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An Allometric Model for Bole Biomass Estimates of Spruce and Aspen in Southwestern Colorado

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THESIS

AN ALLOMETRIC MODEL FOR BOLE BIOMASS ESTIMATES OF SPRUCE AND ASPEN IN SOUTHWESTERN COLORADO

Submitted by

Thomas D. Landis

In partial fulfillment of the requirements
for the Degree of Master of Science
Colorado State University
Fort Collins, Colorado
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July, 1972

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY THOMAS D. LANDIS ENTITLED AN ALLOMETRIC MODEL FOR BOLE BIOMASS ESTIMATES OF SPRUCE AND ASPEN IN SOUTHWESTERN COLORADO BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

AN ALLOMETRIC MODEL FOR BOLE BIOMASS ESTIMATES OF SPRUCE AND ASPEN IN SOUTHWESTERN COLORADO

Destructive samples were taken from 36 Engelmann spruce and 20 quaking aspen in the San Juan National Forest of southwestern Colorado. These samples consisted of bole cross-sectional discs taken at regular intervals throughout the height of the tree.

Through measurements of the sample discs a complete stem analysis was computed for each tree. This stem analysis revealed the volume characteristics of the tree throughout its life. The same sample discs were tested for specific gravity based on the ovendry weight and green volume.

The ovendry weight of the tree trunk or its stem biomass was computed using the cubic volume and the specific gravity of cylinders over the height of the tree. This stem biomass per tree was used as the dependent variable in an allometric regression with various physical dimensions of the tree, such as the bole diameter at breast height (DBH) and total height, as the independent variable. Using these two variables allometric models were constructed for each species and also for the two species combined.

The correlation coefficients for the allometric models were high, ranging from 0.88 to 0.99. The best model was the individual species equation with D^2H (DBH^2 X height) as the independent variable. An All-Trees model was found to be very accurate, a correlation coefficient of 0.99, using D^2H as the independent variable.

The allometric models were used to expand the stem biomass from the sample to a per acre basis, employing the necessary stand parameters. The total biomass per acre values were found to vary between the D^2H model and the model containing only D^2. This variation was attributed to the extrapolation of the D^2 model to trees with diameters larger than those included in the destructive samples.

The net production per acre was computed for each sample plot and elevation. Annual production was found to decrease with a corresponding increase in elevation while the variation in biomass was not as consistent. At the same site and elevation the quaking aspen was found to be a more efficient biomass producer than Engelmann spruce.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont.)

CHAPTER I

INTRODUCTION

Objectives

The purpose of this study was to develop a means of estimating the stem growth of forest trees. This investigation was one segment of the San Juan Ecology Project. This project is concerned with monitoring the possible ecological effects of cloud-seeding in the San Juan National Forest of southwestern Colorado. Theoretically the increase in moisture provided by the weather modification could change the normal growth of the forests in the target area. This study was conducted to derive a method of quantifying the stem growth of the forest in such a manner as to facilitate this objective.

The main goal of this particular study was the formulation of a practical means of calculating the growth and production of forest trees. This objective was approached by destructively sampling trees of the forest stands of the target area of the weather modification. By dissection of the trunks of these samples the total stem-wood value can be measured. The growth of the trees during discrete time intervals can be ascertained by evaluation of the width of the annual growth rings. Eventually these growth values could be correlated with the increase in snow to determine the effect of weather modification on forest growth.

Woodland production has been measured by foresters for many years and the current methods are outlined in several textbooks of forest mensuration (c.f., Husch, 1963; Spurr, 1952). Most procedures, however, use the board foot or cubic volume as a yardstick of the forest. In recent years the term biomass has been established as an alternate means of measuring the trunk of a tree in many ecological studies. In considering the forest in its totality as an ecosystem, the biomass of the individual trees is an excellent mensurational aid with greater application than the strictly production-oriented board foot. In this particular study biomass of the tree bole will be the growth parameter of the forest.

Definitions

Newbould (1967) defines biomass as the total amount of living material present at a given moment in a biological system, in this instance the forest. Odum (1971) defines biomass more simply as merely the weight of a living organism. In this study the term will be restricted to the bole or main trunk of forest trees. Bole biomass will be defined in this investigation as the aboveground portion of the main stem, extending from ground level to the terminal leader. In this context biomass usually includes the living sapwood of the tree but also the heartwood which is usually considered to be no longer alive.

Biomass can therefore be a direct measure of the stemwood portion of a tree. Biomass is usually considered to be a value at one particular point in time. When biomass is integrated over a period of time, primary production is a more accurate term. Gross primary productivity is defined as the total rate of photosynthesis, including the organic matter respired during the period of measurement. In this study we are concerned with net primary productivity which is the rate of storage of organic matter in plants in excess of the amount used in respiration (Odum, 1971). The net primary production that is considered in this study is the annual increment of wood added to the bole of a tree during the growing season.

The standard unit for the measure of the production of an ecosystem is dry weight. This term has several advantages as a forest stand parameter. It serves as a good base when comparing production of various stands because it remains a constant value when considering different forest species or even when comparing the production of a forest to that of a grassland. Kittredge (1944) stated that dry weight is probably the simplest parameter to determine, and since it is desirable to eliminate the variation in moisture content, it is preferable to determine constant ovendry weights. Dry weight is superior to cubic volume estimates of stand production because of the variability of wood characteristics. Therefore the production of stemwood can be better expressed in tons of dry matter instead of cubic meters because the specific gravity of wood varies considerably (Becking, 1962). Thus by using the dry weight of stands, species with various physical properties can be studied and their net production is directly comparable.

The means of determining biomass in this project will be based on the principles of allometry. Allometry may be defined as a mean change of proportions with increase in size, both within a species and between related groups (Reeve and Huxley, 1945). To overcome the obvious difficulties of measuring the dry weight of a stand, it is necessary to correlate easily measurable characteristics such as diameter at breast height (DBH) and total height with bole dry weight (Attiwill, 1962). The allometric theory maintains that in trees the size or biomass is related to a physical dimension of the individual. Since the trial by Kittredge (1944, 1948) on the use of the allometric regression between the amount of leaf biomass of trees and their stem diameter, similar allometric relationships became more and more frequently used.

An allometric relationship or model is simply a linear regression between a bole dimension and the biomass of the stem. This relationship can be expressed in the following form:

$$y = b_o + b_1 X$$

where y is the dependent variable, in this case dry weight; b_o and b_1 are constants to be determined, varying with species and size; and X is the independent variable, such as DBH or height (Richards and Kavanaugh, 1945 and Attiwill, 1962).

In recent years there have been many studies to determine the productivity of forest ecosystems (c.f., Kira and Shidei, 1967 and Ogawa *et al*., 1965). As of this date there has been little or no work done with the species concerned in this study: quaking aspen (*Populus tremuloides* Michx.) and Engelmann spruce (*Picea engelmannii* Parry). There is a definite need for work on these species as they are considered to be the most important timber asset of Colorado and are found in many other regions as well. In the study area of the San Juan National Forest, these species are especially valuable as it is in this area that they attain their highest productivity in the state.

Engelmann spruce is a widely distributed species; its range extends from British Columbia and Alberta, south to New Mexico and Arizona. It is a mountain species and under favorable conditions will grow to a height of 120 feet and a DBH of 30 inches (Harlow and Harrar, 1969). Engelmann spruce is found at elevations of 9,500 to 11,000 feet in the southern Rocky Mountains (Fowells, 1965). According to Miller and Choate (1964) Engelmann spruce is the most important tree from the standpoint of timber volume in the commercial forest of Colorado. Mature spruce sawtimber trees vary from two to five logs in merchantable height throughout most of the range, but grow to a height of as much as eight logs on parts of the San Juan National Forest. The wood of spruce is particularly even-textured with a high strength-to-weight ratio. Although now used almost entirely for lumber this species is suitable for pulp, plywood and other uses (Alexander, 1958).

Quaking aspen is the most widely distributed tree species in North America; its range extends from Newfoundland to Alaska, and south to New Mexico and Arizona (Fowells, 1965). It is fast growing and commonly attains heights of 60 feet and diameters of 2 feet (Harlow and Harrar, 1969). Quaking aspen is at its best in Colorado; the aspen type is the second largest in the state. The largest trees of this species are found in the southwestern part of the state where trees reach 24 inches in diameter and 100 feet in height. Although in the past aspen was not generally thought to be sufficiently productive for a timber crop, this species is becoming more valuable with increases in technology and utilization.

Besides its potential timber value aspen is popular for several other uses. The brilliant fall colors of the foliage provide one of the state's scenic attractions. Aspen stands have root sprouts and other vegetative components that provide excellent forage for both big game animals and livestock. Aspen is also valuable for its soil building characteristics. This species, long considered a weed tree, has many desirable wood properties. It is very satisfactory for industrial uses as it is light, uniform in texture, soft but tough, straight-grained, easy to work, and is tasteless and odorless. It is also quite shock resistant and low in shrinkage (Miller and Choate, 1964).

Scope of the investigation

1. The main objective of this study is to formulate the allometric equations for the bolewood component of spruce and aspen in the San Juan National Forest of Colorado. This will consist of estimating the constants in the regression equations for each species and discovering the physical dimension or combination of dimensions that is best correlated to the dry weight of the bole.

2. Once the allometric models are formulated, they will be used to expand the stem biomass to a per acre basis. This will be done on the basis of inserting the dimensional parameters of the stand into the equations. This technique will necessitate accurate forest sampling to ascertain the proper stand parameters. The biomass per acre will be tabulated for each of the six sampling regions, two for aspen and four for spruce.

3. When the total biomass figures are calculated the various regions may be compared and contrasted. The biomass per acre for Engelmann spruce can be compared between the two study locations of Wolf Creek Pass and Missionary Ridge. The biomass can also be

contrasted between the different elevations of the sampling plots for both species. Since both species are found at the 10,000 foot elevation on Missionary Ridge, the biomass can be compared between the two species at the same site.

4. The net primary production can be computed by integrating biomass over time at each plot. The average annual production can therefore be compared in the same combinations as the biomass per acre.

CHAPTER II

REVIEW OF LITERATURE

Methods of biomass estimation

The study of biomass is a complicated process in any type of vegetation but especially so in an ecosystem as complex as a forest. In recent years there have been several sampling procedures devised to facilitate this process. There are generally two avenues of approach to this problem. The first involves the estimation of plant biomass by non-destructive means. Leith (1965) listed many ways this can be accomplished such as the planimetric method, measurement of litter production, and plant sociology. Most of these indirect methods require considerable mensurational apparatus as well as an extensive expertise on the part of the observer. Another technique used by some investigators involves the procedure of measuring the gas exchange between a plant and its microenvironment. Woodwell and Botkin (1970) discussed this method in length but concluded that gas exchange techniques are adjunct to, but not yet a replacement for harvest techniques.

The second generally recognized procedure for computing forest biomass is the destructive sample. Satoo (1970) stated that estimation of biomass by the harvest method is the basic procedure in production studies. The most obvious method by which to sample forest biomass involves the harvest of all the vegetation present on the study area. These plants are then separated into their component parts, dried and weighed. This method is, of course, a very accurate means to obtain plant biomass, but is limited to small plots and species. Kira and Shidei (1967) proposed that direct measurement or weighing of forest biomass from over a reasonably wide area is quite unrealistic and impractical. The sheer physical dimensions of a forest stand make the actual weighing of the specimens undesirable. According to Satoo (1970) clear-cutting and measuring all the trees in a reasonably large area of forest is laborious and is neither practical nor permitted under most circumstances.

With the exclusion of actual weighing of all the trees, the obvious alternative is to sample the forest population. This sample is usually a plot of various dimensions that is typical of the stand being considered. The vegetation on this plot is then harvested and weighed. This method has the same shortcomings of the previous one as the large amount of material is very difficult to handle. Woodwell and Bourdeau (1965) considered the harvest of plots representative of the vegetation the most straight forward and accurate method of productivity measurement.

An alternative to the plot sampling method is the selection of a number of individual trees that cover the range of sizes present in the study area. Usually sample trees are selected on the basis of their respective diameters. Ovington and Pearsall (1956) related that in forests where the use of harvested plots is impractical, individual plants of various size classes found in the vegetation can be harvested. As with any statistically valid sampling process, the choice of individuals should reflect the characteristics of the population. Even in monoculture stands trees vary in size and proportions so that care in selection of sample trees is important (Ovington et al., 1967).

Whether the sample plot or the sample tree method is chosen, the determination of tree biomass is accomplished by one of two ways. The most obvious is to physically fell the tree, cut the trunk into sections and weigh them. This procedure is the most accurate but has several drawbacks. For one thing the sections, of large trees especially, are likely to be bulky and cumbersome to manipulate. This method would necessitate setting up a scale at the sampling location since the heavy sections could not be transported far. The scale would of necessity be large and therefore the accuracy of the weights could not be very precise. Ovington, Forrest and Armstrong (1967) concluded that because trees are so large, weight determinations are laborious.

In the past few years another method has gained considerable popularity for determining stem dry weight. Stem volumes of the sample trees can be converted to dry weight by including the wood property of specific gravity or wood density in the calculation. According to Zobel, Roberds and Ralston (1969) specific gravity can be expressed as dry weight by multiplying by 62.43, which converts grams per cubic centimeter to pounds per cubic foot. Tree dry weights are then calculated by multiplying this factor by stem volume obtained by standard forestry mensurational procedures (Ovington, 1962; Will, 1964; Duvigneaud and Denaeyer-DeSmet, 1967). This method eliminates the handling of bulky stem samples because only small samples for specific gravity are needed after the necessary stem volume measurements are taken.

Specific gravity variation

The specific gravity of the bole of forest trees varies considerably, both between species and between individuals. Hardwoods as a general rule have higher specific gravity values than do softwoods, although there is a considerable range in both. Variation also occurs with vertical and horizontal position in the bole. In coniferous stems the highest values are found in the outer portions of the lower trunk. A decrease then occurs from the bark inward and from the base upward (Wangaard and Zumwalt, 1949; and Cockrell, 1943).

The general pattern of variation in hardwood stems is approximately the reverse of conifers. The highest values occur in a roughly conical region at the central base. In the vertical direction, from the base upward, the specific gravity first tends to decrease and then increase (Panshin, DeZeeuw and Brown, 1964). However, these are just general trends and several variations and exceptions can be found.

Specific gravity has also been found to vary with environmental and stand properties. According to Paul (1930) environmental conditions at various periods in the development of the tree are the controlling factors in determining the quality of the wood. He especially emphasized the importance of density of stocking and stressed that with medium growth, but not crowded stands, wood of consistently higher quality is produced. Hale and Prince (1940) stated that while broad range climatic conditions over large areas may have a general effect on specific gravity, local variations overshadow the general trends. Therefore, while there is a variation over the geographic range of a species, the inherent variability in the local population is also noticeable. The genetic composition of a species is also known to have a profound effect on specific gravity through growth rate and dimensional properties. Although age has been shown to have an important effect on the density values in trees, the literature varies on the extent of the relationship (Western Wood Density Survey, 1965; Yandle, 1959).

Concerning quaking aspen the characteristic clonal nature of the species was found to have a definite effect. Brown and Valentine

(1963) proposed that natural variation in the specific gravity in Populus tremuloides clones can be attributed to the effect of two factors, genotype and environment. Variation among trees in a clone is entirely due to environmental factors, while differences between clones are caused by both the genotype and the environment.

Biujtenen, Einspahr, and Joranson (1959) found that good growth is associated with somewhat increased specific gravity and that crown class plays an important role in this relationship. According to Kennedy (1968) the most critical wood quality consideration is the effect of rapid growth on density. He cites several authors and concludes that the influence of growth rate in Populus is variable. Valentine (1962) found a positive correlation between specific gravity and mean ring width. Wilde and Paul (1959) studied the effect of soil characteristics on specific gravity. They found that specific gravity failed to show a definite correlation with the composition of soil in mature stands.

Concerning Engelmann spruce a comprehensive study was done by Forrer (1969) on the specific gravity of this species in Colorado and Wyoming. He found that specific gravity varies with vertical height in the trunk. From breast height to 25 feet up the bole there was a marked decrease, but with additional height the value steadily increases for the next 40 feet. Above the 75 foot height the specific gravity tends to decrease once again. Specific gravity was found to decrease with elevation due to the change in climatic variables. The wood density has been found to increase with latitude across the range of the species. Forrer (1969) found an average specific gravity value of 0.334 for the species in Colorado and Wyoming, while Kennedy (1965) found that Engelmann spruce in Canada had a higher value, 0.380.

Specific gravity was also found to vary with other factors in this species. A significant difference was found between sample areas in different National Forests. Site factors also accounted for considerable variation, probably due to the effect of increased growth rate. Specific gravity differences were also detected between dominant and codominant trees where the codominants had significantly higher values because of decreased growth rates (Forrer, 1969).

Stem analysis

Stem analysis is a standard forestry procedure used to determine the past growth of trees. Avery (1967) stated that the most accurate method of gauging accumulated tree growth is through stem analysis. Bruce (1924) reported that the technique was developed in Europe in classic German forestry. The procedure has since been revised and improved by several investigators in the United States. Dwight (1917) related several general improvements of technique that save considerable time in analysis and computation. The advent of calculators and analog computers has reduced the time and effort involved. Pegg (1919) discussed the use of calculators and slide rules in stem analysis calculations. Bruce (1924) related a new technique based on anamorphosis, which is a graphic process converting a series of harmonized curves into a series of straight lines. Williams (1902) discussed the difficulties and errors found in stem analyses, both in the field and in the laboratory. Bentley (1914) gave new methods for recording and tabulating data and presented other improvements over the old system.

One of the best explanations of the technique of stem analysis can be found in Meyer (1953). This technique was used in the present study. Graphs, tables and explanatory text as well as examples make this reference of great practical interest. The precision of the stem analysis is extremely important as the height, diameter, and resultant volumes of the past growth of the tree are a major component of this study. Zobel et al. (1969) stated that one of the weakest links in a study such as this is the inaccurate determination of volume, since any errors in volume will cause large differences in dry weight.

The stem analysis of Engelmann spruce and other species is relatively straight forward because the tree rings are sufficiently distinct. However, in the case of quaking aspen and other diffuse-porous hardwoods, the annual rings are very light and indistinct and are therefore extremely difficult to read. Maini (1967) and Maini and Cayford (1968) presented a good discussion on the growth ring analysis of quaking aspen and its difficulties. Rose (1957) related a technique for differentiating annual rings in diffuse-porous woods. The cores are made translucent by replacing air in the wood with light oil. The samples are then measured under a low-power microscope using transmitted light.

Maini and Coupland (1964) stated that quaking aspen wood is difficult to read due not only to the character of the wood, but also to the presence of false rings and stain due to fungal infection. False rings are found quite frequently in this species and are a definite hindrance in stem analysis. Glock (1937) found that false rings are associated with intervals when growth in interrupted and are most commonly found near forest boundaries. Kirby (1953) discussed the accuracy of field counts of Populus and found that 87 per cent of the counts made in the field were too low. He attributes this to the indistinct demarcation between springwood and summerwood and the presence of decay.

Allometry

The well known principle of allometry formulates the relationship between the amounts of two different parts of an organism. According to the equation the relative rates of growth between two different parts are proportional (Ogawa et al., 1965). Whittaker and Woodwell (1968) stated that study of allometric relationships for individuals of all species show trends in the dimensional relations of plant parts which change gradually with plant size from small shrubs to forest trees.

There are several advantages to the allometric method. The independent variables in the equations are standard forestry measurements. Since many stands have already been measured by these standards, the equations could be applied directly. Another advantage is that an allometric relationship is not necessarily specific to a single tree species, but may be applicable to several species living in the same community and having similar life form. Kira and Shidei (1967) found that the relationship between trunk weight and DBH multiplied by height applied equally well to a tropical rain forest in Thailand and an evergreen broadleaf forest of southern Japan. The allometric relationship was exactly the same in spite of wide variation of climate and great geographical distance.

The precision of these allometric models has been proven in several studies. The correlation coefficients for the method are quite impressive. In a study by Whittaker and Woodwell (1968) a large share of the coefficients were above 0.90 and some even above 0.99. Woodwell and Bourdeau (1968) also found very high correlations between stem biomass and the DBH and height of 3 species of oak and one of pine; the correlation coefficient in this study was 0.97. Ovington _et al_. (1967) studied allometric relationships with

Pinus radiata and found high correlations between dry weight and the dimensions of the bole. This study produced a correlation coefficient of 0.94 between biomass and bole cross-sectional area. These high correlations indicate the type of accuracy produced by allometric models.

There are several independent variables that have been correlated with stem biomass in allometric regressions. The age of the tree has been used in several studies to estimate biomass. Post (1970) found that the stem components of mountain maple and balsam fir were strongly correlated to the age of the tree. Ovington (1957) proposed that there was a statistically valid relationship between age and bole weight when he was working with *Pinus sylvestris*.

Basal area of the bole has also been related to stem volume by several authors. Ovington *et al*. (1967) stated that high correlation between bole biomass and stem cross-sectional area at 130 cm. was observed. Tadaki *et al*. (1961) found a linear relationship between basal area and the bole biomass of *Betula platyphylla*. In a study of *Pinus radiata* in Australia an allometric equation containing basal area multiplied by height was found to have high correlation with bole dry weight (Forrest and Ovington, 1970).

One of the most commonly used independent variables in allometric equations is that of the diameter at breast height (DBH) of tree boles. Baskerville (1966) stated that tree biomass was correlated with stem diameter when he worked with balsam fir. According to Rutter (1955) the dry weight of Sitka spruce and Scotch pine was found to be more closely correlated with stem diameter than other parameters. When working with black spruce in Quebec Weetman and Harland (1964) found that ovendry weight of the boles was significantly related to diameter at breast height. Whittaker and Woodwell (1968) stated that DBH was the best independent variable used in allometric regressions when working with several species in the Brookhaven forest in New York.

Kira and Shidei (1967) also used bole DBH as their independent variable. They found that the allometric regression between trunk weight and DBH sometimes differed in stands of the same species according to the age and habitat. Their recommendation was to introduce tree height as the second dimension. This new combination made the allometric equation applicable to many species and stands throughout Japan. This two parameter system was also more accurate than the one with only DBH. Madgwick (1968) stated that the combination of diameter at breast height squared, multiplied by tree height (D^2H) was highly correlated to tree trunk dry weight in a Pinus virginiana stand. Tadaki, Hatiya and Tochiaki (1969) correlated the ovendry weight of tree boles with D^2H when working with Fagus crenata. This combination of D^2H has been in use for many decades in volume tables, and has been used in many other biomass studies in recent years (Woodwell and Bourdeau, 1965; Ogawa et al., 1967; Satoo, 1970).

Another tree bole dimension often used is the girth or circumference of the tree at breast height. Attiwill and Ovington (1968) found this parameter to be highly correlated with the dry weight of the tree bole and other tree components when he was working with Scotch pine. Bunce (1968) also used girth as the independent variable of the allometric equations of many species in a mixed deciduous forest.

These allometric models have been extremely useful for determining biomass of forest stands all over the world. There are several conditions that must be realized before these equations are accurate. As with all sampling procedures, sample size is extremely important to the precision of the allometric method. Bunce (1968) stated that it is important to obtain as wide a range of sizes as possible in order to avoid extrapolation of the regression. Baskerville (1965) found that for balsam fir, any short cut beyond sampling enough trees to approximate a stand table will lead to erroneous data. Ovington et al. (1967) found that sampling introduces errors into dry weight determinations if the distribution of the sample trees does not exactly reflect the average stand dimensions. Therefore the samples for the allometric equations must represent the range of DBH and height of the stand.

Besides sampling size, other procedures may result in error in this method. The use of an allometric equation derived from a different population is to be avoided. Whittaker and Woodwell (1968) stated that when regressions from one community are applied to another stand of different dimensions and growth rate, error results. Biomass estimates from regressions on stem diameter may be affected by wide errors when allometric models fitted to smaller trees are extrapolated and applied to larger trees. According to Ogawa _et al_. (1965) extrapolation of this type of allometric regression beyond the actually observed range of stem diameter is liable to result in a serious overestimation of stem weight. They found that this error can be negated by replacing DBH in the regression with D^2H. The linearity between stem dry weight and D^2H was found to be valid over a greater range of tree sizes and more accurate than the regression containing DBH only.

Total stand biomass

Once allometric regressions have been formulated for the range of sizes on the study sites, these equations may be used to estimate biomass per acre for an entire stand or even forest. Satoo (1967), working with _Pinus densiflora_, stated that biomass per unit area could be estimated with the allometric models and the frequency distribution of diameters of the stand. He multiplied the dry weight of the stem from the equations by the number of trees to yield stem biomass per area. Baskerville (1965) found that the most precise method to estimate stand biomass was to solve the allometric regressions for each tree and convert the total for all trees to a per unit area basis. According to Madgwick (1968) the regression equations for *Pinus virginiana* were combined with complete stand tallies to estimate stand bole weight. Bunce (1968) also stressed the application of this procedure. He stated that if trees are sampled from representative woodlands, the allometric models will be constructed with enough site variation to provide reasonable estimates for trees in similar adjacent areas. Forrest and Ovington (1970) stated that the weight of all stems were calculated for each plot using the appropriate regression equation obtained from the sample trees, and the known linear dimensions of all trees. This procedure has been well established by other authors (Post, 1970; Tadaki *et al.*, 1961), and has proved to be consistently valid.

Variation of biomass

The stem biomass may show considerable variability, dependent on various factors of the tree or its environment. The age of the specimen is a major influence on its biomass. Ovington and Pearsall (1956) stated that from detailed studies on pine and birch stands, it is evident that dry matter production varies considerably with age. They concluded that the maximum increase in dry weight occurs when full leaf cover of the crown is reached. Ovington (1962) found that in Pinus sylvestris the mean annual productivity of the stand increases with age until about 35 years, after which productivity decreases slightly. Satoo (1970) also found that stand biomass is a function of age, because the stem biomass is accumulated year by year. Zobel et al. (1969) concluded that the age of the stand has the most direct effect of wood characteristics and thus stem biomass.

The density of a forest stand may also affect the biomass of the individual stems. Zobel et al. (1969) stated that it is obvious that differences in stand density will affect the dry weight of the stems per acre. However, Baskerville (1965a) found that stand density had no significant effect on the allometric relationships. The same author in two later articles (Baskerville, 1965b; 1966) changed his conclusion and stated that dry weight increases linearly with increasing density in stands of balsam fir, birch and spruce. Tadaki et al. (1961) agreed with the conclusion above and also found that weight of stems tends to increase with higher stand density.

The elevation of the study site could also effect the stand biomass. Whittaker et al. (1968), while studying an elevational gradient in Arizona, found that plant biomass decreases with a decrease in elevation. Satoo (1970) found the reverse relationship in his studies in the deciduous forests of Japan. He concluded that biomass decreased with increasing altitude. Whittaker (1966) agreed that biomass decreases from low to high elevations, but this relationship is complicated by other factors. This last statement would seem to explain the differences of opinion.

The site quality could explain some of the variation in biomass between stands. Zobel et al. (1969) stated that site quality may have a definite effect on the dry weight of wood per acre. Soil moisture especially may affect stand biomass as it is usually the most limiting factor at a site. Whittaker (1966) discovered that biomass tends to decrease from mesic to xeric sites at any elevation. Ogawa et al. (1965) supported the above conclusion by stating that plant biomass of a forest increases with increasing moisture in the environment.

The extent of leaf persistence of forest species also introduces variability into biomass studies. Kira and Shidei (1967) found that evergreen forests, whether coniferous or broadleaved, apparently are more productive than deciduous forests. Madgwick (1968) reviewed several author's papers and concluded that evergreen forests are the more efficient producers of biomass. Ovington and Pearsall (1956) came to the same conclusion: conifers have a significantly greater annual production than broad-leaved species. They attributed this difference in production to the ability of conifers to photosynthesize during suitable periods in the winter months. In contrast, deciduous species whose leaves persist for only part of the year, must divert some annual production toward the formation of a new leaf crop.

Several other factors have also been found to affect the biomass of forest stands. The geographic region may affect the stemwood output because of the climatic differences (Becking, 1962). The difference in stand origin may also explain some of the variation in tree biomass. For example, Post (1970), while comparing the dry matter production of maple and fir, found the basal sprouting habit of maple gave this species an initial biomass advantage over the seedlings of the fir. Attiwill and Ovington (1968) compared the dry weight estimations of fir with pine stands and concluded that the fir stand had higher values due to the fact that balsam fir is more shade tolerant than the pine. It is obvious from the literature that environmental and other factors definitely introduce considerable variation into biomass studies.

CHAPTER III

COLLECTION OF DATA

Selection of sample plots

The general research area for this project was determined by the geographical limits of the San Juan Ecology Project. The sections in which the many facets of study were conducted had already been delineated. These areas were chosen to best represent the parameters desirable to achieve the objectives of the project. These areas were visited prior to any actual field work to establish the exact locations of the sampling plots.

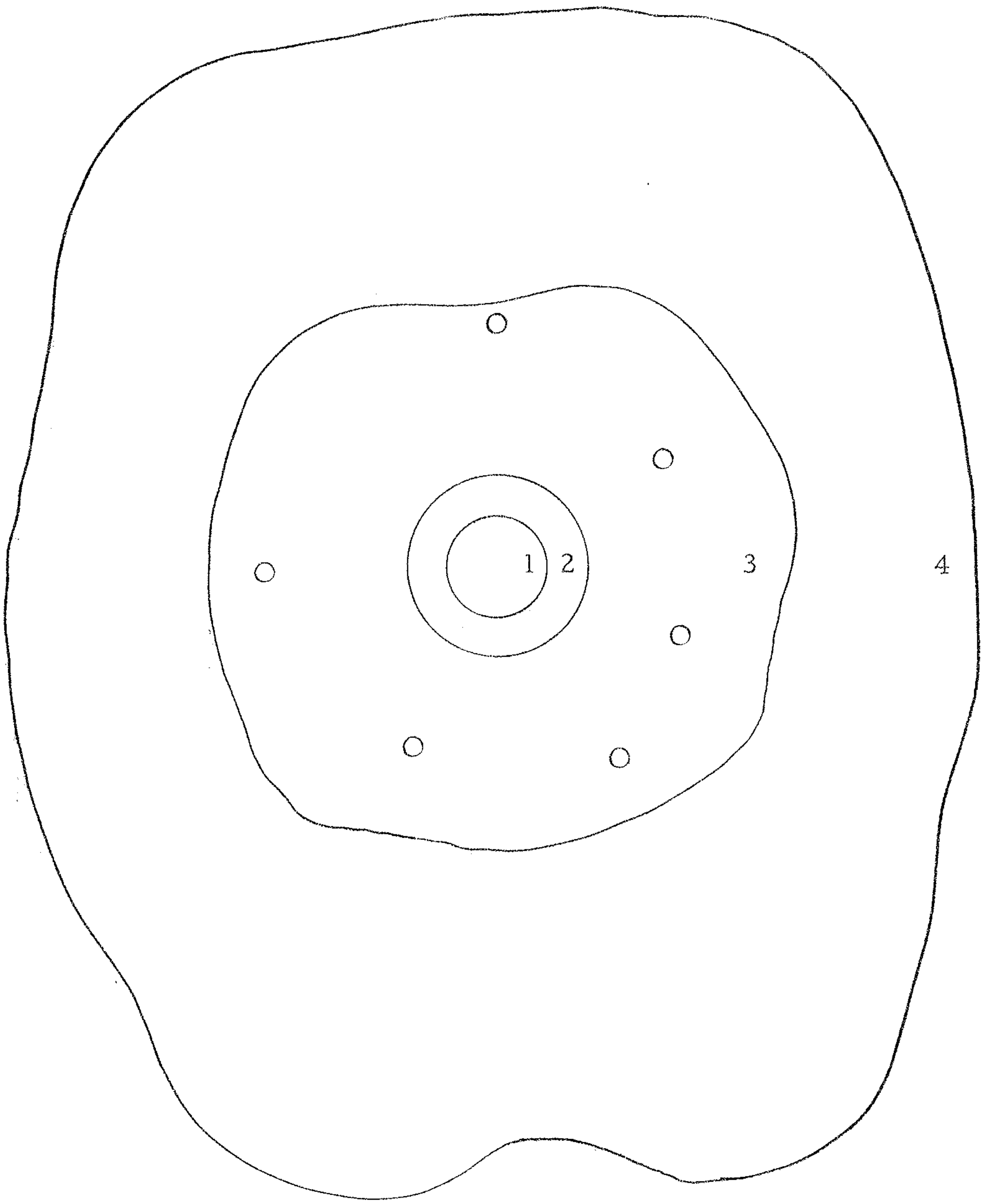
The sampling locations were divided between two distinct regions of the San Juan National Forest: Missionary Ridge and Wolf Creek Pass. These sampling sites were established at elevational increments of 1,000 feet to sample this variation.

Several criteria were considered during plot location. First, the stands being considered were to be representative of the forest types in the area. This prerequisite is basic to any type of research from which inferences about a large population are to be made. One of the factors that was investigated was the stand history. The history of environmental influences such as fire may drastically influence stand parameters. Species composition and stocking levels, including size and age classes of the stand, were considered.

Another consideration that was included in the location of plots was ease of accessibility. Destructive sampling requires a number of large, bulky instruments and considerable equipment. Therefore the plots had to be located within a reasonable distance from a road. Once the destructive sampling processes had begun there was the problem of heavy and bulky samples. Thus, some type of transport vehicle must be available due to the large volume and weight involved.

The type of plot established at the sampling locations is described by Newbould (1967). This is the standard plot used in the International Biological Program (IBP) for analysis of forest ecosystems. The study area is composed of four concentric delineations as shown in Figure 1. The interior circle of this area is known as the sample area. This area is roughly centered around the plot center and contains the weather instruments and other environmental monitoring equipment. The only sampling done here was nondestructive in nature to avoid affecting the other studies such as phenology and water stress.

The sample area is surrounded by a buffer area. This is a band at least two tree heights in width to protect the sample area. This area was not subjected to any type of disturbance so as to provide an effective insulation between the portions of the main plot.



1 = sample area
2 = buffer area
○ = destructive sample trees

3 = measurement area
4 = study area

Figure 1. Newbould's Sample Plot

The third concentric area is the measurement area and was devoted to the destructive sample. This is where the felling of the sample trees took place and the division of these samples into the components. To minimize disturbance and prevent adverse influences on the remainder of the studies, the felling took only a small percentage of the trees present.

The study area is located outside the measurement area and was used mainly as a large buffer zone for the interior study areas. It was in this area that the stand structure subplots were located.

Study locations

Five study locations, three on Missionary Ridge and two on Wolf Creek Pass were used.

Designation		Legal Description
Missionary Ridge	M11	NW$\frac{1}{4}$, SW$\frac{1}{4}$, S1, T37N, R8W, NMPM
	M10	NW$\frac{1}{4}$, SW$\frac{1}{4}$, S11, T37N, R8W, NMPM
	M9	SE$\frac{1}{4}$, NW$\frac{1}{4}$, S27, T37N, R8W, NMPM
Wolf Creek Pass	W11	SE$\frac{1}{4}$, SE$\frac{1}{4}$, S6, T37N, R2E, NWPM
	W10	NW$\frac{1}{4}$, SE$\frac{1}{4}$, S3, T37N, R1E, NWPM

At these five locations the sample plots shown in Figure 1 were established. One plot was located at each sampling location with the notable exception of the 10,000 foot elevation on Missionary Ridge. At this site two plots were established because of the presence of two distinct stands: one of quaking aspen and one of Engelmann spruce.

These two stands were found within a limited distance enabling comparisons to be made between the two.

Selection of individual sample trees

As in the choice of plot locations, it was essential that the individual sample trees possess the physical attributes that are characteristic of the population. The first attribute that was examined was the physical form of the tree. These samples had to be free from any unusual defect, such as butt rot, excessive lean or other characteristics that could influence the biomass. Thus, these trees were chosen to represent the normal physical form and dimensions of the population.

The dimensions of the samples such as DBH and height especially, had to be representative of the stands. These dimensions had to be considered because they were the probable independent variables in the allometric models. It was mandatory to obtain samples from over the entire range of sizes in the area in order to obtain accurate predictions for the allometric regressions.

The actual samples were chosen to adequately cover the entire range of diameters found in the stands. This technique was emphasized in the Review of Literature. Destructive samples were selected at regular intervals of bole diameter for both spruce and aspen at their respective sites. The sample trees for all sample plots are to be found in Appendix B. For illustration, the destructive samples for quaking aspen are listed in Table 1. The wide range of DBH can be seen in this table.

In the case of quaking aspen another factor had to be considered in the choice of destructive samples. The clonal nature of aspen stands introduced another facet into the sampling process. To overcome this characteristic the destructive samples were chosen over a wide area in the aspen stands to compensate for any clonal variation that might be present.

The nature of the populations in this study must be clarified at this point. The study locations were chosen expressly to be representative of the forest stands found in the area. Thus, the populations are of necessity, discrete. This stems from the objectives of the San Juan Ecology Project in general. The target area of the weather modification is a discrete unit, and it is in this area that the sampling was undertaken. Inferences from the related studies were to be limited to this population.

Destructive sampling

The actual felling of the sample trees was one of the most important aspects of the operation. To minimize destruction of the sampling area and reduce damage to the tree itself, accurate felling was a requisite. An opening in the stand was used whenever possible to allow suitable working space. Once the tree was on the ground, there were several dimensional measurements which were recorded

Table 1. Stem Diameters of Quaking Aspen Selected for Destructive Samples

DBH (in inches)
2.54
2.81
3.95
4.50
4.52
5.33
5.47
6.69
6.74
7.34
8.15
8.40
8.62
9.57
9.80
11.60
11.96
12.18
13.30
15.05

before the destructive process was undertaken. The standard forestry measurements of DBH and total height were taken. Each sample tree was also given a number to facilitate data analysis and prevent possible confusion.

It is obvious that several criteria of separation were necessary to delineate between the various components of the sample tree. The thickest shoot leading more or less to the top of the crown was treated as the main trunk. The borderline between trunk and root was the ground level. The branches were defined as any lateral appendages that originate with the bole.

Once the necessary data were recorded the major limbs were bucked to promote rapid measurements. The total height of the main trunk was taken and the bole divided into 3 foot sections, starting at the base. At each of these intervals a 1 to 2 inch disc was cut from the bole as demonstrated in Figure 2. These discs were labeled with the tree number, plot number and disc number. Figure 3 shows the labeling procedure and the disc sampling procedure. These samples were then placed in plastic bags to prevent the accidental loss of the bark. The total plastic bags for each tree were then placed in a burlap bag and each was properly labeled.

Stand parameter measurement

As was emphasized in the Review of Literature, it is extremely important to sample the entire range of dimensional characteristics

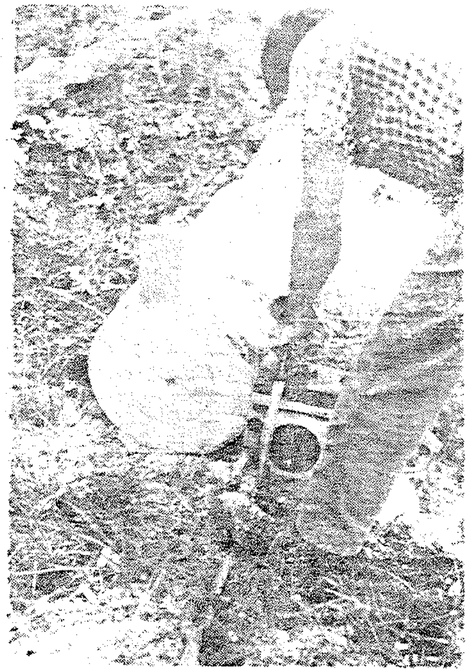


Figure 2. Sample Discs Being Cut From The Bole at 3 ft. Intervals

Figure 3. Labeling of Sample Discs as to Plot No., Tree No., and Vertical Position

of the stand. The stand dimensions of DBH and height are imperative because it is through these values that the stand biomass is to be estimated. These figures are used in the allometric regressions as the independent variable to yield the dependent variable of stem biomass.

The stands at each study location were sampled by means of circular plots. To avoid unnecessary confusion, these will be referred to as subplots. Two subplots were established at each location, consisting of two concentric circles: a one-fifth acre plot for trees 4.0 inches DBH and larger, and a one-twentieth acre plot for trees from 1.0 to 3.9 inches. The smaller plot was utilized to accurately sample the sapling size trees which were too numerous to keep track of in the larger plot.

These two subplots were located in typical areas of the forest at the main sampling locations. The placement was purposely biased to the judgement of the investigators to represent the stand parameters in general. At the aspen locations the two subplots were placed in what was believed to be different clonal groups at a considerable physical distance from each other. The variation due to clonal groups was minimized by this procedure. Admittedly, every clone in the area was not sampled by this procedure but the object was to adequately describe the population at the main study plot.

At each of the subplots the forest was measured in terms required by the allometric process. Each tree, 1.0 inch DBH or larger, was labeled with a numbered metallic tag to assure that the tree could be located in later years or in case of lost data. Once this was accomplished the numbered trees were measured using standard forestry techniques. The species, DBH and total vertical height were recorded. The DBH was read with a metal diameter tape to the nearest 0.1 inch. The height was taken with a clinometer using standard trigonometric principles, accuracy to the nearest foot.

The data for each sampling location is listed in Appendix A by subplot. The figures are given in the form of a stand table, by means of DBH classes with number of trees per class on a per acre basis.

CHAPTER IV

ANALYSIS OF DATA

Stem analysis

The stem analysis was the first to be undertaken. The discs were placed in order of vertical position in the bole. The general procedure followed Meyer (1953). The diameter of each disc was taken with a diameter tape and recorded. This value was then divided by two to give an "average" radius of the section. This average radius was recorded and then marked off on the surface of the wooden disc. This mark is the line along which the growth measurements were taken. The bark thickness was measured along the line and recorded. The total age of the section was then taken, measuring from the cambium inward by decades. This age was then recorded along with the number of decadal increments. These increments were designated by pins placed along the average radius. This procedure is illustrated in Figure 4. The growth was then measured from the pith out to each marking pin. This measurement was recorded to the nearest 0.01 inch.

The above procedure was followed for all of the samples of Engelmann spruce, but difficulties were encountered when trying to measure the quaking aspen discs. As mentioned in the Review of

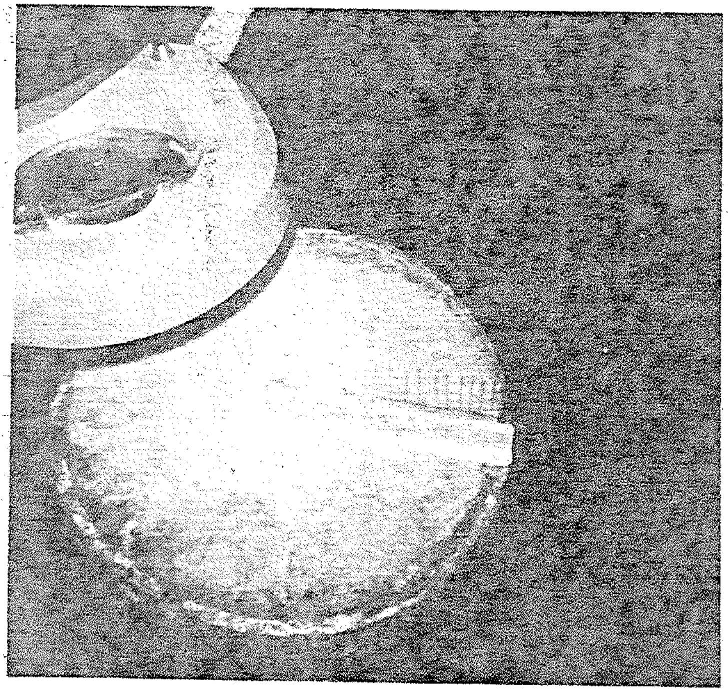


Figure 4. Stem Analysis Measurements Along Average Radius

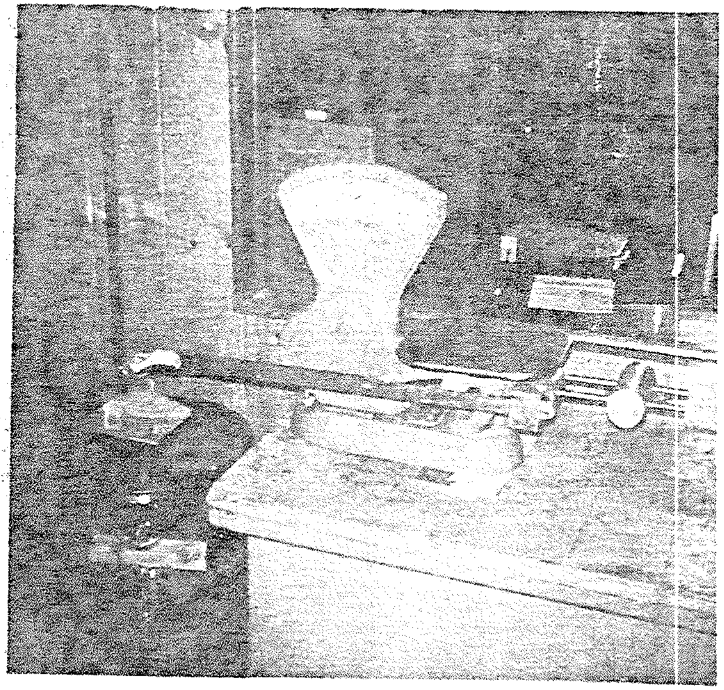


Figure 5. Specific Gravity Measurement Procedure Using Toledo Balance

Literature, the light nature of the wood made the aspen extremely hard to read. From personal communication with Ordell Steen of the Dept. of Botany and Plant Pathology at Colorado State University, a staining procedure was used to clarify the indistinct aspen rings. This stain was originally discussed by Patterson (1959); the saturation procedure by Newsome (1963). The process consists of three steps: a 1 percent phloroglucinol stain, concentrated hydrochloric acid, and a water bath. The size of the sample specimens had to be reduced to use this procedure, so a small section of wood was cut along the average radius. This section was then placed in a large test tube and submerged in the stain. The sample was kept submerged by a notched cork in the top of the tube. The test tube was then placed in a glass dessicator and a vacuum was applied to facilitate saturation. These samples were left under the vacuum for a period of approximately 15-20 minutes. They were then removed and taken from the stain solution and placed in the concentrated acid. The acid changed the samples to a purplish-red color, the annual rings remaining a darker shade. The samples were left in the acid for only a few minutes and then removed to the water bath to rinse off excess acid.

The stain completed, the samples were examined under a low-power dissecting scope at 10X. The same marking procedures were utilized as with the spruce. Pins were placed at each ten year interval, these decadal values measured for the total age of the tree. The presence of wood stain and some decay made the readings in the core of certain discs virtually impossible and these values were omitted.

Specific gravity determination

The specimens used for the stem analyses were the same samples used for specific gravity calculations with some modifications. The specimens for these readings were cut from the sample discs along the average radius in the shape of a wedge. Bark was stripped from this wedge and any shavings were trimmed to give a smooth surface. Large knots or other defects that could introduce error into the readings were avoided.

The method of determining specific gravity in this study was that of the Forest Products Laboratory as described by Heinrichs (1954). This technique is based on ovendry weight and green volume, and is especially useful because irregularly shaped specimens, as in this study, may be used effectively. The technique uses a Toledo pan-balance system with a graduated scale and a central zero point as shown in Figure 5. To each side of this zero point are 25 gram scales, allowing a plus or minus 25 grams to be read directly. This procedure is presented in detail by Collett (1963).

The working formula for specific gravity is as follows:

$$\text{specific gravity} = \frac{\text{ovendry weight}}{\text{saturated weight} \mp \text{float or sink weight}}$$

The plus or minus sign in the denominator depends upon whether the sample has a tendency to sink or float during the displacement measurement. Specific gravity is by definition the ratio of the weight of a given volume of a substance to that of an equal volume of water. Thus if the sample sinks, it is heavier than an equal volume of water and this weight must be subtracted from the saturated weight. Conversely, if the sample tends to float, the reading is added to the saturated weight. In either case the denominator is the weight of a volume of water equal to the volume of the sample.

In most specific gravity measurements, the procedure is to first take the saturated weight, then the displacement weight, and lastly the ovendry weight. As all samples had been stored for a considerable length of time, they were fairly dry. Due to this low moisture content, the ovendry weight was taken first. This procedural change has been justified by Collett (1963), as he found the differences using this change were non-significant. Thus the samples were ovendried first at 105 degrees Celsius for several days. The samples were weighed on a Mettler scale to obtain the ovendry weight; the samples were then placed in perforated bags. These bags were used to hold the samples together under water to bring them back to the condition of green volume. These bags were placed in a large chamber constructed especially for this purpose. They were left submerged in the water, and placed first under a vacuum and then under a positive pressure for several hours to insure complete saturation of between 75 and 100 per cent moisture content. This was done to make sure that the green volume condition had been completely restored. The samples were then removed and the saturated weight taken on the same Mettler scale. This value was recorded and the "green" sample was used for the displacement procedure. This was done on the Toledo balance apparatus as shown in Figure 5. The sink or float weight was thus determined and recorded for each sample.

The specific gravity was then calculated using the formula given earlier. The sources of error in this procedure are related to the surface area of the wedge-shaped samples. When determining the saturated weight, the presence of any excess moisture on the sample surface could affect this value. Because of this possibility each sample was wiped off before this figure was recorded. The displacement procedure could also introduce error if the surface of the sample had any adhered bubbles when submerged. To avoid this, each sample was gently agitated after submersion. The presence of decay in the sample could also affect the specific gravity so all visible signs of this were removed.

Computer analysis

Because of the large sample size and great number of readings per sample, computer analysis was used to facilitate calculations. During the stem analysis a large number of measurements were taken in reconstructing the past growth of the specimen. These values were recorded on data forms and then transferred to data cards for permanent storage. In like manner the specific gravity readings were stored on the data cards that corresponded to the proper tree disc.

Once this data was on the computer cards, a computer program was constructed to perform the desired calculations. A program designed by Pluth and Cameron (1971) was used for the basis of the model. They constructed a volumetric model for stem analysis calculations, using any combination of measurement intervals and form factors. This general program was modified to suit the species and measurement intervals used in this study. After the stem volumes were calculated for each sample tree, the volume was converted to dry weight. This conversion was achieved by considering the specific gravity values for the geometric solid in question, as explained in the Review of Literature.

The computer output of this program produced the stem volume and stem dry weight for each section of the bole. These section values were then accumulated to yield the total figures for each tree.

The weight and volume increment for each specimen was calculated for each decadal period of the tree's life. This program was also designed to compute the volume and dry weight for each year of the growth of the tree. This was achieved through interpolation between the decadal values produced by the main program.

The output also consisted of punching the anticipated linear regression variables on computer cards, in a format that was readily acceptable by the statistical program. The dependent variable or stem dry weight along with the independent variables of stem DBH, DBH^2, and D^2H were computed, because these were the variables most frequently found in the literature.

A computer program, STAT 38R, of the Biometrics Unit at Colorado State University was used for the linear regression calculations. This particular program is primarily used for multiple regression calculations and uses matrix analysis with the stepwise addition of variables. For the desired linear regressions this program was modified by deletion of all the variables except one in each subprogram. In this way the effect of each variable could be investigated independently and its relationship to stem dry weight analyzed.

Each of the three potential independent variables was investigated separately, both in natural form and in logarithmic transformations. These various values were then evaluated in conjunction with the dependent variable of stem weight. The best relationships were chosen on the basis of the highest correlation coefficients produced by the linear regression techniques. The prediction equation for each variable was also developed by this program, giving the regression coefficients and their corresponding standard errors. The analysis of variance tables giving the significance of the various regressions was also an output.

When the best independent variable and corresponding prediction equation was chosen for each species, this equation was then used to calculate the stem biomass on a per acre basis. This equation, when combined with the same independent variables of a measured area of the stand, produced the biomass values for the area. The diameters and total heights of the forest stands were tabulated and transferred to data cards. These values were then inserted in the proper equation and the resultant tree biomass estimated. These tree biomass figures were accumulated into total stem biomass. Then, by multiplying by the proper expansion factor for each plot, yielded total stem biomass per acre for each species.

CHAPTER V

RESULTS AND DISCUSSION

Specific gravity

Because the stem dry weight was to be determined through conversion of cubic volume, the specific gravity values were of definite importance. Due to the considerable variation found in specific gravity values, the sample size and the system of sampling had to be carefully executed. In a study by Forrer (1969) the density of Engelmann spruce was found to vary considerably with height above the ground. This relationship is depicted in Figure 6. Since this sample was taken from the San Juan National Forest, it was originally planned to use these values for converting stem volume to dry weight. However, when samples of wood from this study were measured for specific gravity it was discovered that they were significantly higher than those related by Forrer. The variation of specific gravity found from the samples of this study is shown in Figure 7. It is obvious in comparing Figure 6 with Figure 7 that although the basic trend in the two graphs is similar, the variability is much greater in the samples of this study. Therefore, samples from all trees at regular height intervals had to be taken to insure an accurate sample of this variation.

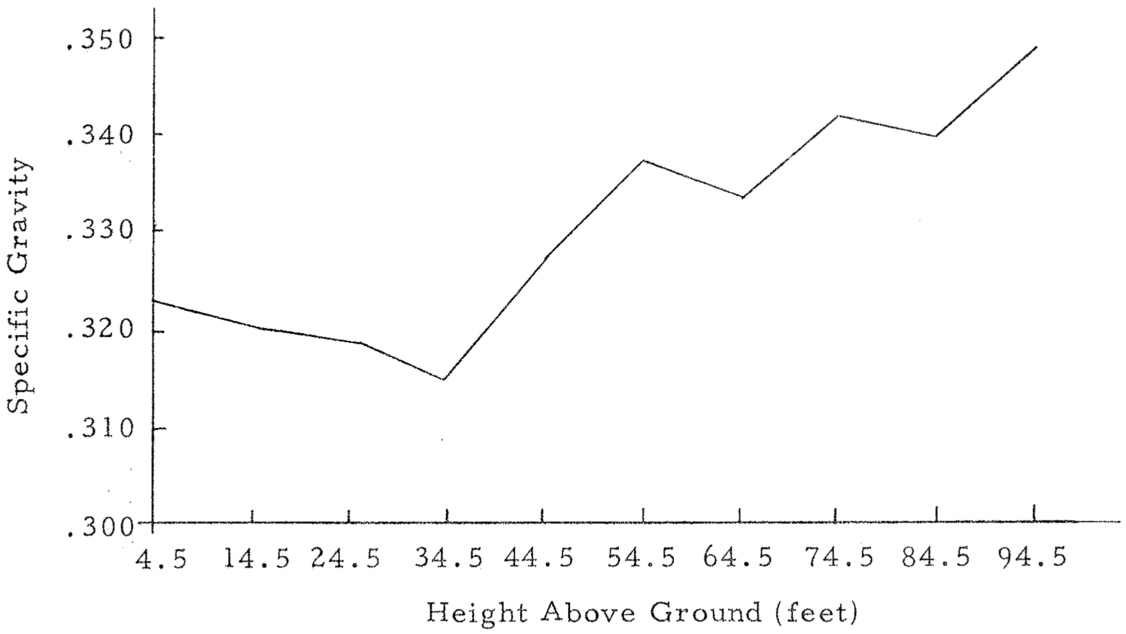


Figure 6. The Specific Gravity Variation of Spruce as Found by Forrer (1969)

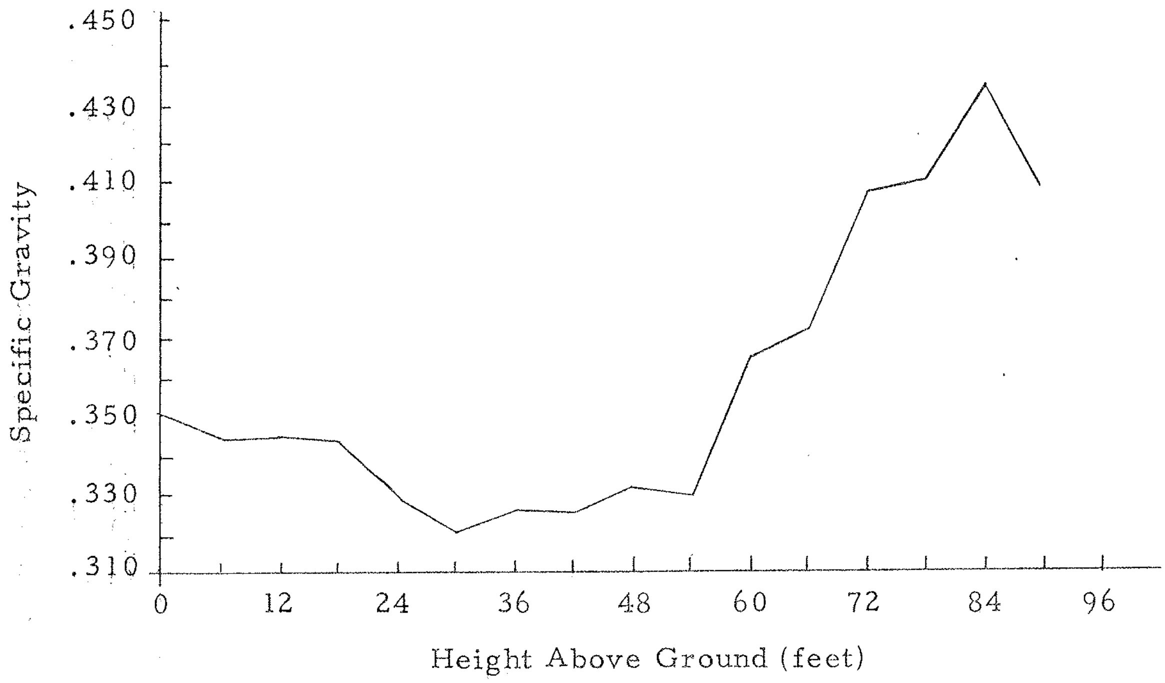


Figure 7. The Variation of Specific Gravity of Spruce With Vertical Height in This Study

It was anticipated that an average specific gravity value could be used to convert stem volume to stem dry weight. It is evident from Figure 7 that the great variation with height would introduce a large error if such an average value was to be used. As a result of this variation, specific gravity values had to be taken on all sample trees at regular intervals along the bole. Specific gravity was taken at intervals of 6 feet to insure the accurate conversion of cubic volume to dry weight.

Figure 8 depicts the variation in specific gravity with vertical height in quaking aspen. Again the range of density observed in this graph would prohibit the use of an average wood density value. This added analysis would definitely increase the accuracy of the stem biomass results and the precision of the prediction models. Brown and Valentine (1963) emphasized the variation to be found in the specific gravity values of this species. Kennedy (1968) listed a range of quaking aspen density values of 0.325 to 0.421, very similar to the range found in this study. Since quaking aspen is well known for the variation in wood properties, the precise measurement of specific gravity in each sample tree is justified.

Stem analysis

This procedure was followed to yield the cubic stem volumes for the sample trees at present and in the past. As stem diameters are taken at regular intervals along the vertical plane of the tree, an

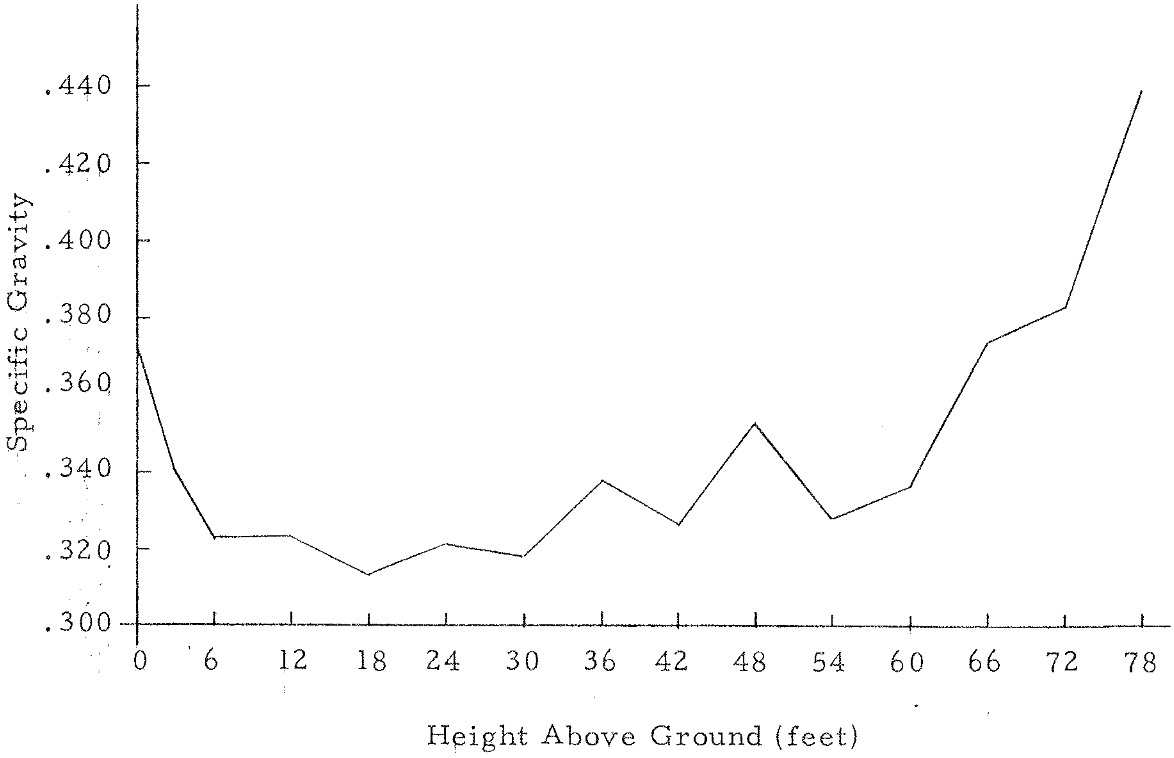


Figure 8. Aspen - Specific Gravity Variation With Height

accurate model of the tree bole can be reproduced. These measurements give a set of taper curves that give a much better estimate of stem volume than standard volume tables based on DBH and height.

These taper curves are depicted in Figure 9. The right half of the graph shows the vertical taper of a typical tree. The radii of the tree at each time period may be read on the abscissa, while the vertical height of the sample may be read from the ordinate. This graph gives an accurate representation of the shape of the tree on a longitudinal plane for the entire age of the specimen. The thin outer area of the taper curves represents the bark thickness, varying gradually with height.

The left half of Figure 9 is a typical height-age curve. Again the ordinate is tree height while the abscissa is tree age in years. This curve depicts the height of the sample during its life span. Thus both the essential dimensions of tree volume calculations are available for reference in one graph. In this way a rapid visual representation can be gained about the past growth of the tree in height, diameter and volume relationships. The past growth pattern is evident because the area between the taper curves represents the approximate volume produced during that ten year period in the tree's life. Thus the growth potential of the tree and its stand can be analyzed.

Another valuable facet of the stem analysis is the fact that the destructive sample can be augmented considerably. Radii

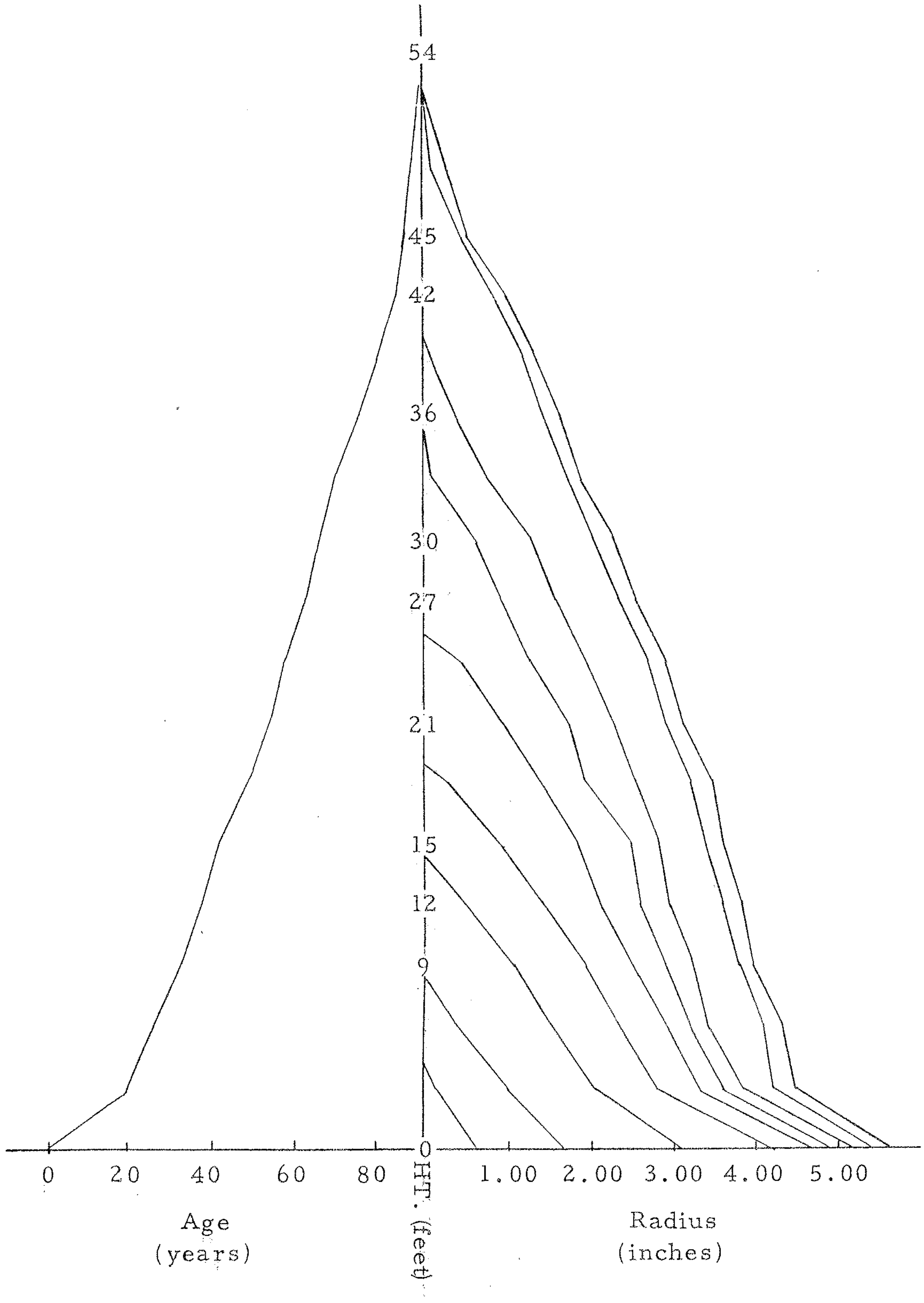


Figure 9. Stem Analysis

measurements at ten-year intervals throughout the life of the sample tree give an accurate diameter-inside-bark measurement of the tree at that time period. These time-based measurements are taken at each height interval along the bole. Again a set of taper curves can be developed for the tree during each decadal time period. In this way additional volume samples are obtained for each decade throughout the life span of the tree. Therefore instead of only one volume measurement per destructive sample tree, it is possible to produce as many as 15 or more volume measurements for old trees.

Allometric models

The use of allometric prediction models has been advocated by many authors in the literature. However, for the species involved in this study there has been little work done. As of this date an allometric model for stem biomass has not been formulated for Engelmann spruce. Concerning aspen, Bella (1970) has proposed a regression for all aerial components of quaking aspen in western Canada. He found very high correlation between stem dry weight and bole DBH squared, multiplied by height (D^2H).

The main objective of this study was to develop the allometric models for Engelmann spruce and quaking aspen in the San Juan National Forest. After the sampling and calculations for stem dry weight were completed, there still remained the question of which tree dimension or dimensions had the best correlation with stem biomass.

The allometric models investigated in this study are tabulated in Table 2. Three independent variables were correlated to stem biomass in standard forms and also when transformed into logarithmic forms. These relationships are visually presented in the scatter diagrams of aspen at Plot 1 in Figures 10 through 13. Figure 10 shows the dependent variable of stem dry weight plotted on the ordinate against the independent variable of stem DBH. The relationship is not linear but shows a curve similar to that of an exponential function.

Figure 11 depicts the change in the relationship when the logarithmic transformation has been applied. The linearity has increased considerably as indicated by the increase in the correlation coefficient from 0.902 to 0.965. Figure 12 shows an exponential transformation, DBH^2, and when compared to Figure 10, the increase in linearity is apparent. As mentioned in the Review of Literature, the addition of tree height as a transformation to simple DBH greatly adds to the precision of the model. This relationship is excellently demonstrated in Figure 13. The inclusion of tree height definitely improves the linear regression because the correlation coefficient increased from 0.902 for simple DBH to 0.998 for the latter transformation.

The combination of destructive samples for both sampling locations of quaking aspen gave a sample size of 20 trees. Through the

(INSIDE BARK)

Table 2. Allometric Models (D = DBH; H = Height; y = Stem biomass)

Sample	r	Standard Error (S_{b_1})	Prediction Equations
1. All Aspen N = 130			
a. $X_1 = \log D$	.974	.04394	$\log y_1 = .26701 + 2.15661 \log X_1$
b. $X_2 = \log D^2$	.975	.02190	$\log y_2 = .26625 + 1.07894 \log X_2$
c. $X_3 = \log D^2H$	.982	.01373	$\log y_3 = -.66958 + .81451 \log X_3$
d. $X_4 = D$	.908	1.76871	$y_4 = -106.81579 + 43.35438 X_4$
e. $X_5 = D^2$	.966	.08481	$y_5 = -16.65650 + 3.56282 X_5$
f. $X_6 = D^2H$	.992	.00059	$y_6 = 3.90698 + .05244 X_6$
2. All Spruce N = 325			
a. $X_1 = \log D$	.970	.02661	$\log y_1 = .36515 + 1.90345 X_1$
b. $X_2 = \log D^2$	.971	.01320	$\log y_2 = .36081 + .95489 X_2$
c. $X_3 = \log D^2H$	.984	.00708	$\log y_3 = -.32910 + .70943 X_3$
d. $X_4 = D$	.877	1.39615	$y_4 = -125.67436 + 45.75097 X_4$
e. $X_5 = D^2$	.969	.04980	$y_5 = -35.73318 + 3.52045 X_5$
f. $X_6 = D^2H$	.995	.00026	$y_6 = 8.38680 + .04557 X_6$
3. All - Trees N = 455			
a. $X_1 = \log D$	.969	.02326	$\log y_1 = .34960 + 1.95522 X_1$
b. $X_2 = \log D^2$	.970	.01155	$\log y_2 = .34590 + .98035 X_2$
c. $X_3 = \log D^2H$	.982	.00662	$\log y_3 = -.39458 + .72861 X_3$
d. $X_4 = D$	.883	1.13156	$y_4 = -120.74951 + 45.19461 X_4$
e. $X_5 = D^2$	.967	.04323	$y_5 = -29.47749 + 3.51268 X_5$
f. $X_6 = D^2H$	.993	.00027	$y_6 = 8.95108 + .04649 X_6$

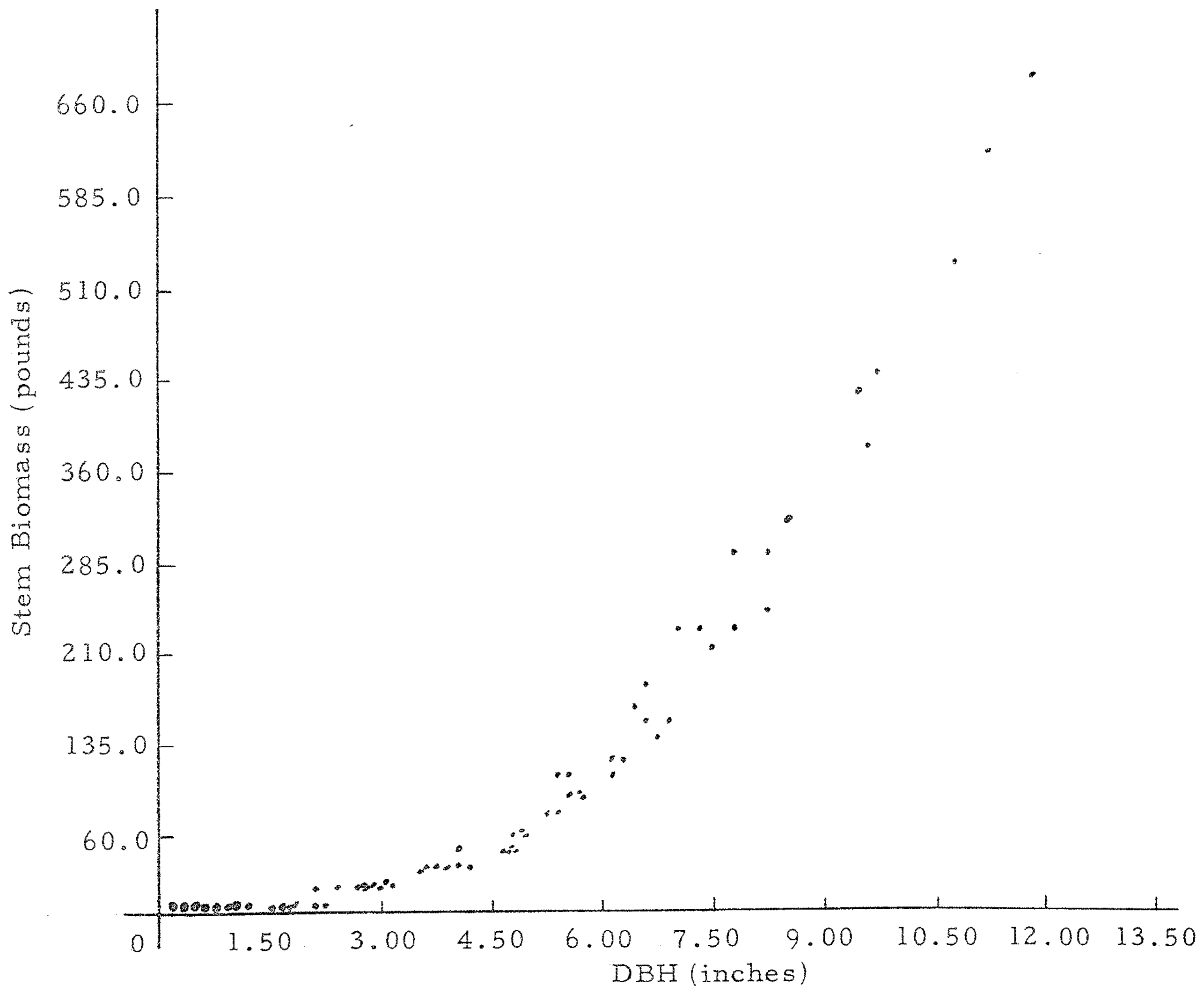


Figure 10. Scatter Diagram of Regression of Stem Dry Weight on DBH

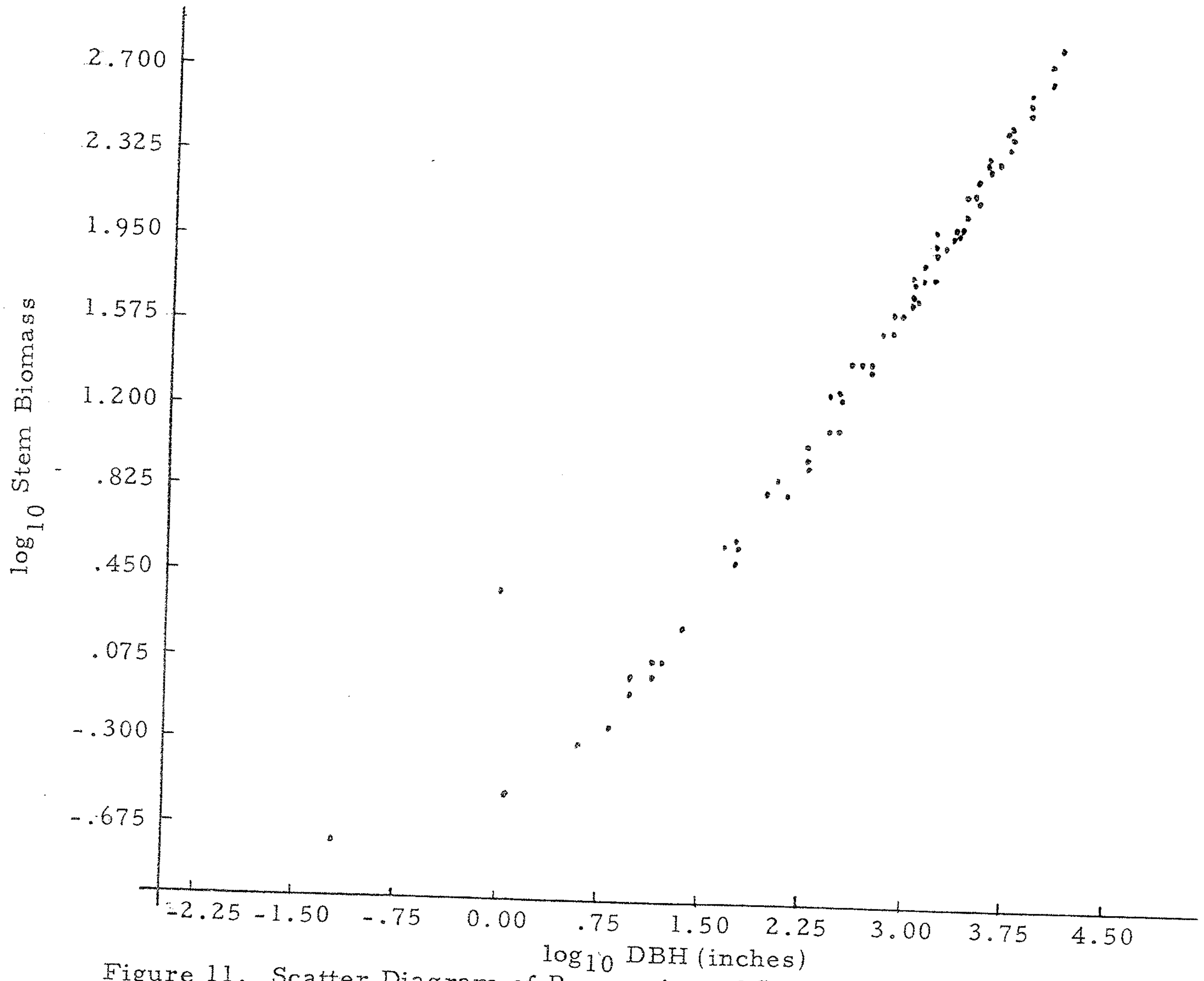


Figure 11. Scatter Diagram of Regression of Stem Dry Weight on Log DBH

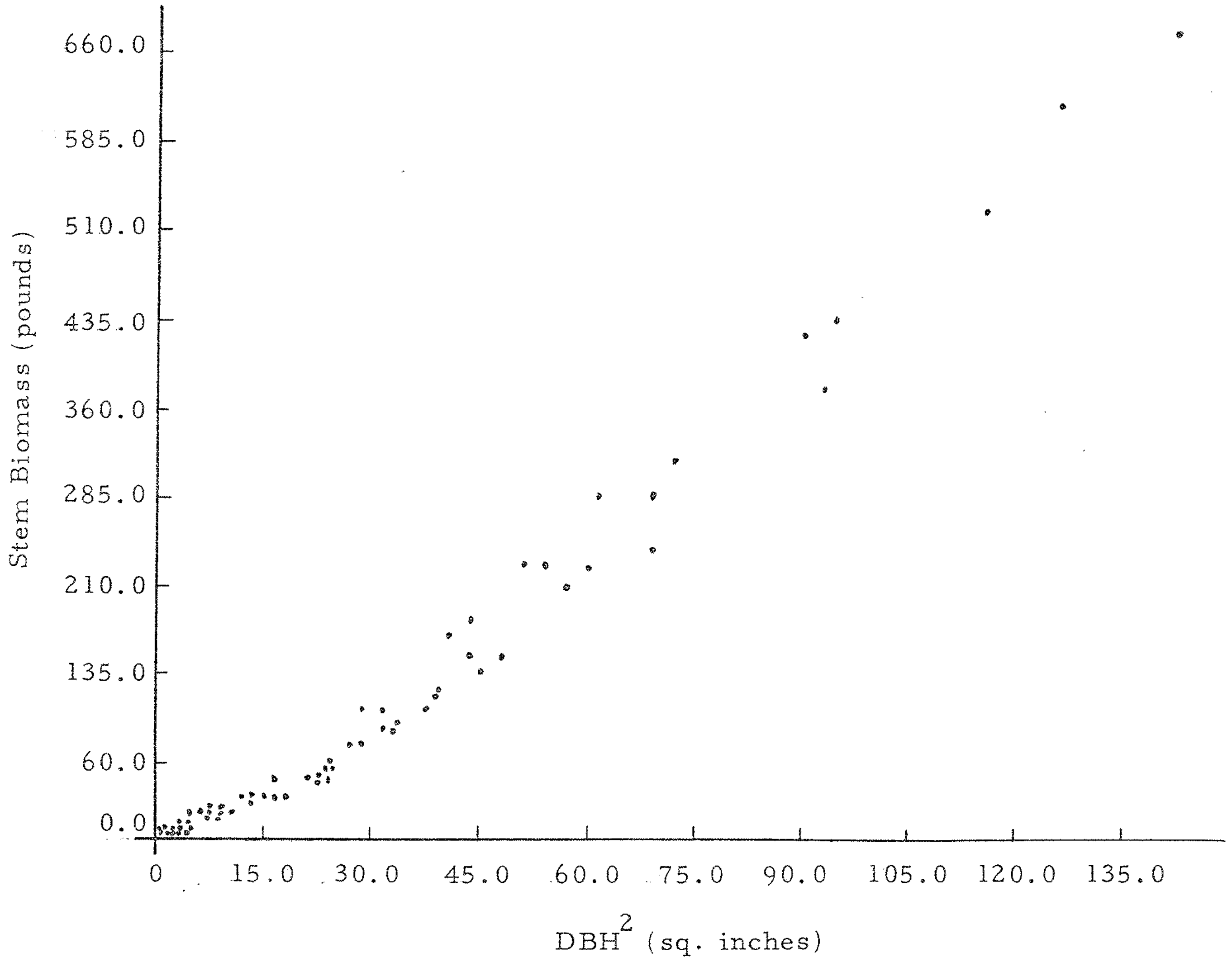


Figure 12. Scatter Diagram of Regression of Stem Dry Weight on D^2

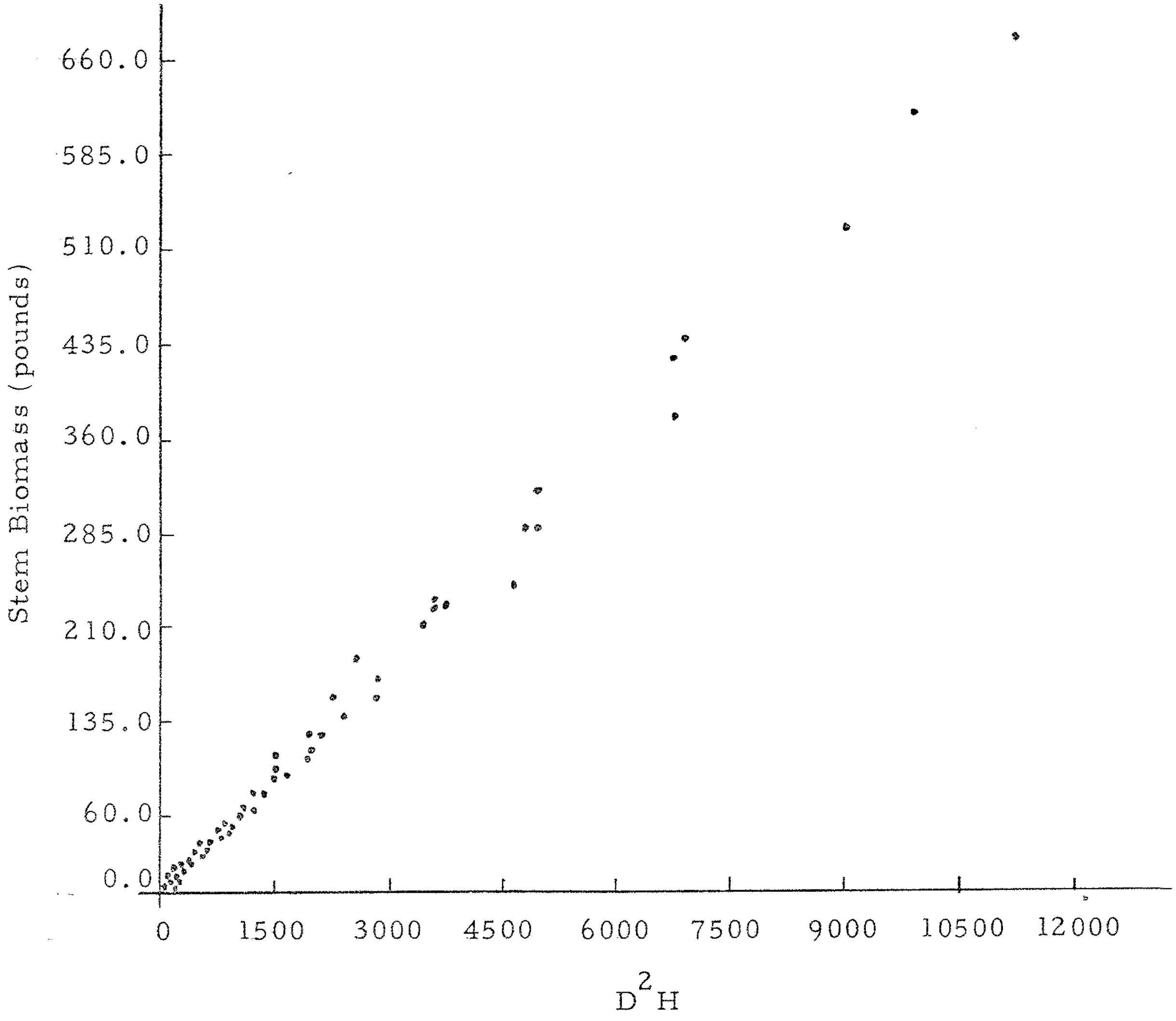


Figure 13. Scatter Diagram of the Regression of Stem Biomass on D^2H

techniques of stem analysis this sample was boosted to 130 trees, illustrating the large increase possible by this procedure. This process was undertaken with the knowledge that these added samples are not independent, but rather confounded as they are expansions of the same sample tree.

The linear regression equations for quaking aspen are given in Table 2. The best correlation obtained is that between D^2H and stem dry weight. This relationship had a correlation coefficient of 0.992. This value corresponds very closely to that obtained by Bella (1970), who also found a very high correlation ($r = 0.996$).

The allometric models for Engelmann spruce are also listed in Table 2, using the same six independent variables as for aspen. The correlation coefficients were also high for this species, ranging from 0.877 to 0.995. It is interesting to note that both the highest and lowest coefficients are found in the regressions of this species. Possibly this phenomenon could be explained by the fact that the widest variations in sampling locations are for this species. Plots vary from 10,000 to 11,000 feet in elevation at two sampling locations which are more than 60 miles apart. Obviously, this great difference in site would affect the stem form and growth properties and thus the allometric models. The sample size is also much larger than that of the aspen, so there is a greater range of tree dimensions represented. The various transformations have a greater effect in improving the linear relationships in this larger sample.

Another model that was considered in this study was between the same independent variables and stem biomass of all trees, irregardless of species. These allometric regressions, listed as All-Trees models, are also found in Table 2, along with their respective correlation coefficients and standard errors. These coefficients are found to be only slightly lower for the All-Trees regressions than those of the species when considered separately. This may infer that the allometric relationships are valid not only for within-species groups but also for between-species samples. It should be noted that the linear regression between D^2H and stem dry weight has one of the highest correlation coefficients listed: $r = 0.993$. This means that stem biomass could be estimated for either species using this model alone.

This all-species relationship has been found in other studies. Kira and Shidei (1967) found that an allometric function is not necessarily specific to a single tree species, but may be common to several species growing together in the same community or having similar life forms. This statement introduces an interesting facet to this study. Kira and Shidei list several allometric relationships between forests of similar form. In this study however, the linear regressions are equally valid for a conifer and a broad-leaved species. These two are quite distant in taxonomic relationships although they are found in similar habitats.

It should be mentioned that this relationship is not so surprising when the growth form of quaking aspen in the San Juan Mountains is considered. While quaking aspen often exhibits a typical hardwood deliquescent form in other parts of its range, the stem form found at the study areas is almost excurrent. There is one main stem for the majority of the vertical plane. This may explain the high correlation found between the two species, as the stem form is similar in both species.

There are numerous advantages to such an overall relationship. The stem biomass may be estimated for all trees in a given stand, regardless of species. The use of only one allometric model for a forest definitely reduces the calculations involved in computing stem dry weight for a mixed stand. When comparing the allometric equations between the All-Trees sample and those for the individual species, the loss in accuracy using the overall regression would be minimal indeed.

The overall allometric model becomes even more appealing when the large range of sampling areas is considered. This regression equation represents not only two vastly different species, but plots over a wide range of geographical and elevational distances. Therefore this allometric model is valid for Engelmann spruce and quaking aspen over the entire range and study area of the San Juan Ecology Project.

Application of the allometric models

The correlation coefficients are very high for all allometric models in Table 2 regardless of the independent variable being considered. The practical application of any of these equations could be easily justified, but certain models have definite advantages over others. Naturally the less complicated the equation, the simplier its use in actual practice. Therefore the equations containing the DBH variable alone would be the easiest to use.

The major advantage of the use of DBH or its transformations as the independent variable is that the stem biomass may be estimated with one measurement only. Admittedly the models using D^2H are the most highly correlated with stem dry weight, but these equations require the additional field measurement of tree height. While the measuring of tree diameters in the field is quick and accurate, the height of the tree presents certain problems. Tree height is usually estimated using trigonometric principles that require moving a given distance from the base of the sample tree. This alone is inconvenient and time consuming especially in stands that have a closed canopy, considerable understory, or are found on steep slopes. The precision of the various hypsometers is also limited. With ordinary field instruments the height of a tree can only be estimated within 2 or 3 feet at best even if all other conditions are optimal.

It can be seen that the inclusion of tree height in allometric models introduces certain problems when these equations are used in some stands. In this study the tree heights were obtained with a clinometer with little difficulty but under the conditions outlined in the previous paragraph, tree height may be impossible to obtain with reasonable accuracy.

The increased precision of the D^2H regressions makes the use of tree height indeed desirable. An alternative to the actual measurement of this dimension is to predict it from a regression of DBH versus tree height. It is important that a separate regression be computed for each site because slight differences in microclimate may change the site index of an area and thus its height-diameter relationship. Ogawa et al. (1965) stated that in a dense, closed forest in which height measurement is difficult, it is recommended to fell as many samples as possible to establish a reliable height-diameter curve. Use of this method may introduce some confounding as the height in the D^2H variable is dependent on the diameter component.

Stem biomass per acre

Once the appropriate linear regressions were established for the sample, the total stem biomass could be estimated. Through the subplots that sampled the parameters of the stands, total biomass per unit area was achieved.

The DBH dimension that was obtained in the stand sampling was diameter-outside-bark and had to be converted to diameter-inside-bark which corresponds to the data used to construct the models. This conversion was facilitated by construction of a linear regression between these two dimensions of the bole. This relationship is portrayed in Figure 14, which is the regression between the two variables. The precision of this conversion is verified by the high correlation coefficient ($r = 1.00$). Through the prediction equation gained by this relationship, the diameter-inside-bark may be obtained when the independent variable of diameter-outside-bark is supplied. The same relationship was computed for quaking aspen with a correlation coefficient of 0.99.

Stem biomass was calculated using four different allometric models from Table 2. The models, listed in Table 3, were chosen for their high correlation coefficients. The results of these expansions are given in the same table for each individual sampling location. The average stem biomass per acre for the locations is given below the values for the individual subplots. The plot numbers are given along the vertical axis.

Certain discrepancies can be observed between the values produced by the various allometric models as depicted in Figure 15, which contrasts the species models containing D^2 and those using D^2H. The biomass per acre is seen to be considerably less in the

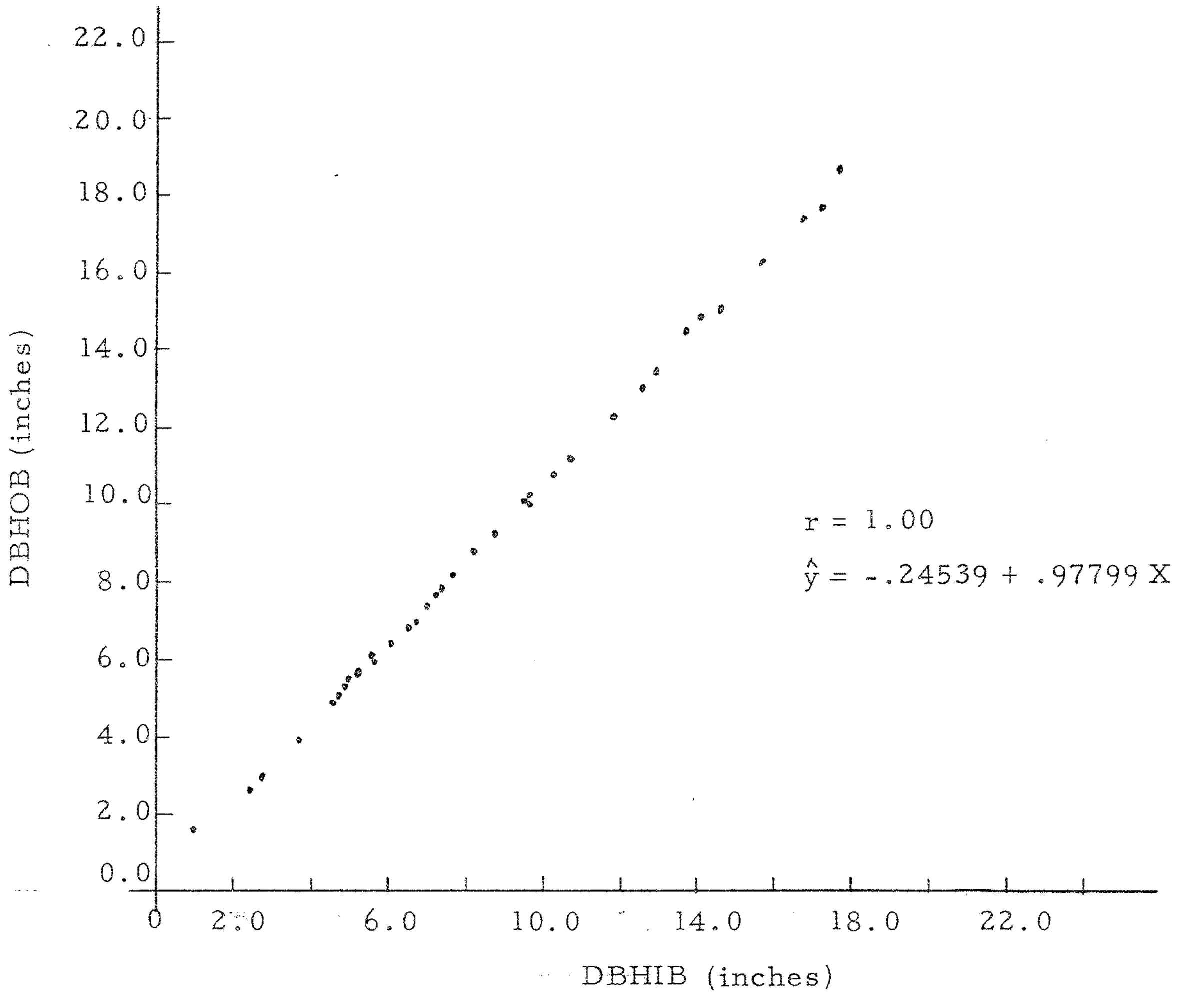


Figure 14. Regression of DBHOB on DBHIB

Table 3. Biomass Per Acre (tons) - using various independent variables and samples

Plot #	All - Trees D^2H	Species D^2H	All - Trees D^2	Species D^2
1 - 1	41.26	42.65	23.10	31.74
1 - 2	53.29	54.65	25.82	37.87
$\overline{X}_1$	47.28	48.65	24.46	34.81
2 - 1	40.53	42.51	36.37	43.34
2 - 2	29.04	30.97	29.19	33.42
$\overline{X}_2$	34.78	36.74	32.78	38.38
3 - 1	42.87	41.77	30.13	26.14
3 - 2	81.21	79.42	73.13	72.01
$\overline{X}_3$	62.04	60.64	51.63	49.07
4 - 1	57.58	56.39	56.62	55.85
4 - 2	55.65	54.50	55.58	54.90
$\overline{X}_4$	56.61	55.44	56.10	55.37
5 - 1	59.25	57.95	54.51	52.54
5 - 2	28.24	27.52	28.12	25.65
$\overline{X}_5$	43.74	42.73	41.32	39.09
6 - 1	54.97	53.81	51.55	50.57
6 - 2	64.24	62.87	49.54	48.04
$\overline{X}_6$	59.60	58.34	50.55	49.31

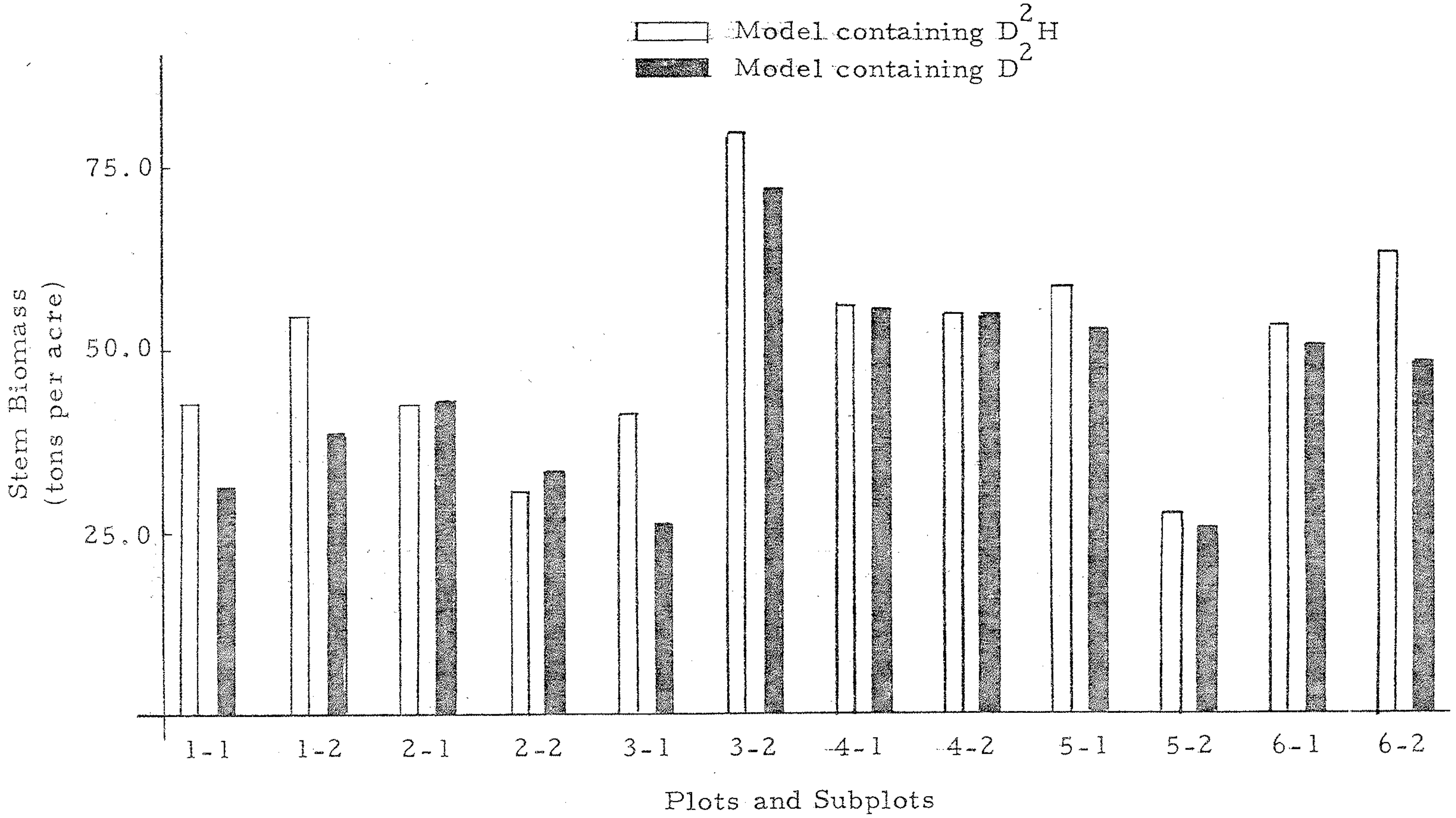


Figure 15. Stem Biomass Comparison

columns corresponding to the models containing D^2 as the independent variable. This deviation is more apparent in some plots than in others, reaching as much as 40 per cent in some samples.

This variation is probably the result of extrapolation of the models to larger trees than were included in the destructive sample. This speculation is verified when the stand tables of Appendix A are compared to the destructive sample sizes in Appendix B. For illustration, the stand table of Plot 4 is given in Table 4. This table may be directly contrasted to the list of destructive samples in Table 5. The trees at this location include every diameter class from 18 inches to 30 inches. This is a definite contrast to the DBH distribution of the destructive samples of Table 5. The largest destructive samples of Engelmann spruce were around 17 inches in diameter, and there were only two of them. From this comparison it is obvious that the sample size of the allometric models was inadequate. Therefore the variation observed in Figure 15 may be partially due to the extrapolation of the D^2 model to larger diameters that it was constructed for.

In the quaking aspen destructive samples the largest tree taken was only 15 inches in DBH. The next largest tree is around 13 inches. When consulting the stand tables for the same species there are many trees from 18 to 22 inches in diameter. The obvious extrapolation of the allometric model to these larger sizes causes a

Table 4. Stand Table of Plot 4 (both 1/5 acre subplots)

DBH Class (inches)	Frequency			
	Total	Aspen	Spruce	Fir
0-2	2	0	1	1
2-4	1	0	1	0
4-6	15	0	7	8
6-8	11	0	8	3
8-10	14	0	11	3
10-12	20	0	16	4
12-14	11	0	10	1
14-16	8	0	6	2
16-18	6	0	6	0
18-20	2	0	2	0
20-22	2	0	2	0
22-24	2	0	2	0
24-26	1	0	1	0
26-28	1	0	1	0
28-30	1	0	1	0

Table 5. Destructive Samples (composite of all spruce plots)

DBH Class (inches)	Frequency (spruce)
0-2	1
2-4	3
4-6	5
6-8	6
8-10	3
10-12	7
12-14	4
14-16	3
16-18	3
18-20	1
20-22	0
22-24	0
24-26	0
26-28	0
28-30	0

serious bias in the estimation of biomass per tree. Necessarily, when there are several trees larger than those used for the model, the error can be very large indeed.

Figure 16 depicts this deviation. This graph is a comparison of the aspen D^2H allometric model and the aspen D^2 model. These equations given similar values at the smaller diameters where the bulk of the data occurred. Any trees over 12 inches in diameter would be grossly underestimated by the D^2 model, as much as 300 pounds in a 20 inch tree. When there are a number of large trees on the plot, the biomass per acre could be considerably less as depicted in Figure 16.

Ogawa et al. (1965) found that extrapolation of the allometric model based on tree diameter beyond the actually observed range of DBH can result in serious error in stem weight estimation. They stated that this danger can be avoided by replacing simple DBH in the allometric equation with D^2H, a quantity closely related to stem volume. They concluded that the linearity between stem weight and D^2H holds over a greater range of tree sizes and with better fit, compared to the case of the simple DBH regression.

Another explanation of the underestimation of large sample trees is that the sample size was expanded by the stem analysis. This procedure biases the sample to some degree. A possible drawback to this method is that the tree heights are determined from a

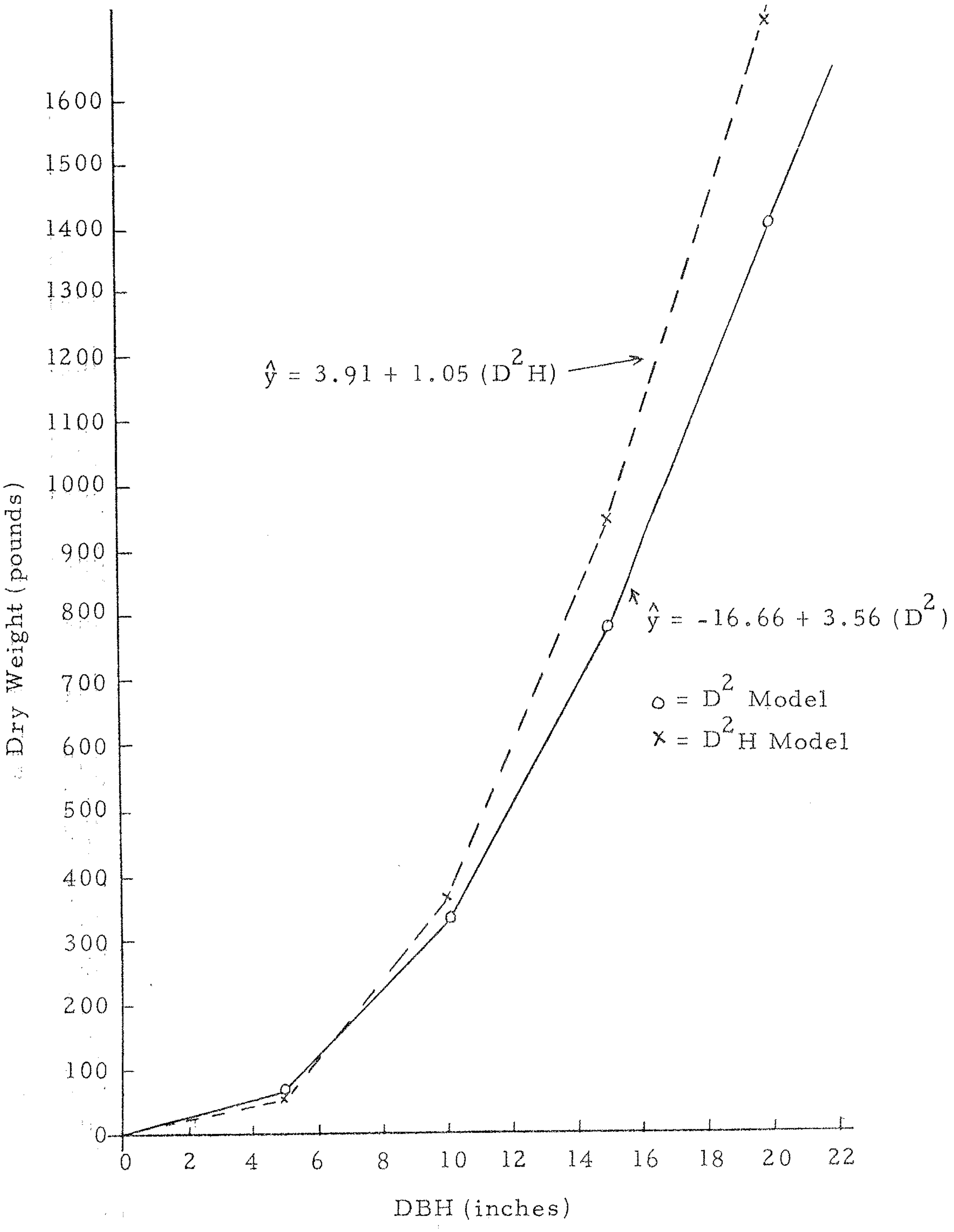


Figure 16. Comparison of Allometric Models Containing D^2 and D^2H for Quaking Aspen

height-age curve for the "daughter" trees. Another problem with this technique is that each "daughter" tree is an image of the original or "parent" tree. The growth rate, genetic differences, and micro-climate may cause this tree to be different than others in the stand. Thus each additional sample is biased to the characteristics of the original tree, and is not independent in the statistical sense. The large number of small "daughter" trees affects the slope of the regression line and may not adequately represent the larger trees.

Another interesting comparison found in Table 3 is that between the All-Trees models and those for the individual species. The stem biomass per acre values are remarkably similar throughout the list of plots. The values between the All-Trees models and the species models have a maximum variation of 6 per cent or less, which is well within the precision of the allometric procedures.

It is interesting to note that the All-Trees equations under-estimate the stem biomass per acre on the aspen plots but the same model overestimates the values for Engelmann spruce. This may possibly be due to the fact that when both species are combined, the typical form of each species has a definite effect. Quaking aspen is normally much taller for a given diameter than Engelmann spruce. Thus when the "average" model is applied to the aspen plots, the "average" function is less than normal, resulting in a low estimate. On the spruce plots the reverse situation applies. The "average" model overestimates slightly the spruce stemwood as this model is biased by the taller aspen.

The total biomass per acre is given in Table 6 using the allometric model for each species with D^2H as the independent variable. This model is the best of all the regressions examined. The total figures for each principal species may be compared in Figure 17.

The biomass values for subalpine fir (Abies lasiocarpa (Hook.) Nutt.) given in Table 6 were computed using the species model for Engelmann spruce. This species was found quite regularly at the plots of higher elevation as an associate of varying magnitude. Because there was no sampling of this species in this study, the spruce model was chosen to estimate the stem biomass at each plot where it occurred. The spruce model was chosen because of the similarity in growth, stem form, and specific gravity between the two species.

The biomass values of Figure 17 are comparable to most of those found in the literature. Bray and Dudkiewicz (1963) found that a Populus tremuloides stand in Minnesota had a total bole weight of 80.96 tons per acre. This value is almost twice the highest value found in this study. Without knowing more about the characteristics of the two stands, it is impossible to speculate on the reason for this large difference. Bella (1970) calculated a value of 38.9 tons per acre for an aspen stand in western Canada. This figure is more the magnitude of this study.

Table 6. Biomass Per Acre by Species (using species D^2H model)

	Species	Biomass/Acre (tons)	Sample Per Plot	Size (N) Per Acre
Plot 1				
	Aspen	48.65	116	580
	Spruce	0.00	0	0
	Fir	0.00	0	0
	Total	48.65	116	580
Plot 2				
	Aspen	36.25	90	450
	Spruce	.40	4	20
	Fir	.09	1	5
	Total	36.74	95	475
Plot 3				
	Aspen	0.00	0	0
	Spruce	51.82	69	345
	Fir	8.83	12	60
	Total	60.64	81	405
Plot 4				
	Aspen	0.00	0	0
	Spruce	50.40	38	190
	Fir	5.04	11	55
	Total	55.44	49	245
Plot 5				
	Aspen	0.00	0	0
	Spruce	41.94	67	335
	Fir	.79	6	30
	Total	42.73	73	365
Plot 6				
	Aspen	0.00	0	0
	Spruce	54.12	42	210
	Fir	4.22	8	40
	Total	58.34	50	250

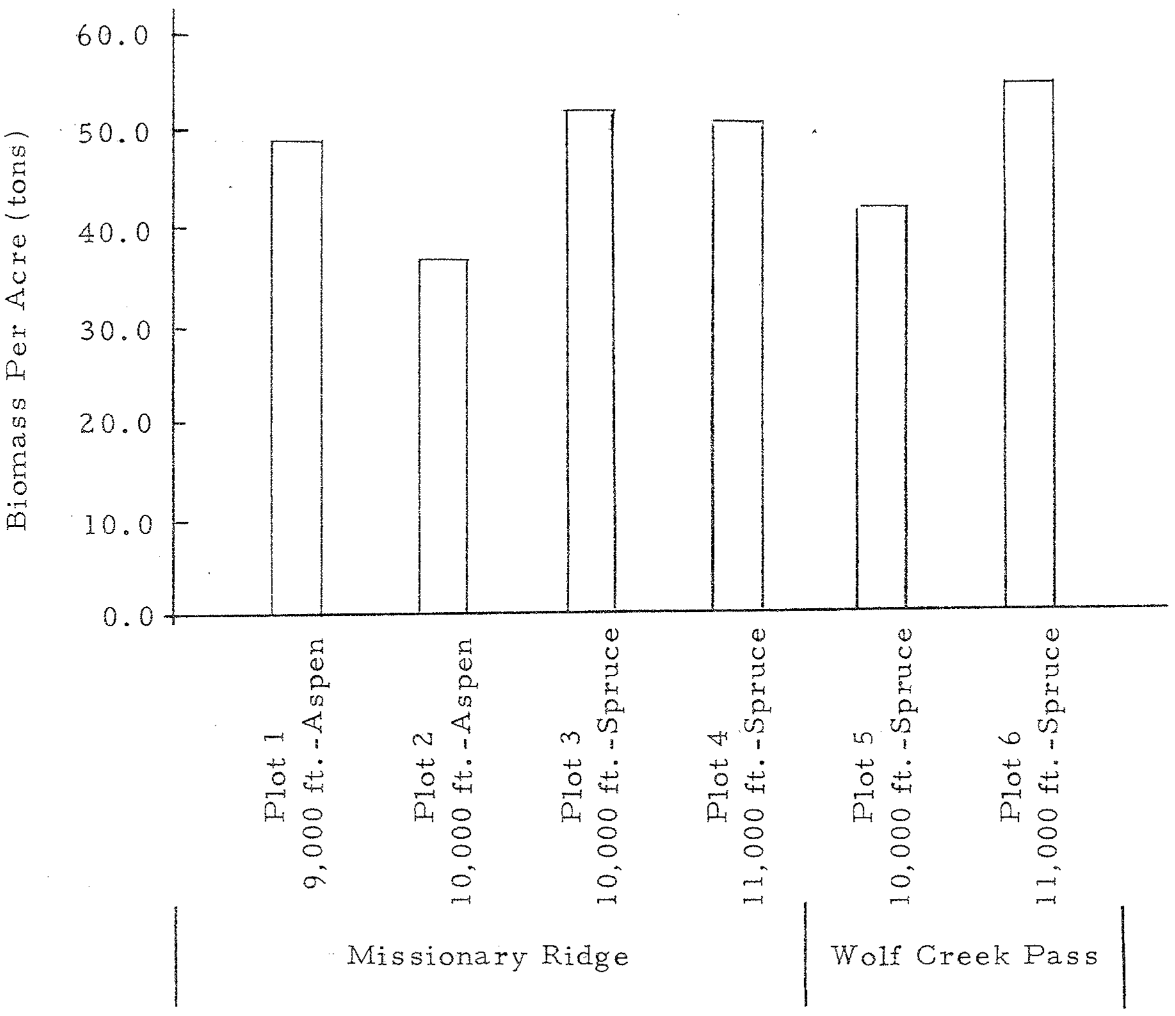


Figure 17. Principal Species Biomass Per Acre

There were no values to be found for Engelmann spruce in the literature but some were found for trees of the same genus. Weetman and Harland (1964) proposed a value for black spruce of 33.08 tons per acre. This research was done in northern Quebec which could explain the lower values compared to those in the San Juans. Black spruce is also, on the average, a smaller tree than Engelmann spruce. Baskerville (1966) found stemwood values of from 0.22 to 2.48 tons per acre for white spruce, depending on the number of stems per acre. These low values were due to the fact that this species was an associate of balsam fir, which had stem biomass values of 24.63 to 43.02 tons per acre.

There are many other stemwood values in the literature for forest stands and species all over the world. Ovington _et al_. (1967) gave a bole weight of 11.89 tons per acre for a _Pinus radiata_ plantation in Australia. Duvigneaud and Denaeyer-DeSmet (1967) found that an oak-ash forest in Belguim had 76.11 tons per acre of stem dry weight. Ogawa _et al_. (1965) discovered that a mixed savanna forest had 29.96 tons of stemwood per acre while an evergreen gallery forest had an extremely high value of 189 tons per acre. Ovington (1957) reported a bole weight of 86.11 tons per acre for _Pinus sylvestris_. Baskerville (1965a) gave a stemwood weight of 21.31 tons for an acre of immature balsam fir. The stem biomass values computed in this study are of reasonable magnitude compared to those in the literature, especially considering the harsh environment of these stands.

Net production

The current net production per year is given in Appendix 3. These values are illustrated graphically in Figures 18 through 23 over time on the abscissa. The small circle and number in the upper right of these graphs is the sample size used to compute each value. The further back in time, the fewer samples because there were fewer old trees sampled.

At the two aspen plots the average production is still increasing in the typical sigmoid fashion of tree growth. This form of the graphs indicates that the aspen are still in the logarithmic phase of growth. The growth appears to be greater at the first plot location, Figure 18, which is located at 9,000 feet in elevation. This is to be expected as at plot 2, 10,000 feet, aspen is nearing its upper elevational limit and tree growth would be expected to be less.

The same general shaped curve is to be found for the spruce plots with the noticeable exception of plot 3, shown in Figure 20. In the other 3 plots the increasing logarithmic relationship can be seen, indicating that these trees are still in the rapid stage of growth and have not yet reached maturity. The graph of plot 3 is not so easy to explain as the growth is seen to have rapidly increased early in the tree's age, and then slowed down for a period. On consulting the

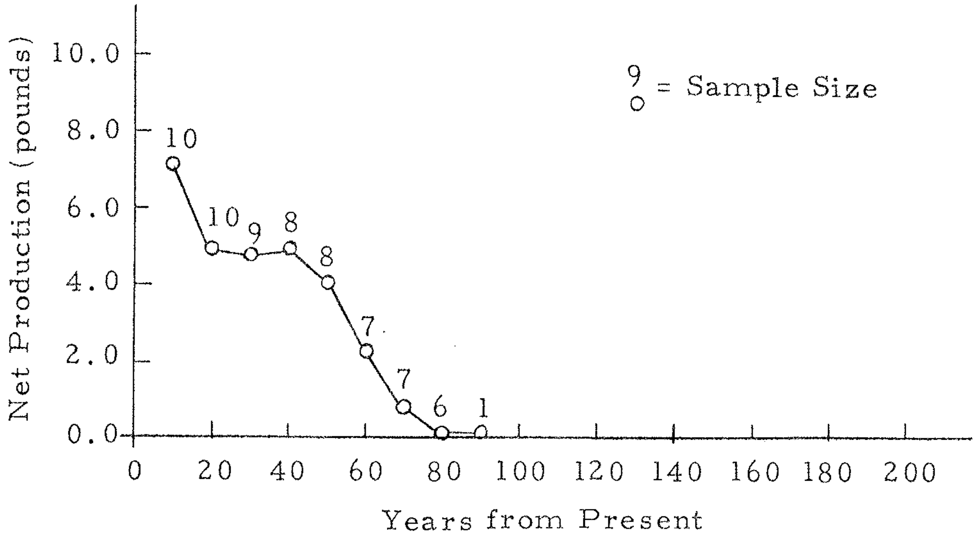


Figure 18. Average Annual Production of Stemwood at Plot 1 - Aspen (per tree)

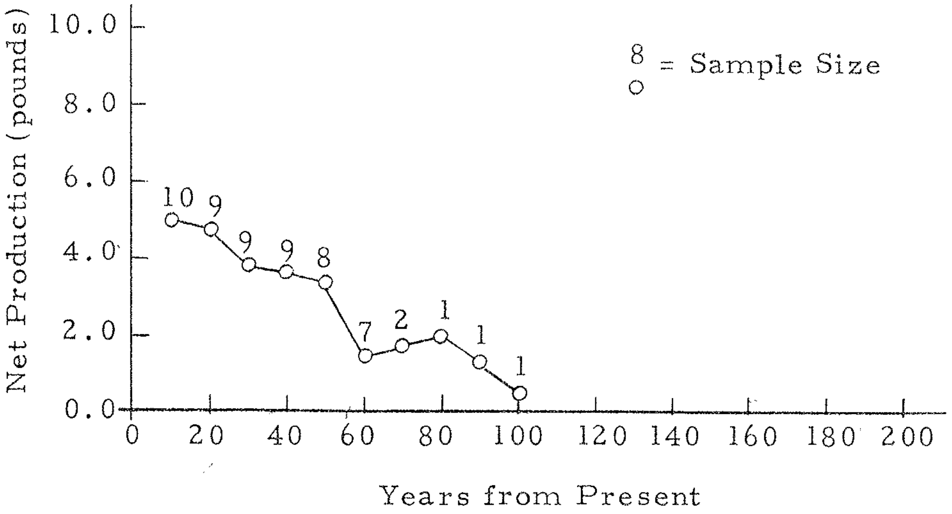


Figure 19. Average Annual Production of Stemwood at Plot 2 - Aspen (per tree)

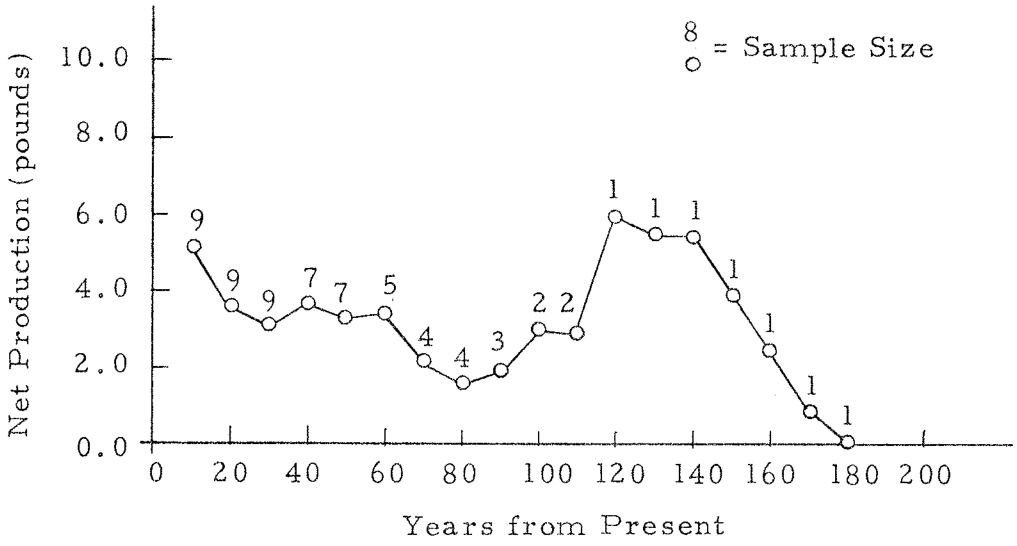


Figure 20. Average Annual Production of Stemwood at Plot 3 - Spruce (per tree)

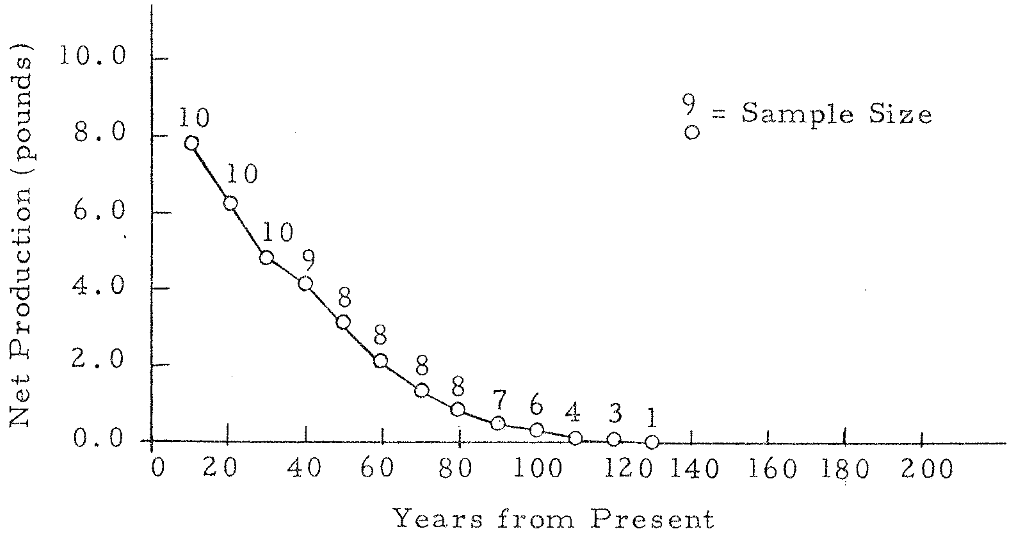


Figure 21. Average Annual Production of Stemwood at Plot 4 - Spruce (per tree)

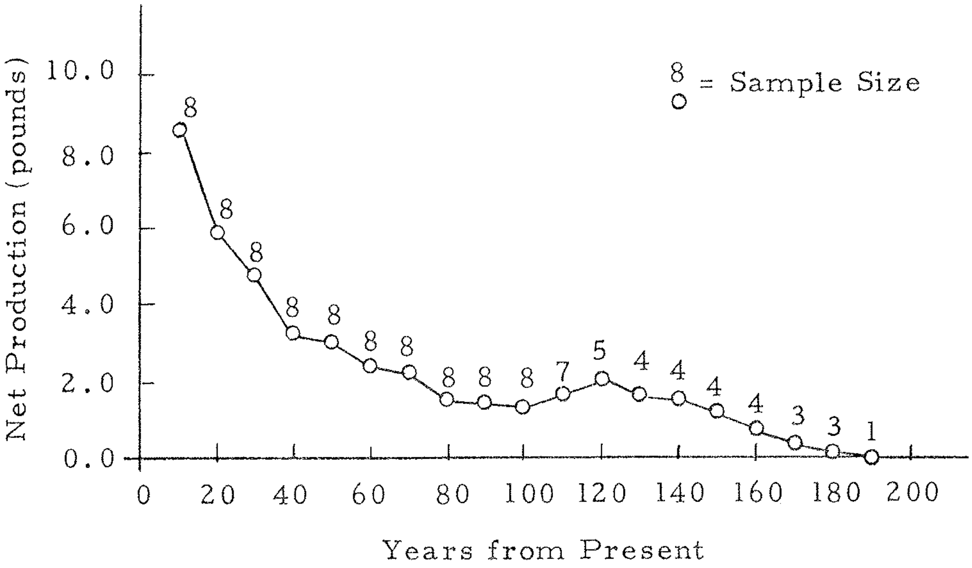


Figure 22. Average Annual Production of Stemwood at Plot 5 - Spruce (per tree)

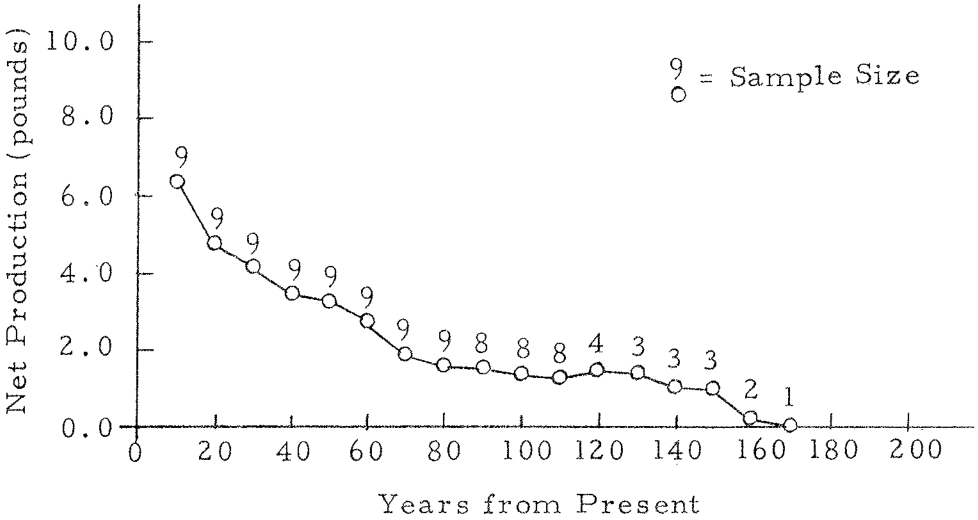


Figure 23. Average Annual Production of Stemwood at Plot 6 - Spruce (per tree)

graph in Figure 20 it can be seen that there was only one sample at the early stages of growth. This occurrence of only one sample could explain this phenomenon. This one tree obviously had very good growth and being that it is the only sample, the values shown are larger than would be expected if more samples were available.

The current annual net production is depicted in Figure 24. The variation between the different plots is evident. The 9, 000 foot plot is the most efficient of all plots, irregardless of species composition. This greater production is to be expected as the environment is more favorable here than at the higher elevations. The growing season is longer by as much as 2 or 3 weeks in some years.

The most productive spruce plot is the 10, 000 foot plot on Wolf Creek Pass. The exact reason for this high figure is complicated by several unmeasured variables. Obviously the site at this location is more suitable for tree growth, but it is hard to quantify this observation without further study of the ecological factors involved.

Variation in biomass and production

Figures 17 and 24 show considerable variation in biomass and production between the sampling plots. The biomass variation with elevation is found to decrease at the Missionary Ridge location, but this trend reverses itself at Wolf Creek Pass. At the two aspen plots there is a large decrease in biomass between 9, 000 and 10, 000 feet in elevation. This can partially be explained by the fact that at the

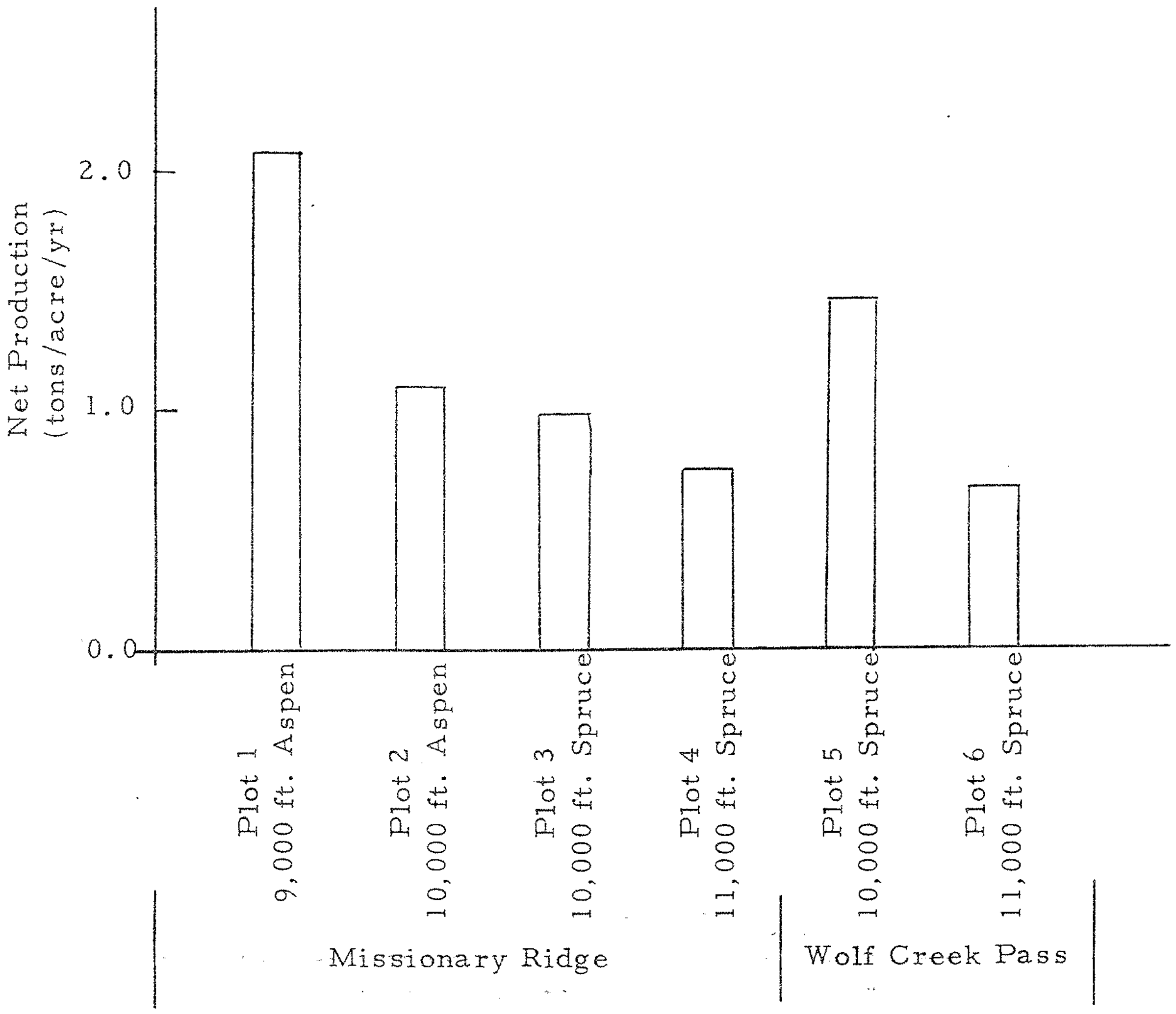


Figure 24. Current Annual Net Production Per Acre

higher elevation the species is at its upper elevational limit and therefore is under greater environmental stress. The length of the growing season is also shorter at the upper elevation.

Engelmann spruce shows decreasing biomass at one location and increasing values at the other between elevations. This contradiction is supported in the literature. Whittaker et al. (1968) found that plant biomass decreases with elevation, while studying an elevational gradient in Arizona. The same author, Whittaker (1966), stated that biomass decreases from low to high elevations. Satoo (1970) found that biomass decreased with increasing altitude while studying deciduous forests in Japan. Whittaker (1966) concluded that this relationship can be complicated by other factors. This statement appears to be valid for this study also, due to the variable results.

The net production also varies with elevation as is apparent in Figure 24. In this case however, there is a definite decrease in net productivity with increase in elevation, irregardless of sampling location. The reason for this trend is probably related to the fact that the growing season is shorter at high elevations due to the possibility of late or early frosts. The temperature range is also more critical for growth at the higher elevations, which also explains the decrease in productivity.

There is another relationship that may be investigated in the bar graph of Figure 17. There is a definite variation between the aspen and the spruce at the 10,000 elevation. These two plots were located at essentially the same site as there was only a few hundred yards between them. The slope, aspect, soil type and other ecological stand parameters were similar due to this close proximity. This is an excellent occasion to examine the variability in production and biomass between a coniferous stand and that of a hardwood.

From Figure 17 the spruce is shown to have a slightly greater stem biomass value than the aspen at the same elevation. This fact could be due to the more dense nature of the spruce stand physiognomy. The more tolerant spruce grows in more dense stands and therefore would have a greater biomass value than the more intolerant aspen.

The aspen in Figure 24 is found to have a greater net production at the present time than the spruce. This observation is contradicted by several sources in the literature. Madgwick (1968) concluded that evergreen forests are more efficient biomass producers than deciduous forests. This conclusion is supported by Kira and Shidei (1967) with data from forests in the Orient. Ovington and Pearsall (1956) also reached this conclusion and attributed the difference in production to the ability of conifers to photosynthesize during suitable periods in the winter months, in contrast to deciduous species whose leaves persist for only part of the year.

The reason for this contradiction may be due in part to the harsh climate of the study area. Due to the high elevation, the soil at the plots may remain frozen during the long winter, making photosynthetic activity at this elevation doubtful for any extended period. Aspen also initiates new growth earlier in the spring than the spruce which gives this species a slight edge on the short growing season. Aspen also has the characteristic of bark containing chlorophyll, which allows this species to photosynthesize year round. Thus the evergreen species may have a lesser advantage over the deciduous aspen.

Another possible explanation for this difference is that the ages of the two stands are not directly comparable. The younger aspen stand may be able to produce at a higher rate than the older spruce. The ability of spruce to endure suppression may also have some effect, as the smaller trees of this species were suppressed, and thus exhibited slower growth.

There are other stand parameters which affect net productivity of stemwood in forest trees. Density, or the number of stems per acre, is known to have a definite effect. The age of the stand is also important as this factor directly influences growth rate. Site quality can positively affect the net production of a tree. These variables were not quantitatively examined in this study so their input can not be analyzed, although their affect is profound in any biomass study.

The net production of stemwood of this study may be compared to other papers. Bray and Dudkiewicz (1963) gave a value of 1.96

tons per acre per year for quaking aspen. This figure agrees very closely with that found at the 9,000 foot elevation of 2.08 tons. The productivity of the 10,000 foot aspen plot is considerably less, but this value is complicated by other factors already explained. Other species for which data occurs in the literature exhibit a wide range in production. Stevens (1963) gave a current annual growth value of 4.50 tons per acre per year for red pine. Weetman and Harland (1964) found a mean annual dry matter increment of 0.50 tons per acre for black spruce. Ovington and Pearsall (1956) reported a maximum value of 0.31 tons per acre for annual net production. Becking (1962) gave a considerable list of annual production for species of trees from the tropics to temperate regions. The values range from 1.5 tons per acre to 9.5 tons per acre per year. The larger figures are for tropical species that have growth almost all year long. Considering the adverse climate and high elevation of the study plots, the net production of the species in this study is of reasonable magnitude.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Samples for determining an allometric model for quaking aspen and Engelmann spruce were collected from 56 trees in the San Juan National Forest in conjunction with the San Juan Ecology Project. The objective of this study was to determine a means of estimating the stem biomass of the two species for future correlation to the possible ecological effects of weather modification.

The statistical population from which the trees were sampled was: all the living Engelmann spruce and quaking aspen of average stem form and free from unusual defect or decay in the study area of the San Juan Ecology Project.

These samples were subjected to standard stem analysis procedures to expand the sample size by replicating the past form and growth of the "parent" tree. Specific gravity determinations were made on each disc. These density values were used to convert the stem cubic volume to stem dry weight.

The stem analysis procedure of expanding the sample size has several disadvantages. One minor point refers to the method of obtaining the height for each "daughter" tree. These heights are calculated from a height-age curve based on the age and height of each section. This value is therefore an "average" figure read from a curve. This procedure is possibly erroneous when height is a major dimension used in the allometric models.

Another condition of this procedure is the fact that the "daughter" trees are images of the "parent" tree at a previous age. This premise is dangerous because these "daughter" trees reflect the same genetic strain and the same microclimate and thus introduce a bias into the sample.

The specific gravity values were found to vary considerably with vertical height in the bole. This necessitated the measurement of wood density at regular intervals in the bole. The use of an average value could seriously affect the precision of the total stem dry weight.

The results of this study produced several allometric models using combinations and transformations of tree diameter and height. These models produced correlation coefficients of from 0.877 to 0.995. The independent variable producing the best model was D^2H or the tree diameter at breast height squared, multiplied by height. This particular model, although more time consuming to use, is better than models containing only DBH. The D^2H regression is also applicable over a wider range of tree sizes than the other models.

The best allometric model depends on several characteristics of the individual study. First the objectives of the project would be very important. The degree of precision desired varies directly with the model selected although all models were of high precision. It is very important to obtain the greatest range of tree diameters possible within the design of the project. This prerequisite removes the erroneous practice of extrapolating beyond the valid range of the regression.

These allometric models are valuable because they allow the estimation of stem biomass from simple forestry measurements. This quality of the models becomes even more useful as the independent variables are available for almost all managed stands. The models of this study are valid throughout the study area of the San Juan Ecology Project. Their application could possibly be extended to the range of the species, but further sampling would be needed before this could be verified.

All-Trees models were developed for the combined sample of quaking aspen and Engelmann spruce. These regressions are valid for both species in any combination with an excellent correlation coefficient of 0.992. Therefore any mixed stand of these species can be measured in terms of stem biomass with only one equation. The precision of this allometric model is quite remarkable considering that this equation is valid for both a hardwood and a conifer. This is due to the similarity of stem form because quaking aspen has an almost excurrent vertical form.

Stem biomass per acre was computed using the allometric model for each species with D^2H as the independent variable. This equation was combined with the stand parameters of diameter and height to yield the stem dry weight of the stand. The values obtained for Engelmann spruce and quaking aspen were reasonable compared to those in the literature considering the harsh environment and short growing season.

Net production per acre was also estimated on a yearly basis. This value is desirable as it allows comparisons of production efficiency between different stands. The productivity of both spruce and aspen tended to decrease with increasing elevation. Stem biomass was found to decrease with an increase in elevation at the Missionary Ridge site, but the reverse relationship was found at the Wolf Creek Pass location. A stand of quaking aspen was found to be more productive at present than a stand of Engelmann spruce at the same elevation and site. It was theorized that the reason for this difference was due to the harsh environment which reduced the photosynthetic activity of spruce during the winter. Aspen also initiated phenological activity first in the spring.

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APPENDICES

APPENDIX A

STAND TABLES
(per acre)

(A = Aspen, S = Spruce, F = Fir)

Plot 1

Subplot 1

DBH Class (inches)	Frequency			
	Total	A	S	F
0-2	840	840	0	0
2-4	160	160	0	0
4-6	0	0	0	0
6-8	30	30	0	0
8-10	135	135	0	0
10-12	85	85	0	0
12-14	5	5	0	0
14-16	0	0	0	0
16-18	0	0	0	0
18-20	0	0	0	0
20-22	0	0	0	0

Subplot 2

DBH Class (inches)	Frequency			
	Total	A	S	F
0-2	1220	1220	0	0
2-4	260	260	0	0
4-6	0	0	0	0
6-8	45	45	0	0
8-10	95	95	0	0
10-12	85	85	0	0
12-14	55	55	0	0
14-16	0	0	0	0
16-18	0	0	0	0
18-20	5	5	0	0
20-22	0	0	0	0

Plot 2

Subplot 1

DBH Class (inches)	Frequency			
	Total	A	S	F
0-2	220	80	100	40
2-4	380	320	60	0
4-6	250	245	5	0
6-8	115	115	0	0
8-10	70	70	0	0
10-12	5	5	0	0
12-14	20	20	0	0
14-16	10	10	0	0
16-18	5	5	0	0
18-20	5	5	0	0
20-22	5	5	0	0

Subplot 2

DBH Class (inches)	Frequency			
	Total	A	S	F
0-2	140	140	0	0
2-4	140	140	0	0
4-6	70	70	0	0
6-8	65	65	0	0
8-10	30	30	0	0
10-12	25	25	0	0
12-14	40	40	0	0
14-16	5	5	0	0
16-18	15	15	0	0
18-20	0	0	0	0
20-22	0	0	0	0

STAND TABLES (Cont.)
(per acre)

Plot 3

Subplot 1

DBH Class (inches)	Frequency			
	Total	A	S	F
0-2	360	0	360	0
2-4	600	0	540	60
4-6	120	0	120	0
6-8	15	0	10	5
8-10	5	0	5	0
10-12	35	0	10	25
12-14	10	0	10	0
14-16	30	0	30	0
16-18	10	0	10	0
18-20	0	0	0	0
20-22	0	0	0	0
22-24	0	0	0	0
24-26	0	0	0	0
26-28	0	0	0	0
28-30	5	0	5	0

Subplot 2

DBH Class (inches)	Frequency			
	Total	A	S	F
0-2	60	0	60	0
2-4	20	0	20	0
4-6	55	0	40	15
6-8	60	0	50	10
8-10	40	0	30	10
10-12	55	0	40	15
12-14	35	0	25	10
14-16	15	0	15	0
16-18	25	0	15	10
18-20	5	0	5	0
20-22	15	0	15	0
22-24	0	0	0	0
24-26	0	0	0	0
26-28	15	0	15	0
28-30	0	0	0	0

Plot 4

Subplot 1

DBH Class (inches)	Frequency			
	Total	A	S	F
0-2	20	0	0	20
2-4	20	0	20	0
4-6	45	0	10	35
6-8	15	0	10	5
8-10	30	0	15	15
10-12	65	0	45	20
12-14	35	0	30	5
14-16	30	0	20	10
16-18	15	0	15	0
18-20	5	0	5	0
20-22	0	0	0	0
22-24	5	0	5	0
24-26	0	0	0	0
26-28	0	0	0	0
28-30	5	0	5	0

Subplot 2

DBH Class (inches)	Frequency			
	Total	A	S	F
0-2	20	0	20	0
2-4	0	0	0	0
4-6	35	0	30	5
6-8	40	0	30	10
8-10	40	0	40	0
10-12	35	0	35	0
12-14	20	0	20	0
14-16	10	0	10	0
16-18	15	0	15	0
18-20	5	0	5	0
20-22	10	0	10	0
22-24	5	0	5	0
24-26	5	0	5	0
26-28	5	0	5	0
28-30	0	0	0	0

STAND TABLES (Cont.)
(per acre)

Plot 5

Subplot 1

DBH Class (inches)	Frequency			
	Total	A	S	F
0-2	120	0	120	0
2-4	160	0	140	20
4-6	95	0	80	15
6-8	80	0	65	15
8-10	15	0	15	0
10-12	20	0	20	0
12-14	5	0	5	0
14-16	10	0	10	0
16-18	30	0	30	0
18-20	20	0	20	0
20-22	0	0	0	0
22-24	5	0	5	0
24-26	10	0	10	0
26-28	0	0	0	0
28-30	0	0	0	0

Subplot 2

DBH Class (inches)	Frequency			
	Total	A	S	F
0-2	140	0	100	40
2-4	320	0	280	40
4-6	100	0	100	0
6-8	60	0	60	0
8-10	25	0	25	0
10-12	20	0	20	0
12-14	30	0	30	0
14-16	10	0	10	0
16-18	5	0	5	0
18-20	0	0	0	0
20-22	0	0	0	0
22-24	0	0	0	0
24-26	5	0	5	0
26-28	0	0	0	0
28-30	0	0	0	0

Plot 6

Subplot 1

DBH Class (inches)	Frequency			
	Total	A	S	F
0-2	20	0	20	0
2-4	60	0	20	40
4-6	55	0	50	5
6-8	25	0	20	5
8-10	20	0	15	5
10-12	55	0	55	0
12-14	30	0	30	0
14-16	10	0	5	5
16-18	20	0	20	0
18-20	15	0	15	0
20-22	5	0	5	0
22-24	5	0	5	0
24-26	5	0	5	0
26-28	0	0	0	0
28-30	0	0	0	0

Subplot 2

DBH Class (inches)	Frequency			
	Total	A	S	F
0-2	240	0	180	60
2-4	80	0	20	60
4-6	35	0	25	10
6-8	5	0	5	0
8-10	20	0	15	5
10-12	10	0	10	0
12-14	5	0	5	0
14-16	10	0	10	0
16-18	40	0	40	0
18-20	5	0	5	0
20-22	10	0	10	0
22-24	5	0	5	0
24-26	10	0	10	0
26-28	0	0	0	0
28-30	0	0	0	0

APPENDIX B

DESTRUCTIVE SAMPLES

Plot 1 - Aspen

Tree No.	DBH (inches)	Height (ft.)
1	12.18	79.1
2	9.80	75.4
3	8.40	60.9
4	6.69	50.0
5	3.95	30.5
6	2.81	27.4
7	8.62	81.3
8	11.96	79.8
9	7.34	58.1
10	5.33	41.1

Plot 2 - Aspen

Tree No.	DBH (inches)	Height (ft.)
1	8.15	51.4
2	5.47	40.4
3	11.60	67.5
4	15.05	70.8
5	2.54	20.5
6	4.50	44.3
7	9.57	60.1
8	6.74	51.5
9	4.52	30.4
10	13.30	69.3

DESTRUCTIVE SAMPLES (Cont.)

Plot 3 - Spruce

Tree No.	DBH (inches)	Height (ft.)
1	3.98	24.5
2	5.00	26.8
3	9.22	52.1
4	10.99	73.5
5	2.98	15.8
7	7.41	48.7
8	10.80	73.3
9	16.29	93.5
10	6.12	33.0

Plot 4 - Spruce

Tree No.	DBH (inches)	Height (ft.)
1	7.88	49.7
2	17.71	86.5
3	6.88	38.5
4	11.07	57.9
5	1.73	9.3
6	2.69	13.5
7	13.40	64.1
8	5.38	26.6
9	10.08	62.1
10	14.93	61.0

DESTRUCTIVE SAMPLES (Cont.)

Plot 5 - Spruce

Tree No.	DBH (inches)	Height (ft.)
1	10.84	59.7
2	8.24	44.0
3	14.57	86.7
4	5.59	23.3
7	12.30	77.5
8	17.42	90.1
9	6.40	29.5
10	10.19	55.8

Plot 6 - Spruce

Tree No.	DBH (inches)	Height (ft.)
1	15.13	84.3
2	8.80	36.0
3	6.83	42.3
4	12.30	60.4
5	4.85	25.0
7	10.03	66.5
8	18.66	83.7
9	12.99	74.3
10	5.50	27.1

APPENDIX C

BIOMASS PRODUCTION

Time Interval (years)	Sample Size	Production (pounds) Average Decadal	Production (pounds) Yearly
Plot 1 - Aspen			
0 - 10	10	71.84	7.184
10 - 20	10	49.93	4.993
20 - 30	9	47.86	4.786
30 - 40	8	49.27	4.927
40 - 50	7	41.53	4.153
50 - 60	7	23.17	2.317
60 - 70	7	8.25	.825
70 - 80	6	1.91	.191
80 - 90	1	.51	.051
Plot 2 - Aspen			
0 - 10	10	49.79	4.979
10 - 20	9	47.03	4.703
20 - 30	9	38.12	3.812
30 - 40	9	36.81	3.681
40 - 50	8	33.78	3.378
50 - 60	7	14.65	1.465
60 - 70	2	17.05	1.705
70 - 80	1	19.91	1.991
80 - 90	1	13.04	1.304
90 - 100	1	5.89	.589

BIOMASS PRODUCTION (Cont.)

Time Interval (years)	Sample Size	Average Decadal	Production (pounds) Yearly
Plot 3 - Spruce			
0 - 10	9	55.44	5.544
10 - 20	9	36.02	3.602
20 - 30	9	30.62	3.062
30 - 40	7	36.51	3.651
40 - 50	7	32.94	3.294
50 - 60	5	34.88	3.488
60 - 70	4	22.31	2.231
70 - 80	4	16.92	1.692
80 - 90	3	19.17	1.917
90 - 100	2	29.53	2.953
100 - 110	2	29.13	2.913
110 - 120	1	59.41	5.941
120 - 130	1	54.47	5.447
130 - 140	1	53.52	5.352
140 - 150	1	38.27	3.827
150 - 160	1	24.60	2.460
160 - 170	1	9.53	.953
170 - 180	1	2.62	.262
180 - 190			
190 - 200			
Plot 4 - Spruce			
0 - 10	10	78.66	7.866
10 - 20	10	61.93	6.193
20 - 30	10	47.27	4.727

BIOMASS PRODUCTION (Cont.)

Time Interval (years)	Sample Size	Average Decadal	Production (pounds) Yearly
Plot 4 - Spruce (cont.)			
30 - 40	9	41.09	4.109
40 - 50	8	31.75	3.175
50 - 60	8	21.28	2.128
60 - 70	8	13.71	1.371
70 - 80	8	7.09	.709
80 - 90	7	5.01	.501
90 - 100	6	2.95	.295
100 - 110	4	2.04	.204
110 - 120	3	.70	.070
120 - 130	1	.23	.023
Plot 5 - Spruce			
0 - 10	8	86.02	8.602
10 - 20	8	59.80	5.980
20 - 30	8	48.37	4.837
30 - 40	8	33.22	3.322
40 - 50	8	30.84	3.084
50 - 60	8	24.54	2.454
60 - 70	8	22.76	2.276
70 - 80	8	15.71	1.571
80 - 90	8	14.84	1.484
90 - 100	8	13.38	1.338
100 - 110	7	16.44	1.644
110 - 120	5	21.19	2.119
120 - 130	4	17.44	1.744

BIOMASS PRODUCTION (Cont.)

Time Interval (years)	Sample Size	Average Decadal	Production (pounds) Yearly
Plot 5 - Spruce (cont.)			
130 - 140	4	16.07	1.607
140 - 150	4	12.40	1.240
150 - 160	4	7.88	.788
160 - 170	3	3.85	.385
170 - 180	3	1.21	.121
180 - 190	1	.24	.024
Plot 6 - Spruce			
0 - 10	9	64.11	6.411
10 - 20	9	48.30	4.830
20 - 30	9	42.05	4.205
30 - 40	9	35.42	3.542
40 - 50	9	33.10	3.310
50 - 60	9	28.55	2.855
60 - 70	9	19.73	1.973
70 - 80	9	16.29	1.629
80 - 90	8	16.16	1.616
90 - 100	8	13.69	1.369
100 - 110	8	12.74	1.274
110 - 120	4	15.21	1.521
120 - 130	3	14.84	1.484
130 - 140	3	11.77	1.177
140 - 150	3	10.01	1.001
150 - 160	3	3.13	.313
160 - 170	1	1.30	.130