satoo (1962) reported that the regression constants did change from stand to stand. Madgwick (1963) also suggested that the relationship between dbh and foliage weight may be affected by stand structure, season of sampling, genetic variation and possibly site quality.

Similarly, the mean tree method has been the subject of a large amount of criticism (Ovington and Madgwick (1959), Fahnestock (1960), Satoo (1962), Madgwick (1963), Baskerville (1965), Attiwill (1966), and Satoo and Senda (1966)). Ovington and Madgwick (1959) suggested that the estimation of each different component should be considered separately. Baskerville (1965) concluded that it is unlikely that a tree which is average in terms of one component will be average in terms of other components. This is, in all probability, related to the fact that the proportions of the different components to the total tree change with tree size. Another problem arises because of the difficulty of locating a tree of exactly average attributes.

Satoo and Senda (1966), after comparing the two methods, reported that estimates using the mean tree method underestimated the results obtained using the stand table-functional relationship method. Similar results were reported by Attiwill (1966). Attiwill concluded:

> "The choice of the tree of mean diameter as a sampling unit for estimating dry weight in forests, therefore has no theoretical basis; estimates so derived may be seriously in error, the magnitude of the error for a particular species depending primarily on the distribution of diameters within the stand. The tree of mean basal area is a more logical sampling unit for estimating total dry weight...."

It is generally conceded that the mean tree method is less desirable than the other method; however, the mean tree method does offer the advantages of speed and ease of application.

Rennie (1966) suggested a method for sampling biomass and pointed out that usually not less than 20 trees must be sampled for a reliable statistical correlation analysis. Rennie favored an approach of mean basal area but cautioned that it is imperative to sample enough mean trees to be within pre-set confidence limits.

Ando et al. (1959) recommended fractional sampling of several trees within a stand to obtain the weight of components. To obtain the weight of components for the stand the ratio of the stand basal area to the sum of the basal areas of the sample trees is multiplied by the sum of the weight of components of the sample trees.

Madgwick (1963) stated that the use of the average tree method gives biased results and since too many trees would be required for random sampling, a method of stratified random sampling (random sampling within size classes) offered the best compromise. A method similar to this was adopted by Weetman and Harland (1964) and by Baskerville (1965 a).

Method of Analysis

In order to determine the number of sample trees required to obtain a desired confidence interval of the mean with some specified degree of confidence, a formula reported by Freese (1962) was used. The formula used was:

$$n = \frac{t^2 \ S^2}{d^2}$$

where: n = number of sample trees required

t = tabular 't (Student's t value)

S^2 = Estimate of the population variance

d = 1/2 confidence interval desired

The numbers of sample trees necessary to have the population mean in the interval of $\pm$ 20.0 per cent of the sample mean with 95.0 per cent confidence were determined. The number of samples required for the estimation of total tree weight, total stem weight, dry needle weight, crown weight, and slash weight were calculated.

The great length of time and high cost of obtaining tree and component weights, prohibit weight measurement of all of the trees within the study area. In order to obtain a precise estimate it would be advantageous to resort to the use of double sampling (sampling with regression). A test of double sampling was carried out following the procedures outlined by Freese (1962). The test was applied for total tree fresh weight only; however, it is highly probable that similar results would be obtained for any tree components. Tree dbh was used as the supplementary variable because of its easy estimation and its high correlation with total tree weight.

Three separate intensities of double sampling were examined. Intensities of three, five and twenty tree subsamples (small samples) were tested and in all cases the large sample consisted of 63 trees. Trees for the subsample sizes of five and twenty were chosen on a random basis. The trees in the three tree subsample test were selected on a systematic basis to include the trees of having the largest, mean and smallest dbh's.

In order to compare estimates obtained by the mean tree method and the stand table-functional relationship method thirty trees were randomly selected. In the former method the sum of the total tree fresh weights were obtained by selecting the tree of mean dbh, obtaining its total tree fresh weight, and multiplying this by thirty. In the latter method the weights of the thirty trees were calculated from the simple linear equation of total tree weight on dbh, developed previously in this thesis. In addition, the actual sum of the total tree weights were calculated.

Results of Analysis

Table 27 presents the number of trees required to have the population mean in the intervals of ± 10, and 20 per cent of the sample mean with a 95 per cent confidence for the estimation of tree and component weight.

Table 27. The Number of Sample Trees Required to have the Sample Mean within Standard Errors of ± 10 and ± 20 Per Cent at the 95 per cent Confidence Level.

Estimated Variable	Number of Sample Trees Required	
	10% Standard Error	20% Standard Error
Total Tree Weight	161	41
Total Stem Weight	151	38
Needle Weight	242	60
Crown Weight	291	73
Slash Weight	46	12

The results presented in Table 27 suggest that a very large number of trees must be sampled to ensure a 10 per cent standard error of estimate nineteen times out of twenty. By accepting a lower standard error of estimate a large reduction occurred. It would appear that it is very worthwhile to accept the small increase in the standard error in order to obtain a large reduction in the number of sample trees required.

The mean total tree fresh weights and standard errors associated with these means obtained by double sampling are presented in Table 28.

Table 28. Mean and Standard Error of Mean Values Obtained Using Double Sampling for Total Tree Fresh Weight (lb).

Double Sampling Intensity	Mean	Standard Error of Mean
20 Sample Trees	442.99	34.79
5 Sample Trees	416.80	32.32
3 Sample Trees	458.45	70.86
Actual Value of 63 trees	437.95	35.11

The preceding results indicate that double sampling with subsample intensities of 20 and 5 trees resulted in lower standard errors than that of the actual population from which the subsamples were taken. This result is due solely to chance and does not invalidate the results, as one would expect that had several replications of the test been carried out this would not have occurred. The results do indicate, however, that very acceptable results can be obtained though the use of double sampling. In addition, the favorable results suggest the desirability of further study, with a large number of intensity replications, to establish the optimum number of subsamples to be taken and the reliability of the results obtained in double sampling.

The sum of total tree fresh weights (in pounds) of 30 randomly selected trees as estimated by the mean tree, and formula-stand table methods are compared in Table 29.

Table 29. A Comparison of the Sum of Total Tree Fresh Weight (lb) of 30 Randomly Selected Trees as Estimated by Two Sampling Methods

Sampling Method	Sum of Total Tree Fresh Weight (lb)
Tree of Mean Dbh	10,980
Formula and Stand Table	11,092
Actual Weights of 30 Trees	11,311

The results presented in Table 29 tend to support previous results which indicate that estimates obtained by the mean tree method are less than estimates obtained using the formula stand table method. Although the difference obtained in this thesis was small it is anticipated that had the range of tree sizes been larger the difference might also have been greater. Further study should be devoted to establishing the magnitude of these differences for the estimation of total tree and component weights.

Summary

The technical problems and costs involved in obtaining the weights of trees and components of trees make it desirable to estimate biomass on a sampling basis. Methods previously used were investigated and their relative merits were discussed. Results indicate that estimates obtained by the formula stand table method exceeded these obtained by the mean tree method.

The number of sample trees required to obtain a sample mean within a specified confidence interval (± 10% and ± 20%) of the population mean, 19 times out of 20, were determined.

The use of double sampling with regression appears to be a very promising and useful tool for estimating many aspects of biomass. Further study of double sampling should be carried out in order to explore the method fully, and to determine the number of subsamples necessary to obtain accurate estimates.

It is apparent that in any study of biomass, the researcher must carefully consider the objective of his research, in terms of the desired accuracy, and carefully balance this with the number of samples required to obtain this degree of accuracy. In many situations it probably will be desirable to accept a lower degree of accuracy in order to reduce the number of samples required per stand, in order to increase the representativeness of the study itself.

WEIGHT SCALING

Introduction

Taras (1956) reported that problems associated with volume measurement were recognized as long ago as 1765. In recent years a voluminous amount of research and literature has been devoted to the topic of weight scaling. According to Taras (1967) the first interest shown in weight scaling occurred around the late 1920's in the Southern Pine Region of the United States. One of the major reasons for the growing interest in weight scaling is the apparent variation in the solid wood content of the cord.

Weight scaling is being used in management planning by some large American forest product companies according to Curtis (1965). He reported that the Buckeye Cellulose Corporation of Florida used weight equations in conjunction with growth prediction methods to optimize and determine their cutting schedules. Curtis reported that more consistant measurements of values, costs and quality can be obtained using a weight as opposed to a volume basis. Eggen (1967) reported that the Kimberly-Clark Corporation now employs weight scaling in their operations in the Northeastern United States.

Weight scaling is employed in Canada as well. Weight scaling was investigated as early as 1928 by the Wood Measurement Committee of the Canadian Pulp and Paper Institute according to Martin and Simard (1959). In British Columbia the use of weight scaling was approved by the Chief Forester of the B. C. Forest Service in 1963. The method and requirements for setting up the scaling facilities to comply with government regulation in British Columbia were prepared by Fraser (1964). There are presently 25 weight scaling operations in British Columbia and this number will likely increase due to the provincial government's close utilization policy.

European experience with weight measurement to facilitate scaling has not been generally as favorable as on this continent. Considerable study of weight scaling has been done in Scandinavian countries (Nylinder, 1967). Steinlin and Dietz (1962) stated that because of the comparatively small amount of wood dealt with and the lack of species homogeneity in German forests it would not be practical to employ weight scaling in Germany. Johansson (1962), and Stemsrud and Gudim (1962) advocated refinements to adjust for variations in moisture content and wood density.

Lange (1962) concluded from his investigations in southern United States that scaling by weight afforded better accounting practices, eliminated conventional cord scaling biases, allowed a greater number of loads to be measured per day, found that stumpage prices were not adversely affected, disposal costs were less, better accuracy was obtained, and quicker, smoother operation could be achieved. Similar advantages were cited by Taras (1956 and 1967), Martin and Simard (1959), Page (1961), Page and Bois (1961), Romancier (1961), Freeman (1962), Lange (1962), Hardy and Weiland (1964), Blair (1965), Curtis (1965), Dobie (1965), Forbes (1966), Row and Guttenburg (1966), and Eggen (1967). Other advantages noted by some of the above authors included safer working conditions, and easier scaler training.

There are however, disadvantages associated with weight scaling. The most prohibitive feature of weight scaling is the initial cost encountered in setting up the weighing facilities. Because of increased moisture loss with time following felling any producer who is unable to dispose of his logs shortly after felling will be penalized by increased volume per unit of weight as his logs dry (Eggen, 1967). Problems also arise because defective and crooked logs may weight as much as sound high quality logs. Page and Bois (1961) pointed out the need to adjust for size and quality in weight scaling of sawlogs. Guttenberg et al. (1960), nevertheless, reported favorable results and stated:

> "Scaling by weight promises equal accuracy and greater day-to-day consistency in predicting lumber yields from Southern pine sawlogs than scaling by traditional log rule methods."

One of the major problems and limitations associated with weight scaling result from the within- , and between-tree variations in specific gravity and moisture content. Hopefully, however, seasonal variations in these factors will balance out over a long period of time thus allowing the use of average values and making it unnecessary to measure these variables for every load. This is the contention of Besley (1967). Some authors (Haygreen (1959), Steinlin and Dietz (1962), and Young and Chase (1965)) have expressed a belief that the use of a dry-weight basis is better.

It should be recognized that this method of scaling is not a panacea for all scaling problems and is best applied only under certain conditions. Favorable conditions include a uniform distribution and limited number of species. Weight scaling would also be more accurate where the ranges in age and size are small and where the logs are free from decay. Factors affecting variations in specific gravity and moisture content were discussed by Besley (1967), Nylinder (1967), and Johnstone (1967 b), and anything which might be done to minimize the variation in these variables would also minimize variations in volume/ weight ratios.

In addition to the actual practice of scaling, weight measurements has several other possible industrial applications. Keen (1963) has carried out a comprehensive study of weights and centres of gravity of several Eastern Canadian tree species. Keen's concern is in the handling of pulpwood and he suggested that such data can be meaningfully employed in equipment design and skidding studies since most equipment is rated in terms of weight. Young and Chase (1965) also noted the possible application of tree weight data to equipment design.

Samset (1962) suggested that tree weight data could be used to determine the power requirements of overhead winches or lines necessary to convey logs. Turnbull et al. (1965), also, noted the utility of weight data in studies of skidding and hauling.

Dobie (1965) stated that the advent of balloon and helicopter logging, and the increased use of public transportation systems by logging concerns, will necessitate an increase in the knowledge of tree weight factors. The assessment of freight charges on a weight basis by rail companies transporting pulp chips has created a need for increased knowledge of the compactibility and density of wood chips (Shultz, 1964). Finally, if Young's (1964) assertions that in the future greater utilization of logging residues such as roots, stumps, and branches which are currently considered unmerchantable will occur, are true, then the only practicable method of measuring these odd-shaped masses is on the basis of weight.

Method of Analysis

The data gathered for this thesis offer little opportunity to study weight scaling per se. However, it is possible to analyse some of the assumptions basic to the theory of scaling by weight, namely the relationship between tree weight and tree volume.

In order to analyze the relationship between tree volume and tree weight a series of simple linear equations were developed. Regression equations of total tree volume (ob) in cubic feet on total stem weight, adjusted for moisture content, in pounds, and on the product of total stem weight times the mean volume/weight ratio of the 63 trees were examined. In addition, the simple linear relationships between the dependent variables, fresh and dry, merchantable and total stem weights (in pounds) and the independent variables total stem volume (ob) in cubic feet, adjusted by the average wood density of the 63 trees, and the combined variable D^2 H (dbh squared times tree height) were analyzed.

Results of Analysis

The mutual relationships between volume (ob) in cubic feet and total stem weight (in pounds) were studied. After adjustment for moisture content, dry total stem weight accounts for 95.8 per cent of the variation in tree volume. The regression equation is:

$$\text{Vob (cu. ft.)} = 0.04043 \text{ DSWt (lb)} - 0.207$$

$$SE_E = 1.029 \text{ cu. ft. } (12.4\%) \quad r^2 = 0.958^{**}$$

The simple linear regression equation of volume (ob) in cubic feet on the product of total stem weight (lb) times the mean volume/weight ratio, was:

$$\text{Vob (cu. ft.)} = 0.223 + 0.9585 \text{ (TSWt x 0.02154)}$$

$$SE_E = 0.789 \text{ cu. ft. } (9.6\%) \quad r^2 = 0.975^{**}$$

These results indicate that 97.5 per cent of the total variation in cubic feet volume can be attributed to the product of total fresh stem weight times the mean volume to weight ratio.

The results indicated that tree volume (ob) in cubic feet adjustment for wood density accounts for 95.7 per cent of the variation in dry total stem weight (DTSWt.) in pounds, and 97.4 per cent of the variation in fresh total stem weight (FTSWt.) in pounds using the equations:

$$\text{DTSWt. (lb)} = 13.813 + 0.897\ (\text{Vob (cu. ft.) x density})$$

$$SE_E = 25.14 \text{ lb. } (12.1\%) \quad r^2 = 0.957^{**}$$

$$\text{FTSWt. (lb)} = 1.788\ (\text{Vob (cu. ft.) x density}) - 0.588$$

$$SE_E = 38.4 \text{ lb. } (9.9\%) \quad r^2 = 0.974^{**}$$

Tree volume (ob) in cubic feet adjusted for wood density was also used in simple linear relationships with fresh and dry merchantable stem weight (in pounds). The regression equations developed are:

$$\text{FMSWt. (lb)} = 1.877\ (\text{Vob (cu. ft.) x density}) - 78.08$$

$$SE_E = 38.15 \text{ lb } (11.58\%) \quad r^2 = 0.977^{**}$$

$$\text{DMSWt. (lb)} = 1.737\ (\text{Vob (cu. ft.) x density}) - 53.03$$

$$SE_E = 18.28 \text{ lb } (10.4\%) \quad r^2 = 0.980^{**}$$

Volume adjusted by density accounted for 98.0 per cent of the variation in dry merchantable stem weight and 97.7 per cent of the variation in fresh merchantable stem weight.

The combined variable D^2H adjusted by wood density accounted for 94.9 per cent of the variation in dry total stem weight (DTSWt.) in pounds and 96.0 per cent of the variation of fresh total stem weight (FTSWt.) in pounds. The regression equations are:

$$\text{FTSWt. (lb)} = 26.46 + 0.0050\ (D^2H \times \text{density})$$

$$SE_E = 47.90 \text{ lb } (12.4\%) \quad r^2 = 0.960^{**}$$

$$\text{DTSWt. (lb)} = 26.84 + 0.0025\ (D^2H \times \text{density})$$

$$SE_E = 27.59 \text{ lb } (13.2\%) \quad r^2 = 0.949^{**}$$

Simple linear regression relationships were developed using fresh and dry merchantable stem weights on D^2H adjusted by wood density. The regression equations are:

$$\text{FMSWt. (lb)} = 0.0052\ (D^2H \times \text{density}) - 49.66$$

$$SE_E = 48.57 \text{ lb } (14.7\%) \quad r^2 = 0.963^{**}$$

$$\text{DMSWt. (lb)} = 0.0027\ (D^2H \times \text{density}) = 16.55$$

$$SE_E = 26.48 \text{ lb } (15.0\%) \quad r^2 = 0.958^{**}$$

Discussions of Some Internal Factors Which Affect Tree Weight

The two most important factors affecting tree weight are specific gravity, and moisture content. The purpose of this chapter is to examine the within, and between tree variations of these factors in lodgepole pine.

Moisture content

In excess of 50 per cent of the total fresh weight of a tree consists of water. The amount present varies not only within the tree but also with species, age, site, season, and time of day (Kramer and Kozlowski, 1960). After a thorough investigation of bark moisture content, Srivastava (1964) concluded that variations may also be related to exposure, temperature, atmospheric relative humidity, and to the growth conditions of the plant. It appears, therefore, that differences both within and between species are caused by a large number of internal and external factors.

Perhaps the most striking variation in moisture content within a tree is the variation between the heartwood and the sapwood. Besley (1967) reported that for some species the moisture content of sapwood may be three times as great as the moisture content of the heartwood, while in other species, notably Eastern hemlock (*Tsuga canadensis* (L.) Carr.), and balsam fir (*Abies balsamea* (L.) Mill.) the moisture contents of the two types of wood may be equal.

Moisture content is generally regarded to increase with increasing height within the tree (Raber (1937), Ovington (1956), Gibbs (1958) Etheridge (1958), Kramer and Kozlowski (1960), and Coutts (1965)). The combined effect of the type of wood (sapwood or heartwood) and its position within the tree was investigated by Nylinder (1967). Nylinder's results indicated that the heartwood varies very little regardless of position in the stem but the moisture content of sapwood varies greatly depending on position within the tree.

Etheridge (1958) reported that tree moisture content increased with tree vigor. This was substantiated by Coutts (1965) who reported that dominant trees have a higher moisture content than suppressed trees. Gibb's (1958) work indicated that tree moisture content reaches a maximum shortly before the resumption of active growth, and that the amount of moisture diminishes through the summer and early fall. Summer and winter differences are consistent and considerable (Raber (1937), Jensen and Davis (1953), Kramer and Kozlowski (1960), Besley (1967) and Nylinder (1967).

Variations in forest tree moisture content may also occur diurnally (Raber (1937), Kramer and Kozlowski (1960), and Jameson (1966)). This situation occurs when transpiration during the day exceeds the uptake of water by the roots. The deficit, so created, is replenished at night when transpiration is minimal. Jameson (1966) suggested that diurnal variations follow meteorological conditions.

Specific gravity

Wahlgren _et al_. (1966) stated that specific gravity is the simplest and most useful index to the suitability of wood for many important uses. Because of the strong relationship between specific gravity and the strength properties of wood (USDA, 1965 a) specific gravity affects structural lumber, plywood, laminated arches and beams, and high-quality transmission poles and piling. Specific gravity is a determinant of the shrinkage, elasticity, hardness (resistance to wear and marring), workability, and paintability of wood. Specific gravity or wood density is of interest to the pulp and paper industry because it gives an indication of fibre content of a piece of wood, and thereby an indication of the possible pulp yield. In weight scaling specific gravity is of prime importance because it is an index of the weight per unit volume of wood, and thus is related to volume per unit weight.

Many factors, including the amount of summerwood produced, growth rate, stem and crown characteristics, position within the tree, site and geographic location, inheritance, species, tree age at the time of wood formation, and the health and vigor of the tree influence specific gravity. Differences in specific gravity result from differences in cell thickness, cell density, cell length, the amount of extractives, and the volume of mechanical tissue (Spurr and Hsuing (1954), McKimmy (1959), and USDA (1965 b)).

Summerwood, often called latewood, is that portion of the annual growth ring formed in the latter part of the growing season, and has thicker cell walls and smaller lumens than the earlier formed springwood. Because of these anatomical differences summerwood is denser than springwood and consequently, as the proportion of the annual growth ring composed of summerwood increases the specific gravity of the wood laid down during the growing season increases. This was demonstrated by the research of Alexander (1935), Larson (1957), Wakefield (1957), McKimmy (1959), Risi and Zeller (1960), Keith (1961), Littleford (1961), Wellwood and Wilson (1965), Wilfong (1966), and Nylinder (1967). Larson (1957) reported that the amount of summerwood formed is affected by tree age at the time of wood formation, position within the tree, stand density, and possibly the quality of the site on which the tree is growing.

Generally, there is an inverse relationship between specific gravity and growth rate. Larson (1957) and McKimmy (1959) reported that such factors as site, stem class, tree age, position within the tree, and ring age from pith confound this relationship. Maximum specific gravity is reported to be coincident with moderate growth rates (Alexander (1935), Wakefield (1957), and Keith (1961). Wellwood and Smith (1962), and Fielding and Brown (1960) also found significant relationships between specific gravity and rate of growth.

The majority of investigations have shown that specific gravity increases with increasing age (number of rings from pith) in species having a distinct transition between earlywood and latewood (Risi and Zeller (1960), Littleford (1961), Wellwood and Smith (1962), Knigge (1963), and USDA (1965 b)).

Because specific gravity is related to growth rate it would seem logical that, in even-aged stands, trees of a smaller size would have higher specific gravity. This hypothesis is not conclusively supported by research reported in the past. Risi and Zeller (1960), Wheeler and

Mitchell (1962), and Gilmore (1963) have reported that dbh is not significantly related to tree specific gravity. In opposition to these results, Stage (1963), Christopher and Wahlgren (1964), Baskerville (1965 b) and the Forest Service (USDA 1965 b) have reported significant relationships of tree specific gravity on dbh. Due to the method of sampling used in the last reference cited (USDA (1965 b)) the result may be largely an age effect.

The influence of crown characteristics on tree specific gravity is not clear. Spurr and Hsuing (1954) reported that no relationship exists between density and crown length. Stage's (1963) results indicated that the ratio of crown length to tree height was significantly related to specific gravity thus refuting Larson's (1957) data. Knigge (1963) suggested that wood density increased with increasing crown size and growing space.

Wellwood and Smith (1962) reported that rapidly grown crown-formed wood has a lower density than bole-formed wood. Other researchers including: Larson (1957) Wahlgren and Fassnacht (1959), Risi and Zeller (1960), Littleford (1961) Conway and Minor (1961), Tackle (1962), Stage (1963) Knigge (1963), Wahlgren et al. (1966), Besley (1967), and Nylinder (1967), have reported the importance of the influence of height within the tree on specific gravity. The work of these authors indicates, however, that this influence may result in within, as well as, between species differences.

Factors such as site condition, environment, and geographic location greatly influence growth rate, summerwood formation, stem and crown characteristics, and tree vigor and consequently influence wood density. Larson (1957), and Wilde and Paul (1959) discussed some relationships between specific gravity and soil properties. Physiographic and climatic factors were shown to influence specific gravity by Wheeler and Mitchell (1962), Gilmore (1963), Knigge (1963), and the U.S. Forest Service (USDA, 1965 b). Larson (1957), McKimmy (1959), Fielding and Brown (1960), Wheeler and Mitchell (1962), Gilmore (1963) Knigge (1963), and the U.S. Forest Service (USDA, 1965 a and b) observed changes in specific gravity with changes in latitude and longitude.

One of the major sources of variation in specific gravity between trees is attributable to inheritance (Larson (1957), McKimmy (1959) Keith (1961), and Wellwood and Smith (1962)). This affords an opportunity to the forester to develop genetically superior trees through selective breeding as pointed out by Stonecypher _et al_. (1964).

The following values for the specific gravity and density of lodgepole pine were published by the Canadian Government (Can. Dept. N.A. and N.R., 1956):

a. Specific Gravity:

basic (gr. vol. and o.d. wt.)	= 0.40
oven-dry (o.d. vol. and o.d. wt.)	= 0.46
nominal (a.d. vol. and o.d. wt.)	= 0.41

b. Density (lb/cu. ft.):

green	= 40
air-dry	= 29

Frood (1963) reported an average specific gravity of 0.402 for extractive-free lodgepole pine samples gathered in central Alberta. Tackle (1962) obtained values of 0.392 and 0.396 for average tree and breast height specific gravities, respectively, for lodgepole pine. The Wood Handbook (USDA, 1955) reported the green volume specific gravity of lodgepole pine (as determined from increment cores taken at breast height) to be 0.38.

Method of Analysis

The main purpose of the analysis was to study the within and between tree variations in the specific gravity and moisture content of the lodgepole pine trees. The data used to analyse these variables were based on measurements made from the discs, collected as described previously in this thesis (see Data Collection). The analysis was carried out using the same regression elimination procedure described previously, and was divided into two distinct parts. The first part of the analysis studied the within tree variations in specific gravity and moisture content, and the second part analyzed the between tree variations in these two variables.

To analyze the within tree variations, specific gravity (oven-dry volume basis) and moisture content (expressed as a per cent of the fresh weight), determined at various heights in the tree were used as dependent variables on the independent variables: height above ground, dob, dib, age, (rings from pith) and mean radial growth rate (dib / (2 x age)) at the point in the tree where the dependent variables were measured. A total of 545 specific gravity and moisture content measurements from 63 trees were involved.

Average tree values for moisture content and specific gravity (converted to a green volume basis) were calculated and used as the dependent variables in the analysis of between tree variations. These dependent variables were used in a multiple regression analysis on the independent variables dbh, height, crown length, crown width, age, total tree weight, dry needle weight, volume (ob), height to live crown, basal area, crown volume, crown surface area, number of needles, mean radial growth rate (bh) and bark per cent.

Results of Analysis

Within tree variation in specific gravity and moisture content.

The means, standard deviations, and maximum and minimum values obtained for sections taken at various height intervals in the tree are presented in Table 30.

Table 30. Mean, Standard Deviation, Maximum and Mimimum Values of Specific Gravity and Moisture Content for 545 Discs of Lodgepole Pine.

Characteristic	Mean	Standard Deviation	Maximum Value	Minimum Value
Specific Gravity*	0.4805	0.0426	0.6367	0.3450
Moisture Content (%)	44.97	7.35	66.67	24.46

*Note: specific gravity is based on oven-dry volume.

The specific gravity values presented in Table 30 are based on oven-dry volume. The values are higher than the 0.46 shown on page 107 The standard deviation indicates that the variation in specific gravity is small. Moisture content is more variable than specific gravity, as indicated by the larger range in the data and larger standard deviation for moisture content.

Table 31 presents the simple correlation coefficients for moisture content and specific gravity, and several tree section variables.

Table 31. The Correlation of Moisture Content and Specific Gravity to the Height, dob, Dib, Age and Mean Radial Growth Rate of Section Measurements of 63 Lodgepole Pine Trees .

Section Measurement	Correlation Coefficients (r)	
	Moisture Content	Specific Gravity
Height above ground (ft)	0.6315**	-0.3875**
Dob (In)	-0.3601**	0.1274**
Dib (in)	-0.3689**	0.1325**
Section age (yr)	-0.6090**	0.3645**
Section specific gravity	-0.3534**	1,0000**
Mean radial growth rate (mean ring width)	0.4665**	-0.3654**

The results in Table 31 suggest that both moisture content and specific gravity are most strongly correlated with height above ground. The results indicated that specific gravity decreases and moisture content increases with increasing sampling height in the tree. Moisture content increased and specific gravity decreased with decreasing section age. The effect of section age is undoubtedly related to the fact that section age decreased as the sampling height increased.

Mean radial growth rate was positively correlated with moisture content and negatively correlated with specific gravity suggesting that fast growing trees probably have lower specific gravity and higher moisture contents than slowly growing trees. As was expected moisture content and specific gravity were negatively correlated indicating that as the wood content per unit volume increases the water content decreases.

A multiple regression equation of specific gravity on the section variables, height, dob, dib, age, and mean radial growth rate accounted for 20.0 per cent of the variation. Section height, the best independent variable, accounted for 15.0 per cent of the variation with a standard error of estimate of 0.039 (8%) in the relationship:

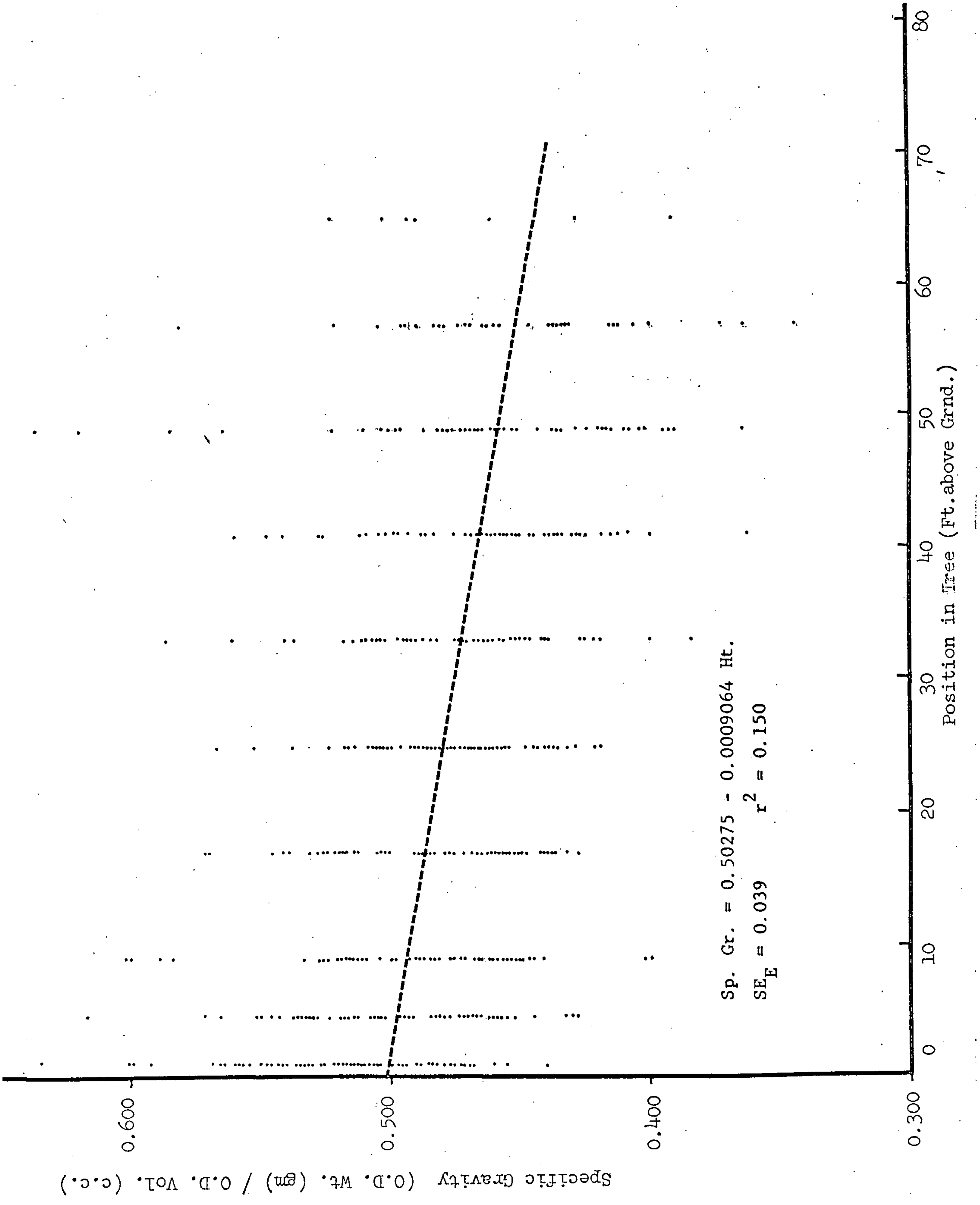
$$\text{Sp. Gr.} = 0.503 - 0.000906 \text{ Ht.}$$

$$SE_E = 0.039 \qquad r^2 = 0.150^{**}$$

This simple linear relationship is shown in Figure 17.

A multiple regression analysis of moisture content on section height, dob, dib, age, and mean radial growth rate accounted for 43.9 per cent of the variation, and the combination of the independent

Figure 17. The Relationship between Specific Gravity and Position in the Tree.



variables height above ground, section age, and mean radial growth rate accounted for 43.3 per cent of the variation. The best simple linear regression was:

$$\text{M. C. } (\%) = 38.72 + 0.2545 \text{ Ht.}$$

$$SE_E = 5.70\% \qquad r^2 = 0.399^{**}$$

This simple linear relationship accounted for 39.9 per cent of the variation with a standard error of 5.70% (12.7%), and is presented in graphical form in Figure 18.

Between tree variation in specific gravity and moisture content

Average tree values for specific gravity (converted to a green volume basis), and moisture content were used to analyse between tree variation in moisture content and specific gravity. Average tree specific gravity had a mean of 0.423 and a range from 0.315 to 0.540 Average tree moisture contents ranged from 24.46 per cent to 66.67 per cent, with a mean of 44.96 per cent. Table 27 presents the simple correlations between average tree specific gravity, and moisture content, and several tree variables.

Figure 18. The Relationship between Moisture Content and Position in the Tree.

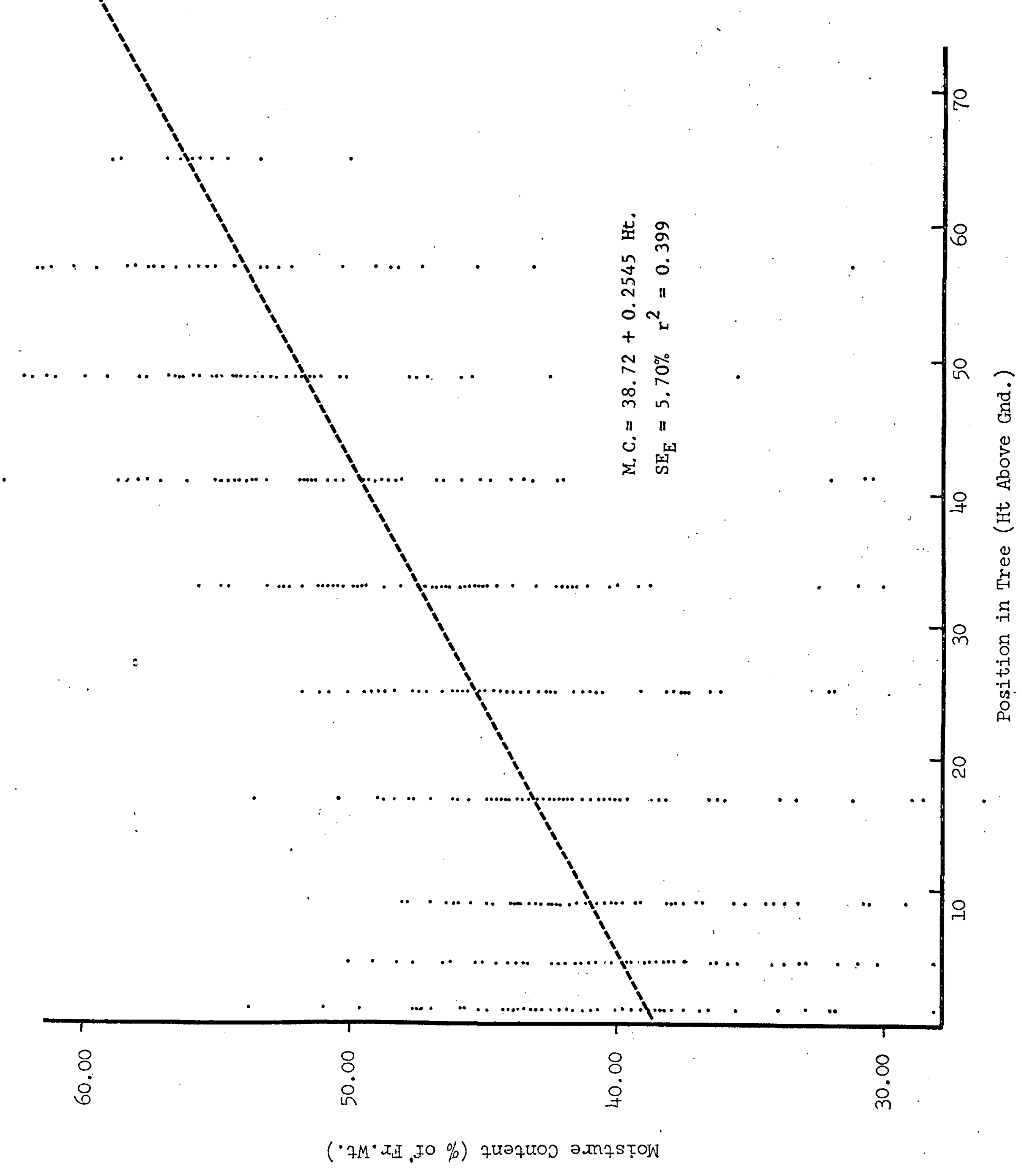


Table 32. The Correlation Coefficients Between Specific Gravity and Moisture Content and Several Tree Characteristics for 63 Lodgepole Pine Trees.

Tree Characteristics	Correlation Coefficients (r)	
	Moisture Content	Specific Gravity
Dbh (in)	0.4026**	-0.3961**
Height (ft)	0.4182**	-0.2986**
Crown length (ft)	0.3013**	-0.2626**
Crown width (ft)	0.5123**	-0.3264**
Age (yr)	0.4193**	-0.1761**
Total tree weight (lb)	0.4279**	-0.3626**
Dry needle weight (lb)	0.4976**	-0.3179**
Tree volume ob (cu. ft.)	0.4055**	-0.3869**
Ave. specific gravity	-0.2640**	1.0000**
Height to live crown (ft)	0.1786**	-0.0719**
Tree basal area (sq. ft.)	0.3915**	-0.3827**
Crown volume (cu. ft.)	0.4546**	-0.3139**
Crown surface area (sq.ft.)	0.5019**	-0.3370**
Number of needles	0.4450**	-0.2818**
Mean radial growth (bh)	0.3639**	-0.3942**
Bark per cent	-0.0395 ns	0.1488**

The results presented in Table 32 suggest that between tree differences in tree moisture content are most closely related to characteristics of the crown (with the exceptions of crown length and height to live crown) and this in turn is probably closely related to the influence of crown characteristics on evapo-transpiration, and photosynthesis. Crown width and crown surface area were the two variables most closely associated with tree moisture content differences.

Measures of tree size were found to be most closely associated with tree specific gravity. The negative correlation coefficients suggest that as tree size increased tree specific gravity decreased. The results suggested, as did the analysis of within tree variation, that as tree specific gravity increased tree moisture content decreased. Due to the even-aged nature of the trees analysed tree size is an indication of tree vigor and consequently it is possible to indirectly conclude that tree specific gravity decreased, and tree moisture content increased with increasing tree vigor.

A multiple linear regression analysis of tree specific gravity on dbh, height, crown length, crown width, tree weight volume (ob), dry needle weight, height to live crown, basal area, crown volume, crown surface area, number of needles, and mean radial growth rate (bh) accounted for only 31.3 per eent of the variation with a standard error of 0.021 (7.8%). The best simple linear regression of tree specific gravity was on dbh.

$$\text{Tree Sp. Gr.} = 0.458 - 0.005399 \text{ dbh}$$

$$SE_E = 0.021 \qquad r^2 = 0.157^{**}$$

The preceding relationship accounted for 15.7 per cent of the variation and had a standard error of estimate of 0.021 (7.8%).

A multiple regression analysis of tree moisture content on the same independent variables cited in the preceding paragraph plus specific gravity and bark volume per cent accounted for 51.0 per cent of the total variation. The best simple linear regression was:

$$\text{Tree M. C. (\%)} = 36.205 + 1.828 \text{ CW}$$

$$SE_E = 4.08\% \qquad r^2 = 0.262^{**}$$

Crown width accounted for 26.2 per cent of the variation in tree moisture content, expressed as a percentage of fresh weight, with a standard error of estimate 4.08% (9.3%).

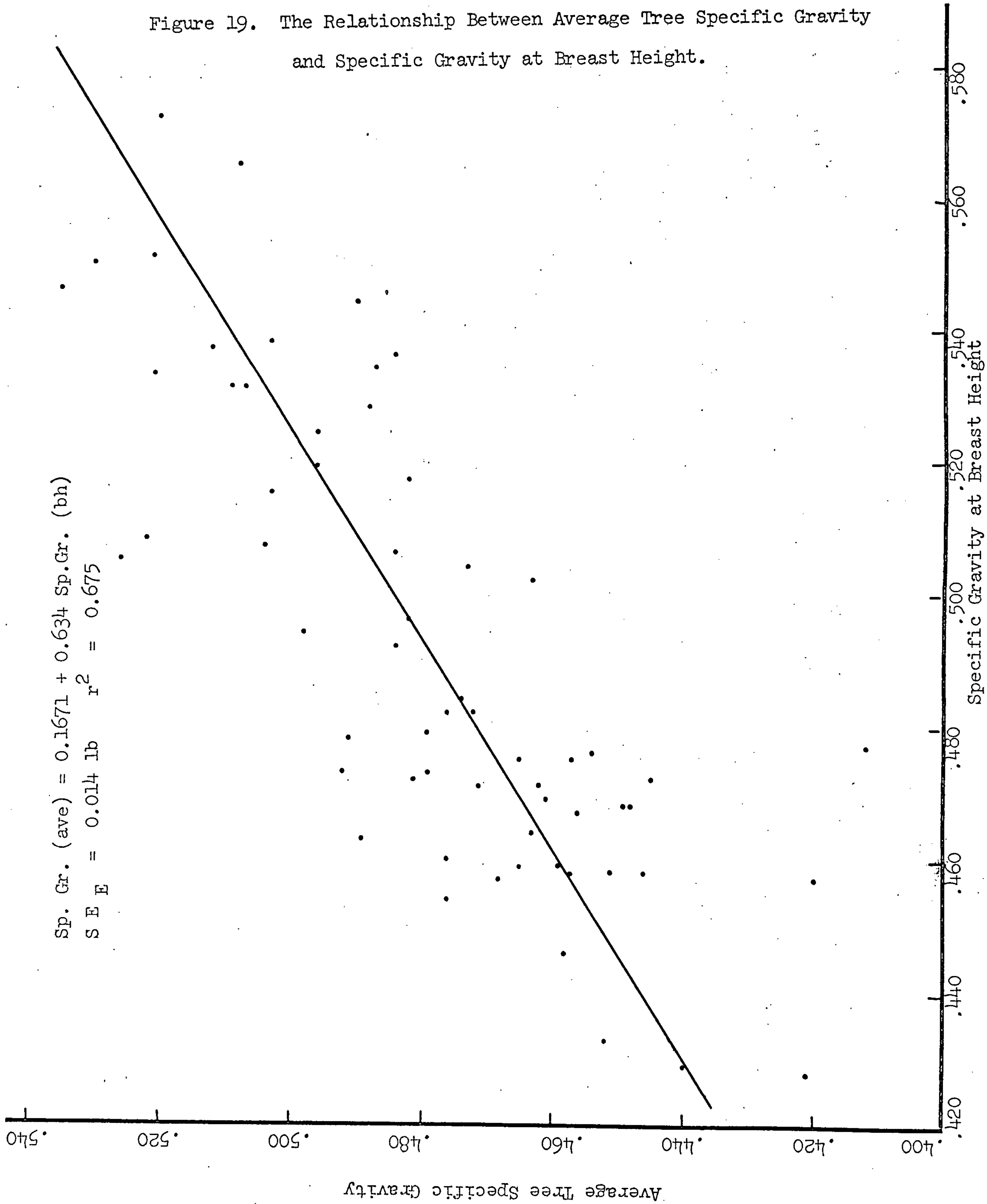
The equation of the simple linear regression of average tree specific gravity on breast height specific gravity was:

$$\text{Sp. Gr. (ave. tree)} = 0.1456 + 0.64008 \text{ Sp. Gr. (bh)}$$

$$SE_E = 0.013 \qquad r^2 = 0.675^{**}$$

This relationship accounted fof 67.5 per cent of the variation, having a standard error of estimate of 0.013 (3.1%). Figure 19 presents the relationship between average tree specific gravity and specific gravity

Figure 19. The Relationship Between Average Tree Specific Gravity and Specific Gravity at Breast Height.



at breast height on an oven-dry basis.

A simple linear regression of average tree moisture content on moisture content breast high accounted for 47.3 per cent of the variation with a standard error of 3.45 per cent (7.7%). The equation was:

$$\text{Ave. M. C. } (\%) = 21.178 + 0.585 \text{ M. C. (bh)}$$

$$SE_E = 3.45 \qquad r^2 = 0.473^{**}$$

The relationship is presented in Figure 20.

Summary

Where the value of the raw material is low, weight scaling offers several advantages over conventional scaling. However, as yet very little study has been directed to analysing factors which influence the weight of wood such as moisture content and specific gravity (wood density).

The analyses carried out in this thesis point out that easy and accurate conversions can be made between the volume and weight of trees if data are available on the average wood density or volume/weight ratios is available. On the basis of these results it appears that, when they are needed, for example, to "control" the rate of forest inventory depletion, accurate estimates of volume can be obtained through weight scaling.

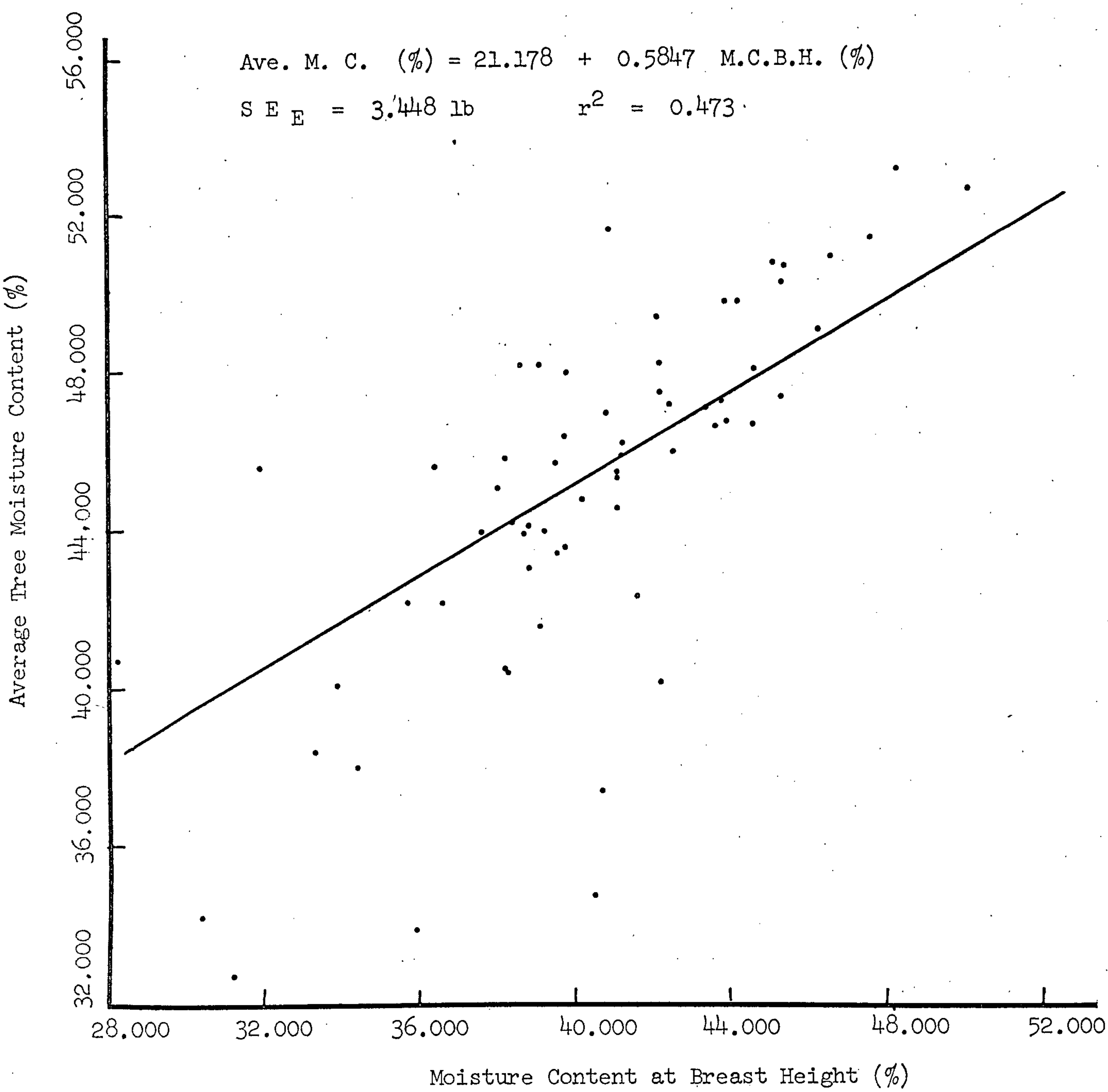


Figure 20. True Relationship Between Average Tree Moisture Content (%) and Moisture Content (%) at Breast Height.

Analyses of the within and between tree variations in moisture content and specific gravity were carried out. The results of these analyses have demonstrated the variability of moisture content (C. V. = 16.3%) and specific gravity (C. V. = 8.9%) in lodgepole pine trees. Height within the tree is the most important factor affecting moisture content and specific gravity. Low specific gravity and high moisture content are characteristic of fast growing trees. Between tree variations in specific gravity and moisture content are most closely associated with the size of the tree and the properties of the crown, respectively.

It is apparent that average tree specific gravity and moisture content can be accurately estimated from the combination of measurements of specific gravity and moisture content taken at breast height and regression techniques. Further study should be devoted to analysing variation in specific gravity and moisture content due to changes in location and season.

CONCLUSIONS

The weights of the various components of lodgepole pine increase with tree size; however, the proportion of the total tree weight contained in these components are highly variable and may increase or decrease as tree size increases, depending upon the component studied. Using regression techniques it is possible to obtain accurate estimates of the component weights of trees from a single measurement of dbh, tree basal area, or tree height. The crown and needle characteristics of lodgepole pine are highly variable.

Double sampling with regression offers an easy and reliable method of estimating forest tree biomass. Further study should be devoted to investigate this method more thoroughly. In most studies of biomass it will probably be desirable to accept a lower degree of accuracy in order to increase the representativeness of the conditions investigated.

Variations in specific gravity and moisture content, both within and between trees, appear to be relatively minor problems in the weight scaling of lodgepole pine. If data, such as presented herein, are available on moisture content and wood density, conversions can be easily made between volume and weight.

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APPENDIX I. A Summary of Previous Investigations of Biomass, Foliage, and Slash.

Investigator	Location	Plant Community	Characteristics Investigated	Variables	Best Variable	Other Comments
Ando et al (1959)	Japan	Cryptomeria japonica	Leaves & twigs			Suggested a method of sampling
Ando (1965)	Japan	Pinus thumbergii	Branch, stem	Site Index and density		In closed stands site index and density had little affect.
Attiwill (1966)	Australia	Eucalyptus	Crown weight	dbh & BA	BA	Objected to use of mean tree sampling method
Baskerville (1965a)	Canada	Abies balsamea	Several components			Ave. diameter depends upon component measured
Baskerville (1965b)	Canada	A. balsamea & P. glauca	Several components	Density		Discussed the affect of stand density on dry matter production.
Bakserville (1966)	Canada	A. balsamea & P. glauca	Roots, and lesser veg.	Density		Total increased and lesser decreased with inc. density.
Boyer and Fahnestack (1966)	U.S.	Pinus palustris	litter & flash fuels	Stand BA		Increased with increased stand BA
Brown (1963)	U.S.	Pinus resinosa	crown wt.	dbh		Investigated influence of site index and density
Brown (1965)	U.S.	P. resinosa & P. banksiana	crownwt.	dbh & cr. length	dbh	Studied influence of stand density
Bruce (1951)	U.S.	P. palustris & P. serotina	crown wt.			Tables for open and closed stands.
Burns & Irwin (1942)	U.S.	P. strobus & P. resinosa	needle wt.	vol. inc.		Needles more efficient at wider spacing
Cable (1958)	U.S.	Pinus ponderosa	needle surf. area	dbh		Relationship unchanged for different sizes, densities, and ages.
Cel'niker (1963)	U.S.S.R.	Broad-leaved trees	number of needles	dbh		Close relationship observed
Chandler (1960)	U.S.	conifers	slash			slash amount affected by tree size and species
Dieterich (1963)	U.S.	Pinus resinosa	surface fuel	density & age		BA good and age improved prediction
Fahnestack (1960)	U.S.	many species	crown wt.	dbh & cr. length	dbh	Developed regression equations to predict crown weight
Hall (1965)	U.S.	Pinus resinosa	stem growth			Stem growth related to amount of foliage above it
Harada & Satoo (1966)	Japan	Cryptomeria japonica	stem wt.	height		Varied with stand age and region
Hatiya et al (1966)	Japan	Pinus densiflora	foliage wt.	season		Site quality and density had little effect on seasonal variation
Kern (1962)	Germany	P. abies & A. alba	foliage wt.	several variables	cr. surf. area	Differences between the two species small
Kiil (1965)	Canada	P. glauca & P. contorta	slash wt.	dbh		Sl. wt. /merch. cu. ft. varies with dbh
Kittredge (1944)	U.S.	Pinus ponderosa	foliage wt.	vol. incr. BA & dbh		Relationship unchanged by age, density and tree size

LaMois (1958)	U.S.	Pinus resinosa	needle wt.	density & site		Both variables affect amount of fuels
Loomis et al.(1966)	U.S.	Pinus echinata	foliage & branch wt.	several variables	diam. cr. base	Cr. length/height adjusts for density & bole form
Madgwick (1963)	U.S.					Suggested sampling method
Mar: Moller (1947)	Denmark	P. abies & Q. robur	litter	density		Thinning reduced amount of organic matter
Molchanov (1949)	U.S.S.R.	Pine (presumably Pinus sylvestris)	needle wt.			Needle weight was directly proportional to volume increment regardless of age and density
Muraro (1964)	Canada	Pinus contorta	slash wt.			Height & SI didn't signfficantly affect branch litter distrib.
Muraro (1966)	Canada	Pinus contorta	slash wt.	dbh		Wt. / cu. ft. vol. varied inverly with dbh
Ovington (1956)	U.K.	Several species	biomass	many variables		cr. wt. increased with age; bole wt/unit canopy increased with age and height
Ovington (1957)	U.K.	P. sylvestris	biomass	several variables		Studied changes in tree weight distribution
Ovington (1962)	U.K.	Many species				Discussion of biomass and quantitative ecology
Ovington & Madgwick (1959)	U.K.	P. sylvestris	biomass			Discuss need to consider each component separately.
Pojakova-Mincenko (1961)	U.S.S.R.	Broad-leaved trees	foliage	dbh & vol. incr		Close relationship observed between foliage wt. and volume and dbh increments
Rennie (1966)	Canada	Pinus reginosa	biomass			Proposed sampling method
Rogerson (1964)	U.S.	Pinus taeda	foliage wt.	dbh & BA		Observed a close relationship
Satoo (1962)	Japan		foliage wt.	dbh		Sampling
Satoo (1965)	Japan		foliage wt.			Sampling
Satoo & Senda (1966)	Japan	Cryptomena japonica	biomass			Studied mean tree and formula stand table methods
Schopfer (1961)	Germany	Picea abies	slash & foliage wt.	dbh		Used double logarithmic transformation
Smirnov (1961)	U.S.S.R.	Broad-leaved trees	crown wt. etc.,			Linear relationship between leaf wt. and stem wt. leaf wt. and branch wt., and branch wt. and stem wt.
Stiell (1962)	Canada	Pinus resunosa	foliage wt.			Foliage wt. /tree increased with wider spacing
Stiell (1966)	Canada	Pinus resinosa	foliage wt.			Studied influence of spacing on crown wt.
Sundahl (1966)	U.S.	Broad-leaved trees	crown & tree wt.			Weight tables prepared
Tadaki (1965)	Japan	Acacia mollissima	foliage wt.			Studied biomass and leaf area index
Tadaki (1966)	Japan	Several				Discussion of leaf biomass of stands and trees
Tadaki & Kawasaki (1966)	Japan	Cryptomeria japonica	foliage biomass			Max. production - pole stage
Tadaki & Shidie (1960)	Japan	Ulmus parvifolia	foliage wt.	season		Discussed seasonal variations
Tadaki et al.(1961)	Japan	Betula platyphylla	biomass	BA		Studied influences of stand density
Tadaki et al.(1962)	Japan	Castanopsis cuspidata	biomass	BA & dbh		Discussed stand structure and productivity
Tadaki et al.(1963)	Japan	Acacia mollissima	biomass	BA		Studied productivity
Vaidya (1963)	U.S.	Pinus palustris	biomass	dbh & height		Influence of site quality discussed
Weetman & Harland (1964)	Canada	Picea mariana	biomass	dbh & volume		

Wendal (1960)	U.S.	Pinus serotina	Fuel wt.			Fuel weight tables
Wendel et al.(1962)	U.S.	Pinus serotina	Forest fuels	dbh & stocking		Weight of understory vegetation & litter
Whittaker (1966)	U.S.	Q. alba & S. sempervirons	biomass			Influence of site and location on biomass
Wile (1964)	U.S.	P. rubens & A. balsamea	crown wt.	dbh & cr.l. & CW	dbh	Used double logarithmic transformation
Whitkamp (1966)	U.S.	Pinus sylvestris	biomass			Soil-biomass relations discussed
Yamamoto (1965)	Japan	Betula platyphylla	foliage	height & age		Wt. increased with height and age
Young et al.(1964)	U.S.	Several species	biomass			Weight tables by dbh and height
Zyijaev (1964)	U.S.S.R.	Larix sibiriea	foliage wt.	many variables	vol. cai	Several relationships

APPENDIX II — Logarithmic Relationships of Tree and Tree Component Fresh Weight (lb) on Dbh (in)

The following formulae are based on data obtained from 63 lodgepole pine trees ranging in diameter at breast height from 4.3 inches to 10.9 inches (ob).

1. Total Tree Weight (above a 1 foot stump):

$$Y \text{ (lb.)} = 2524.49 \log_{10} \text{dbh (in.)} - 1578.0$$

$$SE_E = 76.27 \text{ lb. } (17.42\%) \quad r^2 = 0.926$$

2. Total Stem Weight (above a 1 foot stump):

$$Y \text{ (lb.)} = 2157.32 \log_{10} \text{dbh (in.)} - 1335.16$$

$$SE_E = 65.92 \text{ lb. } (17.01\%) \quad r^2 = 0.925$$

3. Merchantable Stem Weight (1 foot stump to 4 inch top (ob):

$$Y \text{ (lb.)} = 2273.33 \log_{10} \text{dbh (in.)} - 1485.97$$

$$SE_E = 64.51 \text{ lb. } (19.58\%) \quad r^2 = 0.934$$

4. Tree Crown Weight (needles plus branches):

$$Y \text{ (lb.)} = 367.17 \log_{10} \text{dbh (in.)} - 242.84$$

$$SE_E = 18.08 \text{ lb. } (35.90\%) \quad r^2 = 0.826$$

5. Tree Slash Weight (needles plus branches plus non-merchantable top):

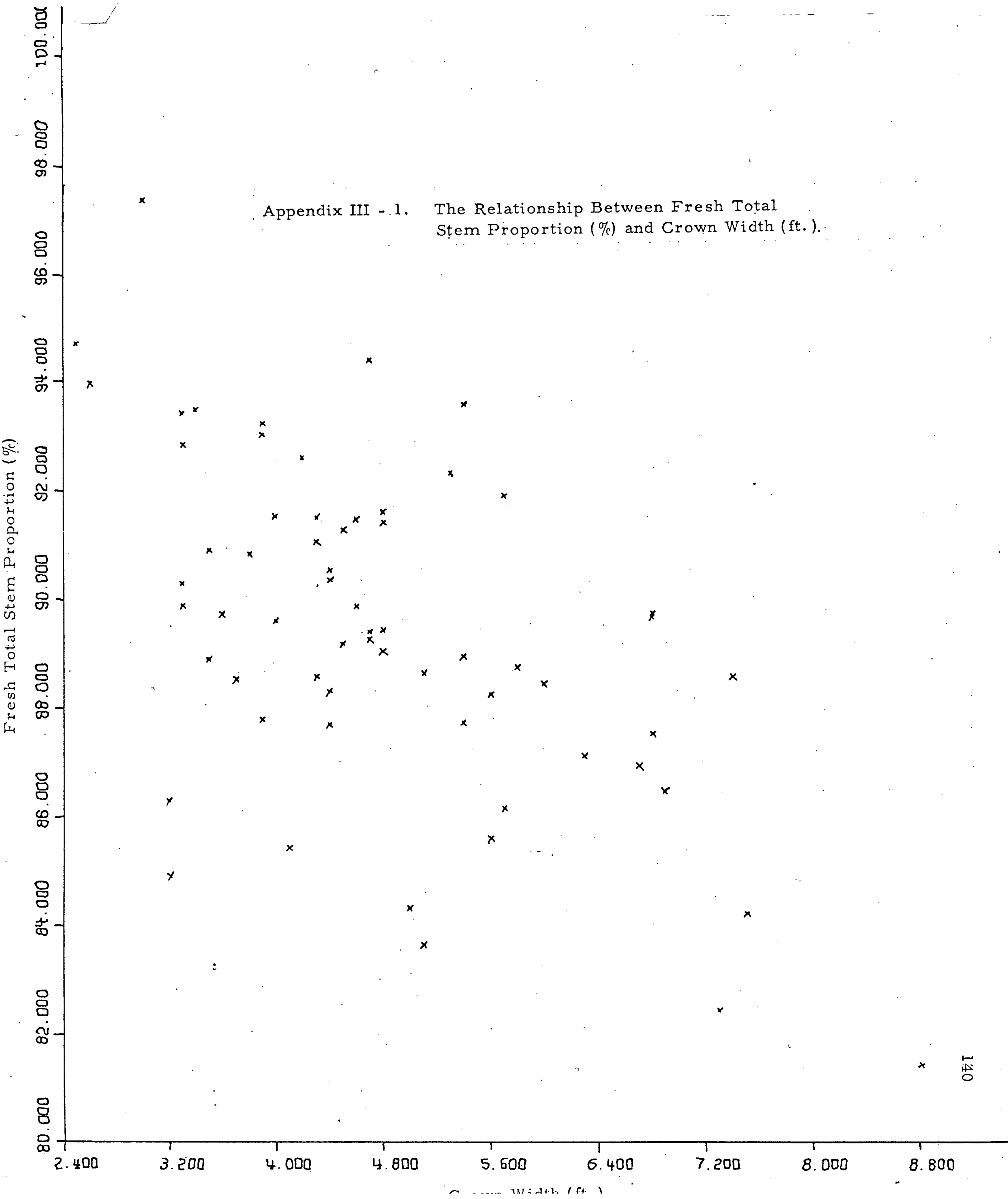
$$Y \text{ (lb.)} = 251.17 \log_{10} \text{dbh (in.)} - 92.03$$

$$SE_E = 25.61 \text{ lb. } (23.59\%) \quad r^2 = 0.525$$

6. Dry Needle Weight:

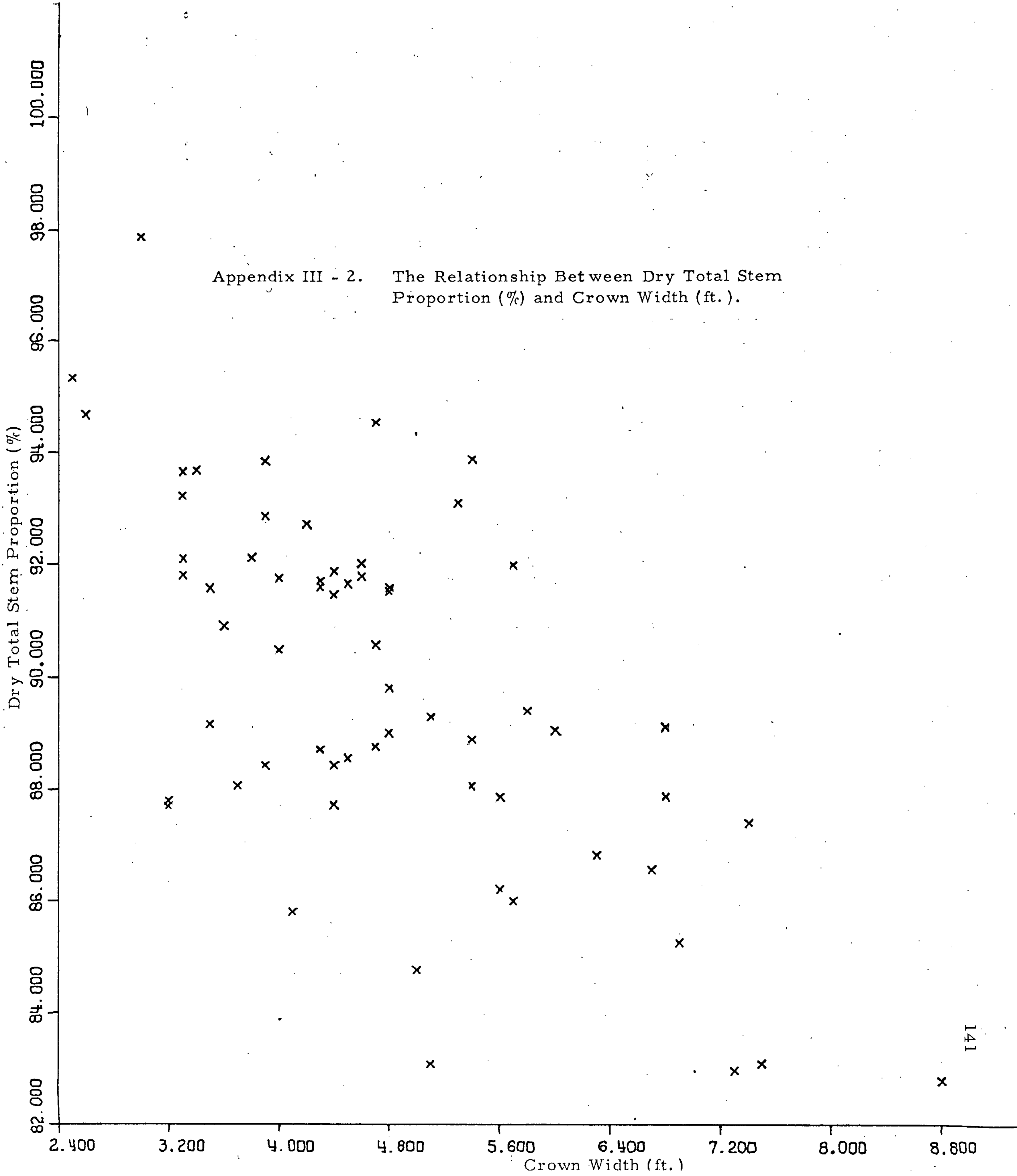
$$Y \text{ (lb.)} = 72.08 \log_{10} \text{dbh (in.)} = 46.51$$

$$SE_E = 3.93 \text{ lb. } (35.57\%) \quad r^2 = 0.795$$

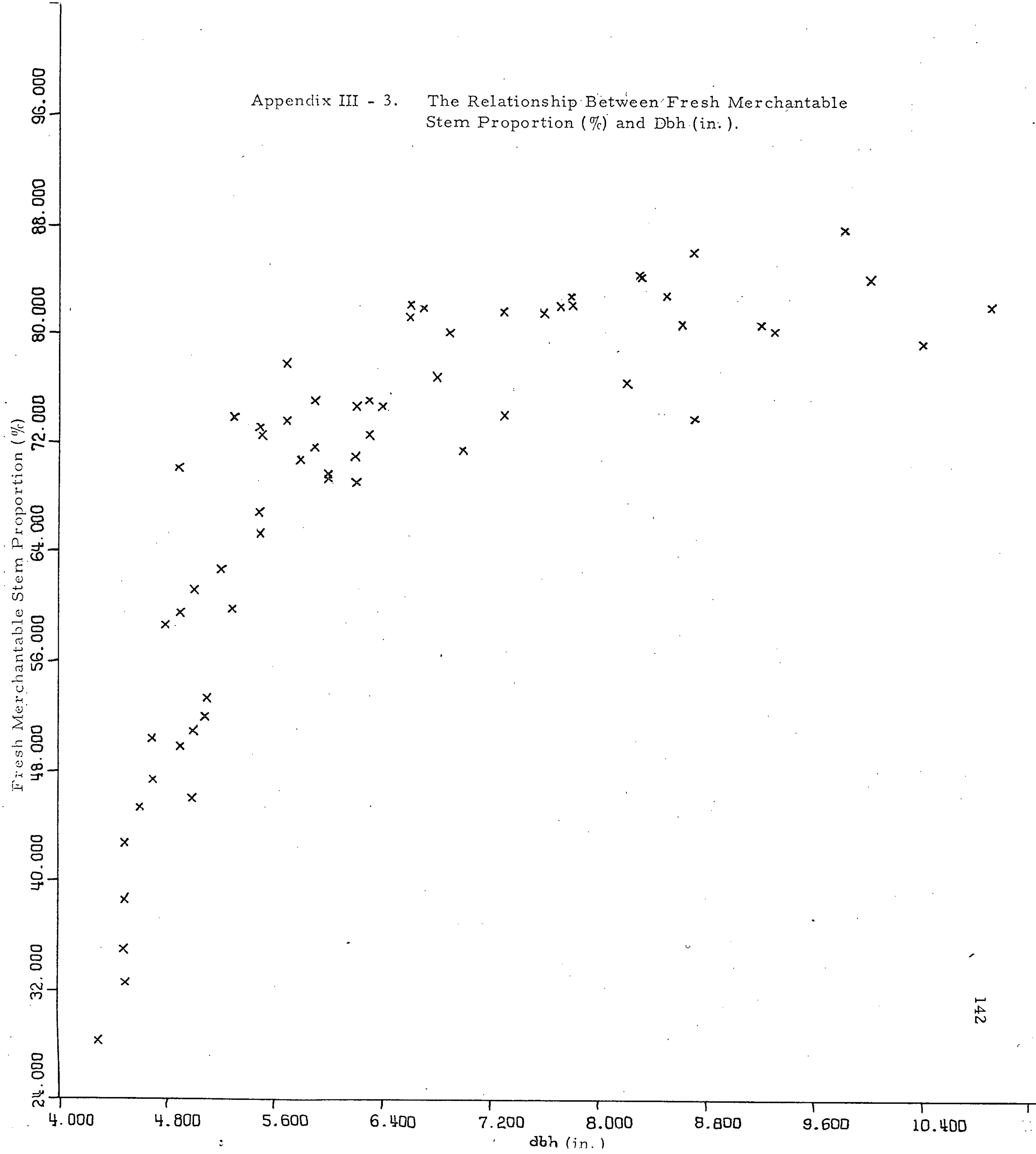


Appendix III - 1. The Relationship Between Fresh Total Stem Proportion (%) and Crown Width (ft.).

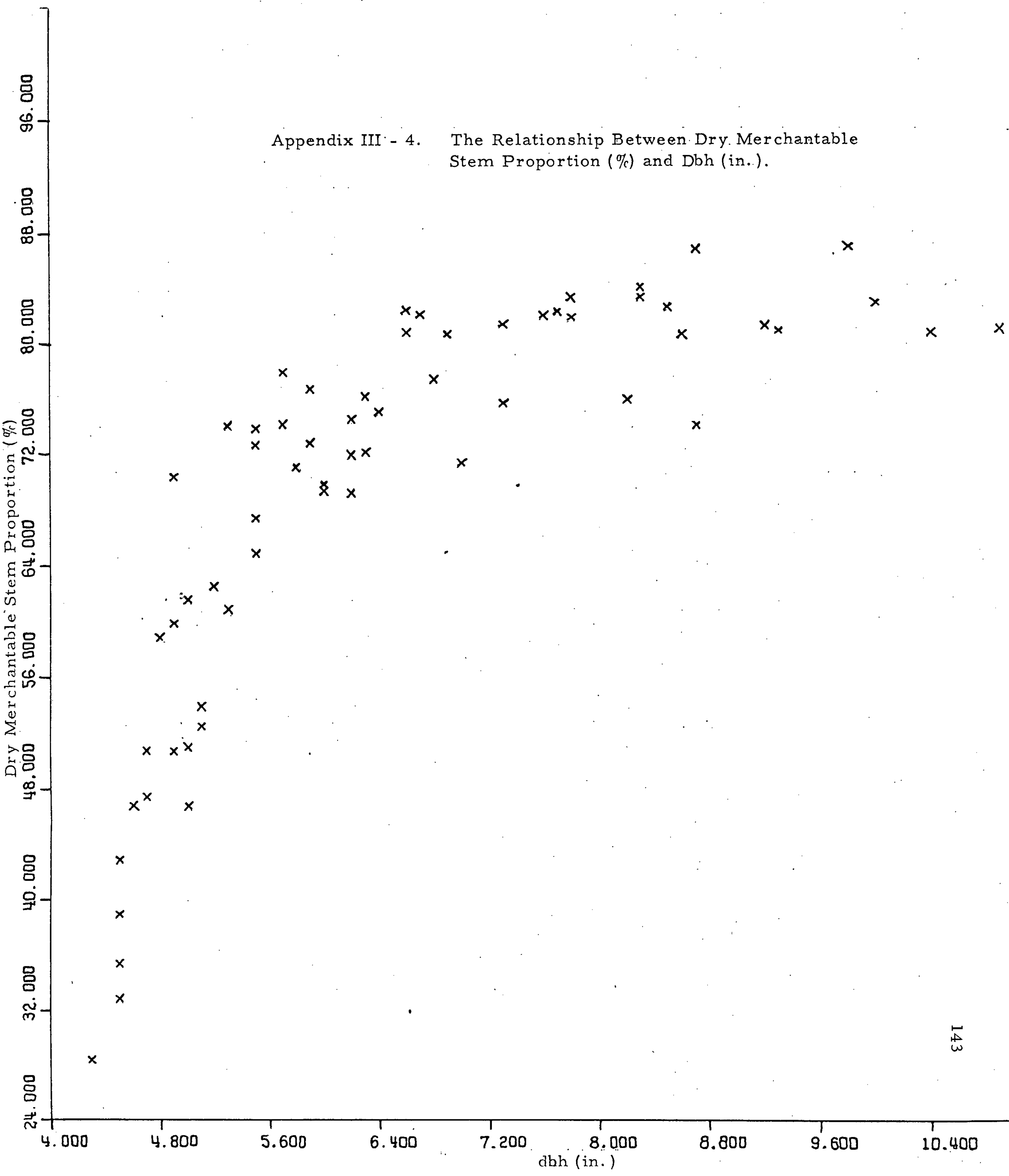
Appendix III - 2. The Relationship Between Dry Total Stem Proportion (%) and Crown Width (ft.).



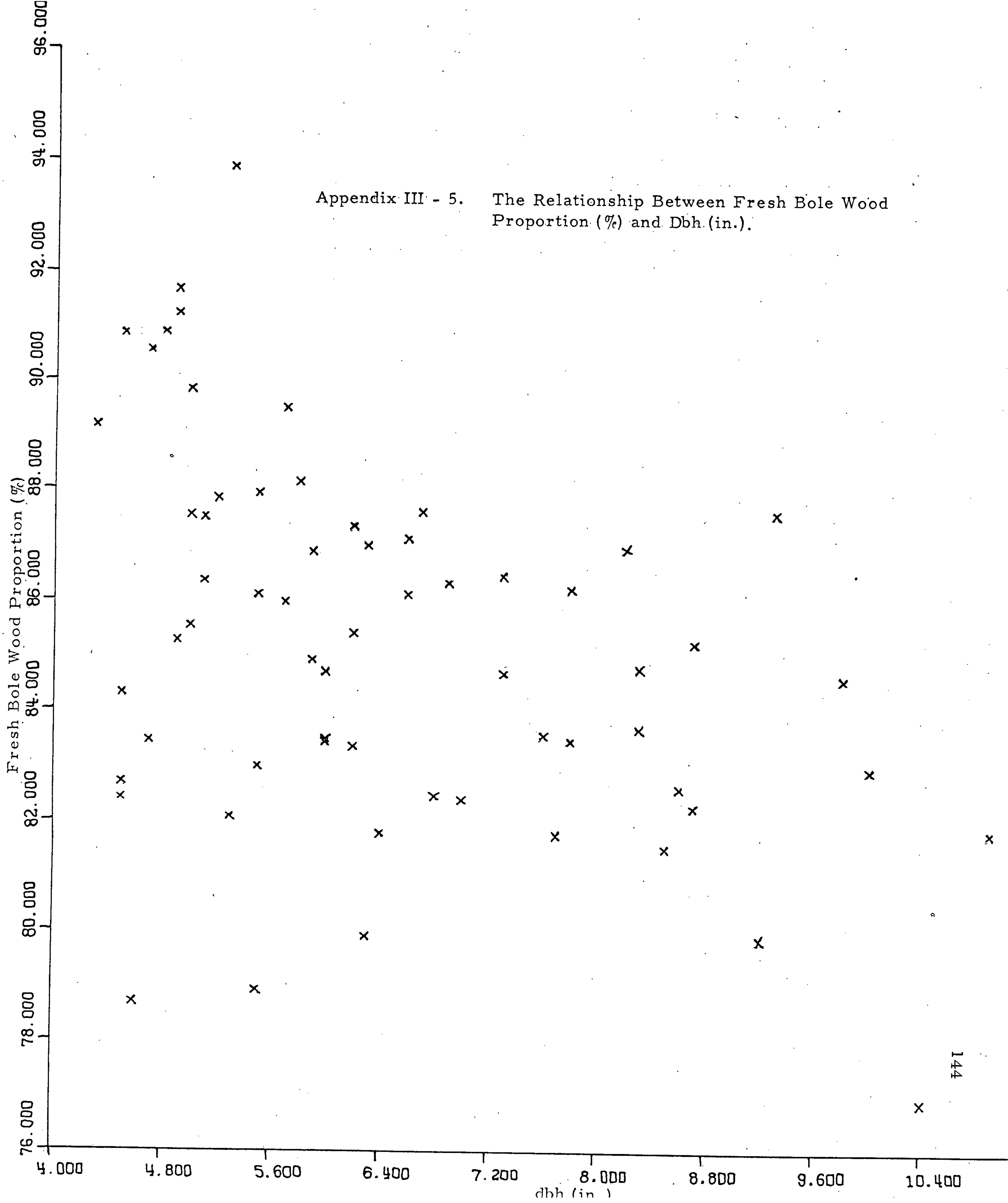
Appendix III - 3. The Relationship Between Fresh Merchantable Stem Proportion (%) and Dbh (in.).



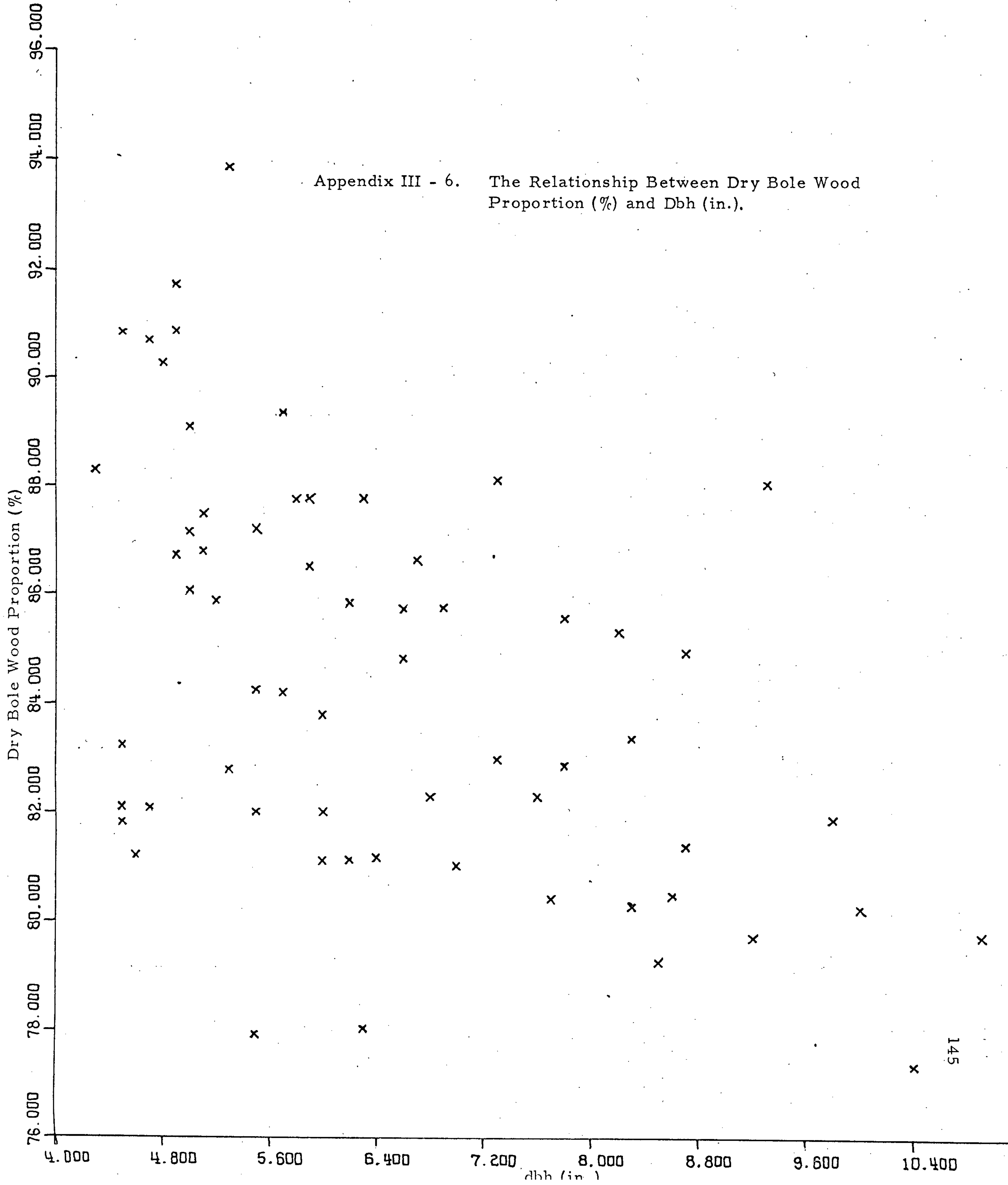
Appendix III - 4. The Relationship Between Dry Merchantable Stem Proportion (%) and Dbh (in.).

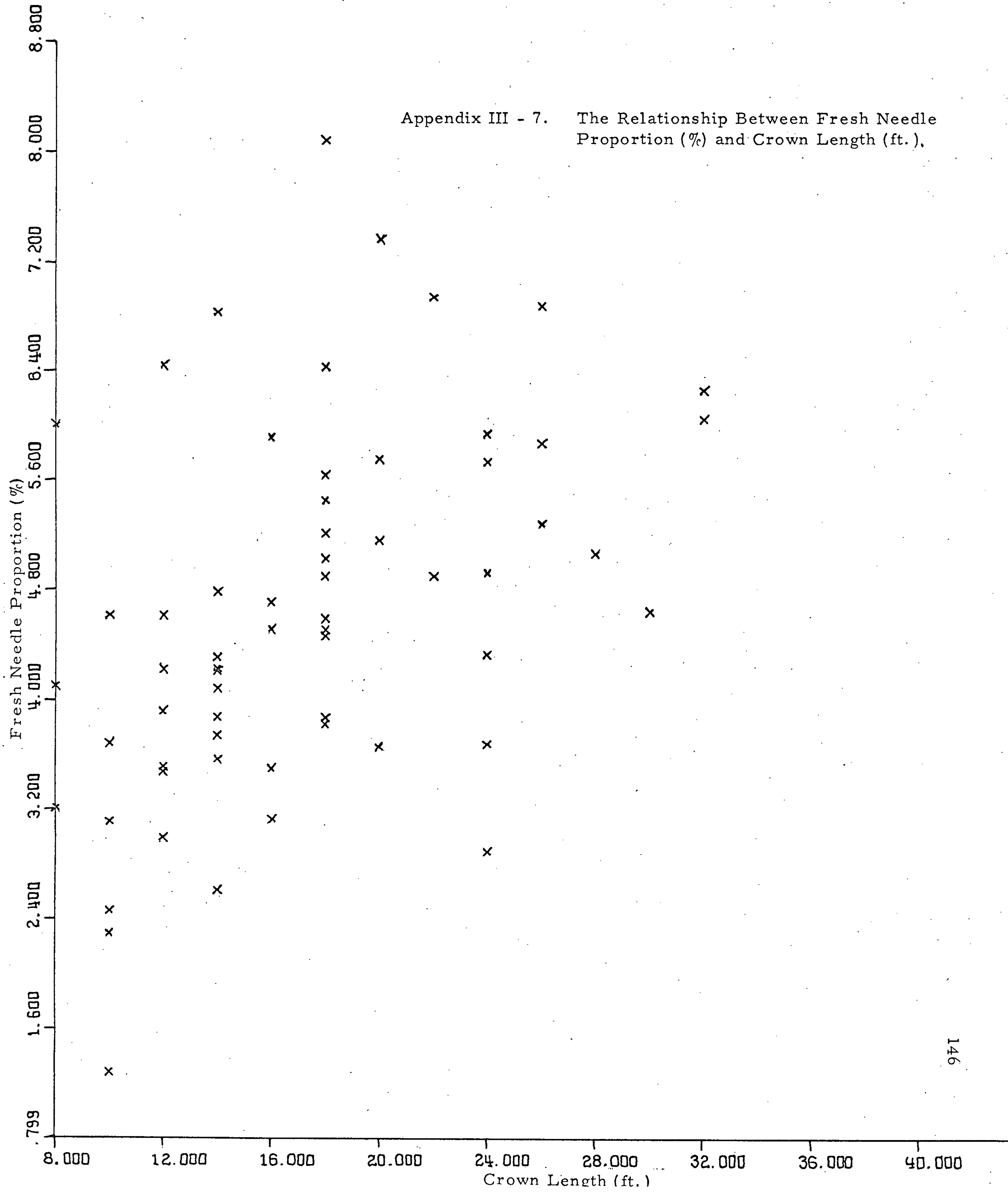


Appendix III - 5. The Relationship Between Fresh Bole Wood Proportion (%) and Dbh (in.).



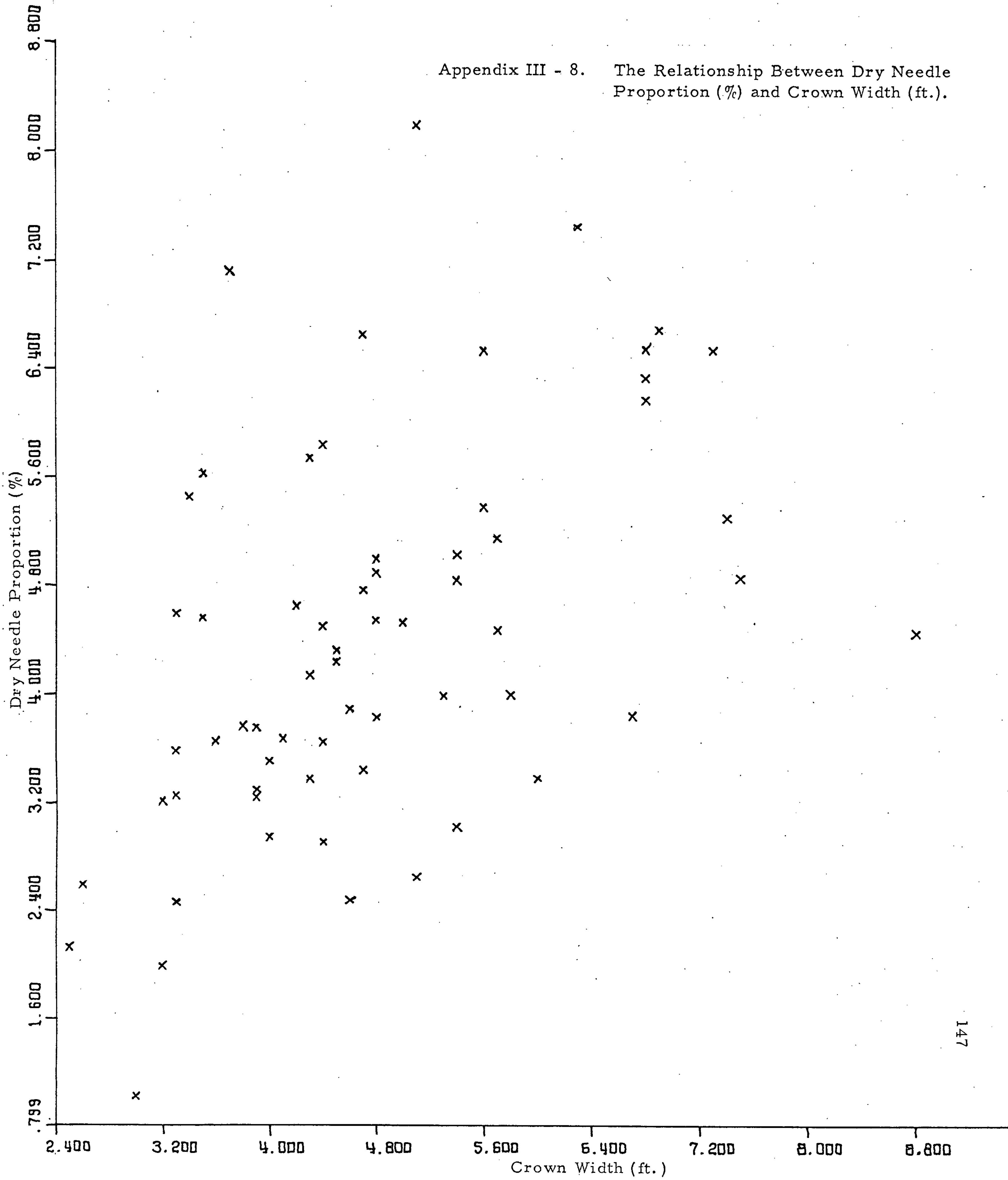
Appendix III - 6. The Relationship Between Dry Bole Wood Proportion (%) and Dbh (in.).

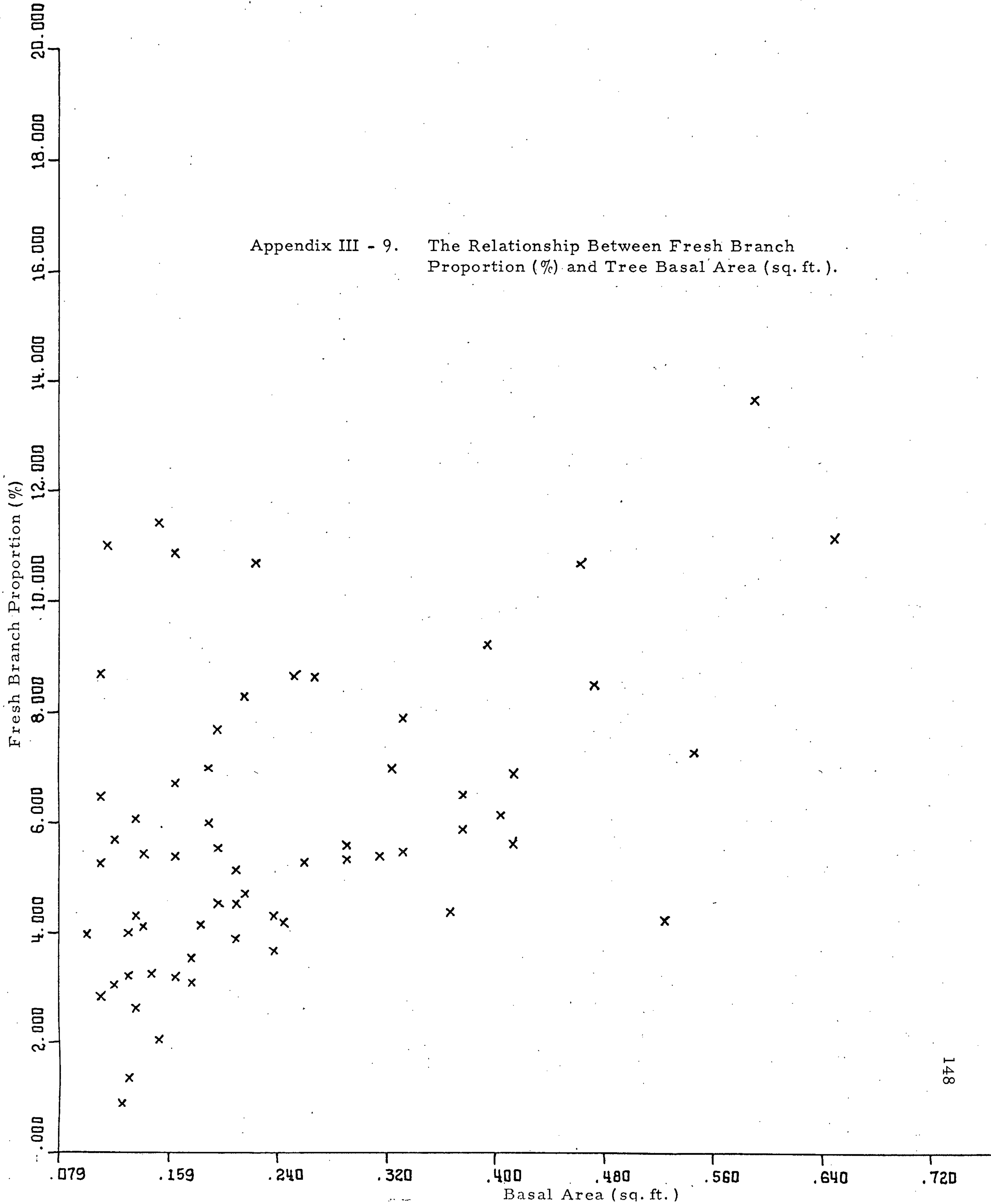




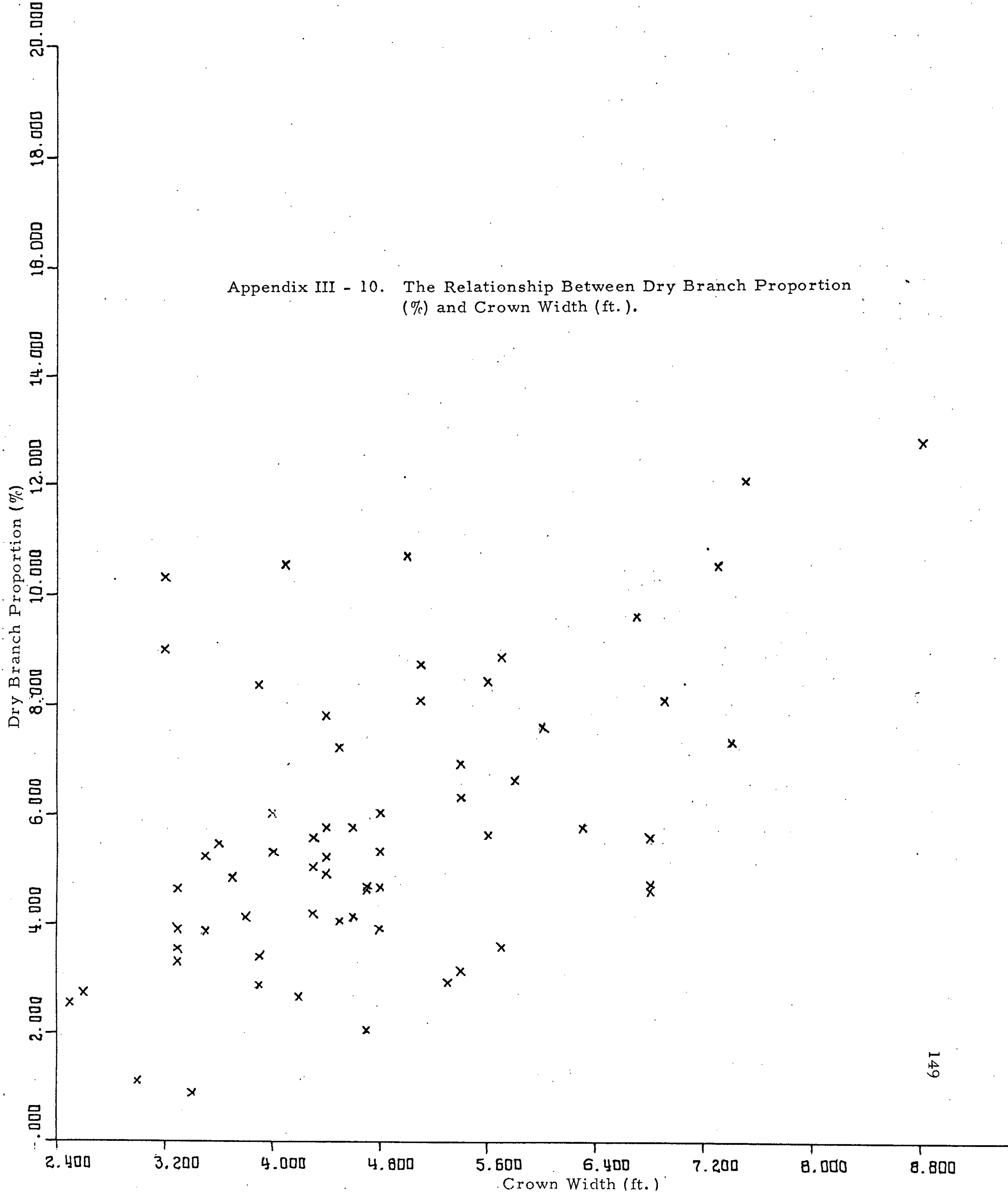
Appendix III - 7. The Relationship Between Fresh Needle Proportion (%) and Crown Length (ft.).

Appendix III - 8. The Relationship Between Dry Needle Proportion (%) and Crown Width (ft.).



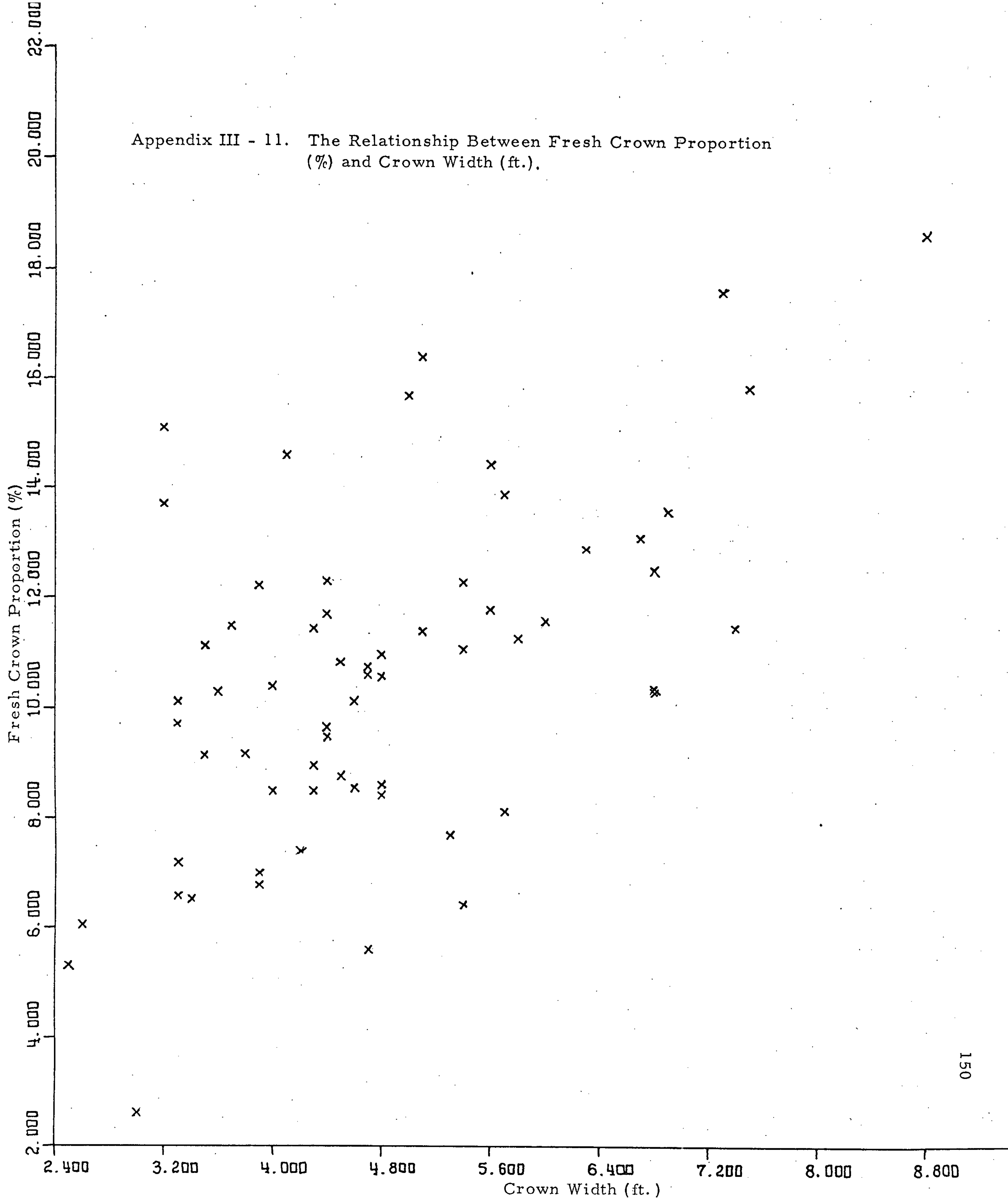


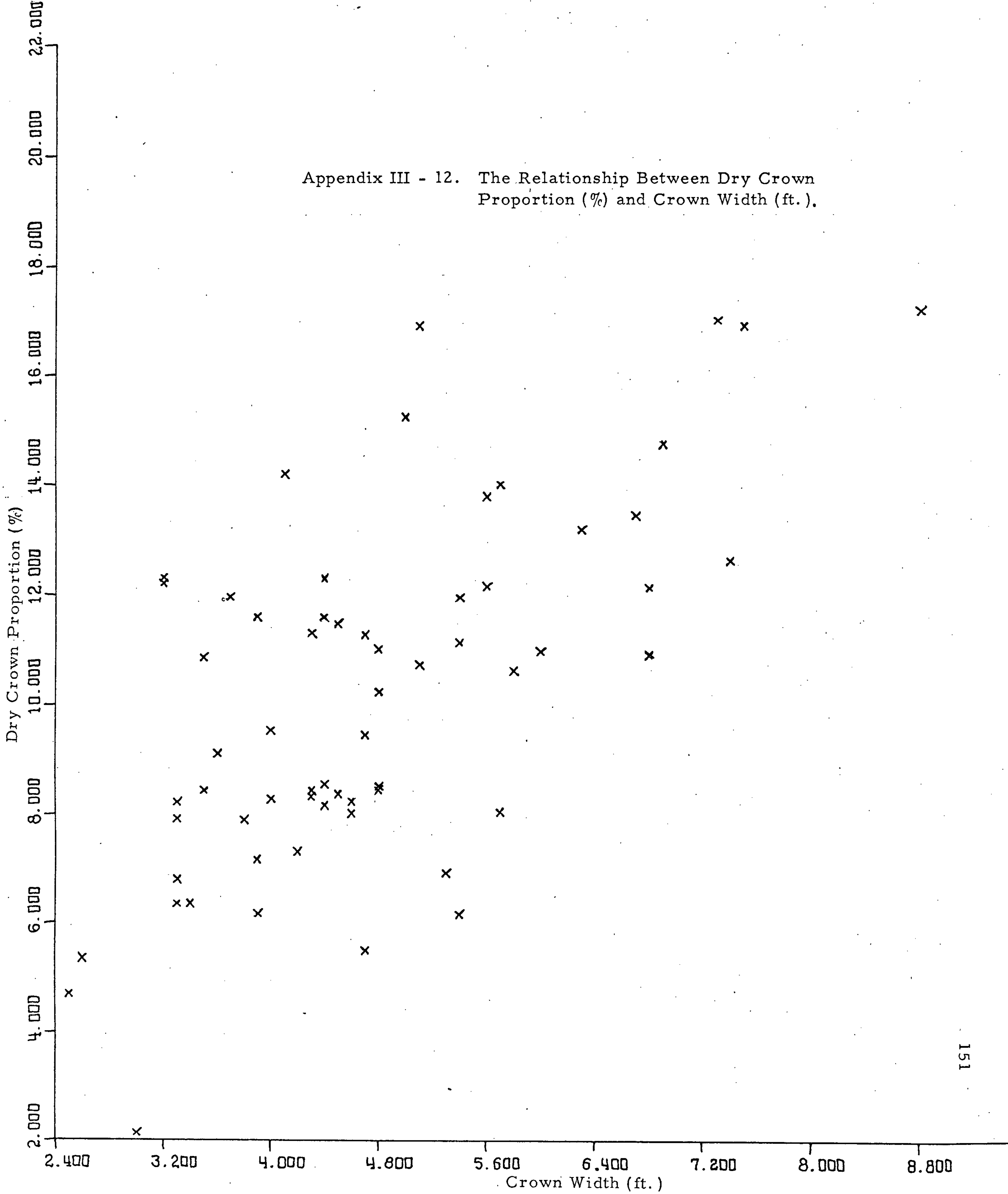
Appendix III - 9. The Relationship Between Fresh Branch Proportion (%) and Tree Basal Area (sq. ft.).



Appendix III - 10. The Relationship Between Dry Branch Proportion (%) and Crown Width (ft.).

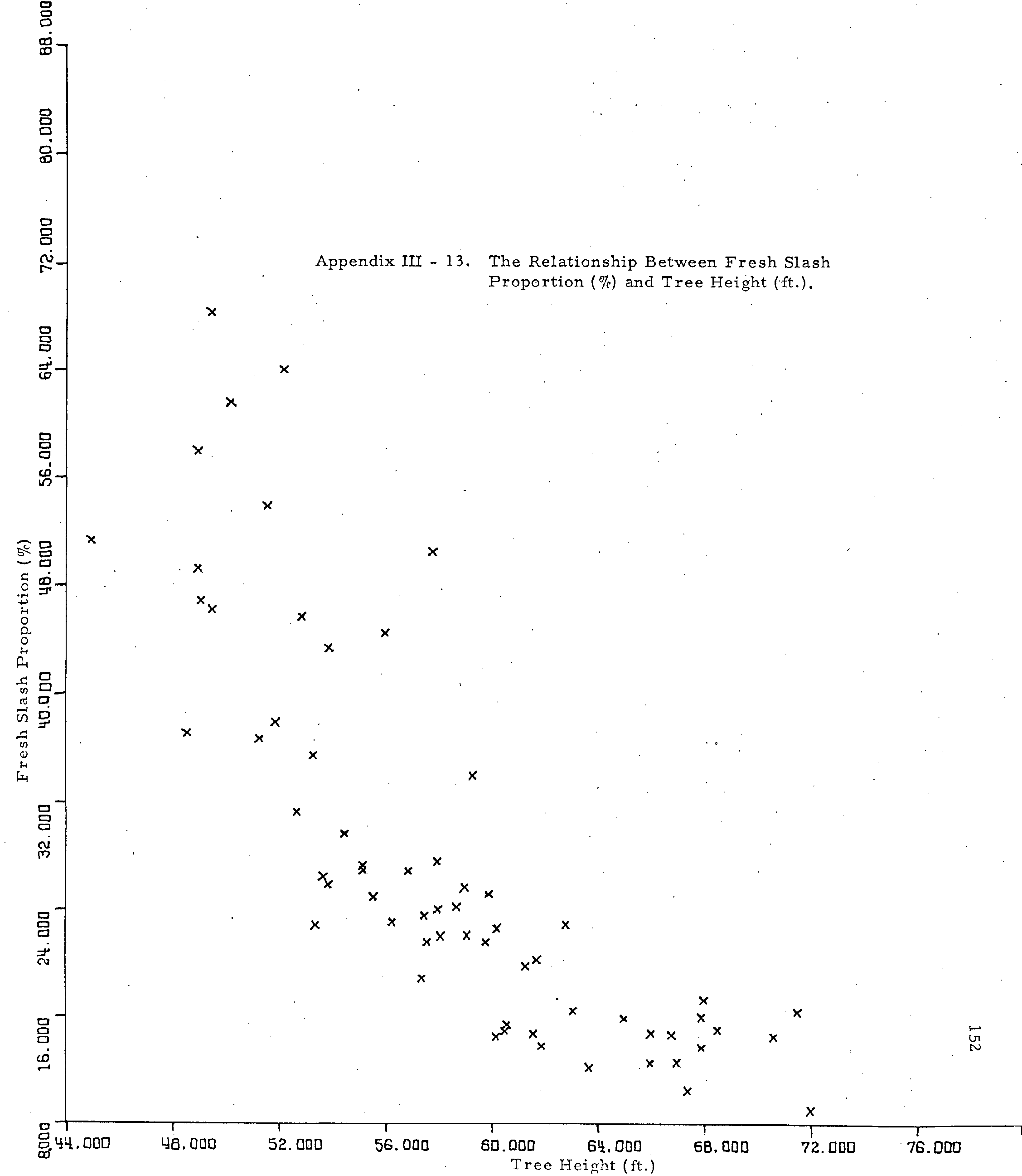
Appendix III - 11. The Relationship Between Fresh Crown Proportion (%) and Crown Width (ft.).





Appendix III - 12. The Relationship Between Dry Crown Proportion (%) and Crown Width (ft.).

Appendix III - 13. The Relationship Between Fresh Slash Proportion (%) and Tree Height (ft.).



Appendix III - 14. The Relationship Between Dry Slash Proportion (%) and Tree Height (ft.).