T H E S I S

GROWTH OF JUVENILE LODGEPOLE PINE IN RELATION TO SOIL AND SLOPE

Submitted by
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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY Gerald Outslay ENTITLED Growth of Juvenile Lodgepole Pine in Relation to Soil and Slope BE ACCEPTED AS FULFULLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF FORESTRY

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Permission to publish this report or any part of it must be obtained from the Dean of the Graduate School.

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Chapter I

INTRODUCTION

With increasing emphasis being placed on intensive forest management, the problem of adequately evaluating environmental variables of a site as to their effect on tree growth becomes evident. Many attempts have been made to solve this problem but results have been limited. Consequently, there is a continued striving for accurate site evaluation so that good estimates of future timber yields can be made. Auten (1945) mentions that differences between site qualities have long been recognized among foresters and these differences have been expressed by site-index curves. However, these curves are only useable where there is standing timber. What about abandoned crop land, cut-over and partially cut timberlands, or land supporting very young stands or very old decadent stands?

The Problem

Gaines (1949) notes several cases where site index has little or no relation to the ease with which natural regeneration is established. He states that the growth of trees in early years sometimes shows little or no relation to their subsequent growth, thereby rendering valueless height-over age curves necessary in determining site index in young stands. Site index limitations and the need for supplementary or perhaps entirely new criteria for site evaluation must be recognized.

In the Central Rocky Mountain Region insufficient work has been done in determining site quality for our indigenous tree species, especially in lodgepole pine, Pinus contorta Dougl. Troxell (1954) stated that lodgepole pine, a species of the cooler elevations of the Rocky Mountains, is quite suitable for pulpwood. Smithers (1956) found that lodgepole pine yielded high quantities of cellulose volume, an advantageous feature of a pulpwood species, especially on the "medium" and "good" site. Since indications are that pulp production in this region will be a reality in the not too distant future, more accurate site evaluations are necessary if lodgepole pine is to be properly managed.

Where pure evenage stands of lodgepole pine reproduction under 25 years of age are present or where reproduction is absent, no reliable site quality classification scheme is available. Present information indicates that a very high percentage of the average total height growth in mature stands of lodgepole pine has occurred by the time the trees have reached 60 years of age.

The problem is to determine site-growth relationships in various stands of lodgepole pine and to eventually develop methods for predicting the site productive capacity for the land. Study of site-growth relationships in pure evenage stands of juvenile lodgepole pine may produce the needed information for solving this pressing problem and, consequently, result in optimum development of forest management.

Scope and Objectives

The ultimate goal in this study is to see if there are significant correlations between forest growth and associated environmental factors. Smithers (1956) states that assessing the productive capacity of forest lands in terms of site quality is without doubt one of the most difficult problems facing forest research workers at present. Substantial gains toward a method of site quality classification in lodgepole pine can be noted by Smithers and his associates in Canada, but these findings are not completely applicable to the Central Rocky Mountain region. Coile (1952) states that soil properties which may be significantly correlated with forest growth in one region may not be significantly correlated in another region because of different tree species, climate, length of growing season, length of day, or action of other limiting soil factors.

This study attempted to bring to light important relationships between tree growth and environmental factors by measuring certain important factors. By reviewing previous research, from field observation, and from suggestions made by forestry personnel, specific factors will be investigated. From these sources the following questions seem to be most important: (1) will the percent slope and slope position influence growth of lodgepole pine; (2) how will precipitation and aspect affect development of lodgepole pine; and (3) how do the physical soil properties and the soil moisture regime influence tree growth?

Considering this study basic to the research necessary for developing workable site quality classification, aspect and precipitation were eliminated as variables by limiting the study to one aspect within a uniform macroclimate.

The major objectives of this study are as follows:

1. To determine relationships of slope percent and slope position to expression of dominance in lodgepole pine.
2. To determine any significant correlations with physical soil properties and the soil moisture regime to growth of lodgepole pine.
3. To infer from the resulting data practical recommendations for future projects and for development of site quality classification.

Definition of Terms

The following definitions will apply:

Codominant trees - Trees with crowns forming the general level of the crown cover and receiving full light from above, but comparatively little from the side, usually with medium sized crowns more or less crowded on the side.

Dominant trees - Trees with crowns extending above the general level of the crown cover and receiving full light from above and partly from the side; larger than the average trees in the stand, and with crowns well developed but possibly somewhat crowded on the sides.

Juvenile trees - Trees twenty years of age or less.

Site index - An expression of forest site quality based on the height of the dominant stand at an arbitrarily chosen age.

Site quality - A designation of the relative productive capacity of a site with reference to the species employed; the volume or the average height of dominant and codominant trees at a given age is usually used as a standard for classification.

Stem analysis - The measurement of stated cross sections of a tree to determine its growth and development at different periods of its life. syn. tree analysis.

Chapter II

REVIEW OF LITERATURE

The influence of environmental factors on the growth of trees is continually receiving greater recognition in forest management planning. Studies concerned with evaluating these factors in lodgepole pine stands, however, are inadequate. Literature pertaining to the important variables of aspect, soil, and topography has been reviewed and will be grouped under the headings: (1) the influence of aspect, (2) the importance of topography, (3) soil influences on various tree species, and (4) soil influences on lodgepole pine.

The Influence of Aspect

The relationship of aspect to tree growth is of major concern. Some researchers have observed important correlations. Auten (1937a) found that yellow poplar on moist sites (north and east slopes, bottoms and coves) grew at a significantly faster rate than on dry sites (south and west slopes and ridges). Dwight (1912) noted that the south and west aspects in the Rocky Mountain Reserve were the drier sites. Inhibited tree development could generally be anticipated on these sites. Dwight suggested that the influence of aspect on the character of the stand was expressed through its influence on factors governing the character of reproduction.

McArdle and Meyer (1930) found that aspect was an important factor in regulating the productivity of forest sites. They found that Douglas-fir growth was greater on north facing slopes than on south facing slopes. Locke (1941) stressed that direction of slope affected availability of moisture, nitrogen, and essential chemical elements to plants by the greater activity of soil organisms on north slopes than on those facing south. Horton (1958a), in his studies with lodgepole pine, noted different leader growth rates of saplings according to aspect of site. He observed that the longest terminal growth occurred on south aspects and under level terrain conditions. Anderson (1959) worked with lodgepole pine on north and east slopes in Colorado. He found that the east aspect provided significantly better growth as indicated by site index than did the north aspect. Smith and Bajzak (1961) could not find aspect and shape of contours significantly associated with site index of Douglas-fir, western red cedar, or western hemlock.

Some researchers have found that the best tree growth occurred on north aspects, and others have stated that the south aspect provided the greatest tree growth. Although the investigators disagree on which is the best aspect, the consensus seems to be that aspect is an important influencing factor upon tree or stand growth rates.

The Importance of Topography

Any information concerning topographic influence on tree growth is of special value in the Rocky Mountain region due to the limited research that has been undertaken in this region. Several researchers have found data supporting the significance of topography from their studies in other regions. Turner (1937) found slope and aspect in Arkansas to be highly influentual in the determining of low site value of mountain soils with slopes greater than 40%. Auten (1945) and Locke (1941) found that topographic position, slope, or aspect may be related to site quality only in areas of rolling topography. Smith and Bajzak (1961) found site index to be highest on middle slopes with water seepage and lowest on high slopes and swamp areas. Their studies also showed that site index decreased rapidly when slopes were greater than 20%. Metz (1950), as mentioned by Coile (1952), determined that height growth in loblolly pine increased with decreasing surface drainage. Gaiser (1950) found that mean site index of loblolly pine was higher on land of poor surface drainage than on land of good surface drainage. Surface drainage is directly related to ground cover and steepness of topography.

Coile (1952) found that the relative topographic position and the distance from the soil surface to the water table both influence water supply to the soil and to the tree roots. Thus, he maintained that the relative topographic position was indirectly related to forest productivity. He found that subsurface irrigation resulting from seepage on mountain slopes and fluctuating water table in the alluvial flood plain of streams were important factors in productivity that may be independent of "above soil" profile features.

Smith and Bajzak (1961) correlated better site quality to concave curvature of land profile and contour.

No definite, clear-cut, individual correlation appears evident between topography and tree growth. The effect of topography on water penetration and development of the soil seems to be the critical factor in determining the relationship of topography to tree growth.

Soil Influences on Various Tree Species

It is well understood that the soil plays a major role in overall site productivity. Auten (1936) found close correlations between growth of black locust and black walnut and those properties of the subsoil comprising plasticity, compactness, and structure, which influence drainage and aeration. Coile (1952) correlated increasing forest growth to increasing depths to mottling. Cooper (1942), from his studies in the loblolly pine region, found best tree growth occurring on plots showing the smallest degree of erosion. Studies conducted by Hicock et. al. (1931) showed no relation between the acidity of any soil horizon and site index of red pine. They found increasing site index correlated to increasing percent silt plus clay up to 25% in the A horizon. The best correlation was shown between increasing site index and increasing nitrogen content of the A horizon.

Storie and Wieslander (1949) determined that growth of conifers in California appeared to be governed by soil depth and texture characterisitics, soil permeability, chemical properties, drainage, and runoff. Tarrant (1949) concluded that the nutrient content of the soils appeared to be too high to limit Douglas-fir growth, and therefore the soil's physical characteristics should receive study. Wilde (1946) pointed out that optimum growth of white pine was confined to the heavier soils with a "fair" content of moisture and available nutrients. Wilde, Paul, and Mikola (1951) compared growth data with soil analysis. They determined that aeolian sand and moss peat soils with a "deficiency" of absorbing colloides, a lack of nutrients, and an impeded drainage were associated with land of questionable value for timber production on a commercial basis.

<u>Characteristics of the Soil Profile</u>

Many investigators have found important correlations between forest growth and specific soil properties. Auten (1937b) found that 60% of the variation in height of yellow poplar was explained by the age of the tree and depth of the A_1 soil horizon. He showed that the depth of organic matter penetration in the surface soil horizon, taken as the integration of meteorological and biological factors of site, offered a valuable index to site quality evaluation for yellow poplar. Auten (1945) also determined in his studies that depth to "tight subsoil" and thickness of the organically enriched A_1 horizon was directly correlated with site index. Chemical analysis of the soil in question revealed no relation between site index and calcium, magnesium, phosphorous, potassium, or pH. Coile (1935) observed site index of shortleaf pine to be related to the texture-depth index of a soil profile, and later Coile (1948) found the soil characteristics of depth or thickness of the A horizon to be significantly related to site index in shortleaf and loblolly pines.

Crossley (1951) stated that Cajander (1926) related high site quality to the presence of calcium and nitrates in Scotch pine and birch stands. Haig (1929) found several important correlations through his studies. He determined that colloid content and silt plus clay content both were favorably correlated with site quality, and that values for the A horizon soil appeared superior to similar values for the other horizons. He also found that the organic matter content within the range of 2 to 10 percent and soil reaction measured in pH values had only negligible influence on site quality.

Auten (1945), Coile (1948), Hill, Arnst, and Bond (1948), Lutz and Chandler (1946), Pearson (1931) Tarrant (1949), and Turner (1937) all noted that soil depth, measured either for the entire profile or for specific horizons, was found to be or believed to be closely related to site quality. Lutz and Chandler (1946) stated that in small regions of uniform climate parent material is probably the most important single factor in determining the character and productivity of soils. Smith and Bajzak (1961) found that soil with rapid permeability represented the highest site quality.

Hilgard (1930) pointed out that stunted native tree growth in the Rocky Mountain Region was not due so much to lack of plant "food" in the soil as to unfavorable physical conditions. Shallowness and extreme heaviness of the soil were among the most common conditions. Hill, Arnst, and Bond (1948) found that on Douglas-fir sites soil depths less than 30 inches were associated with a lower site index value. Hofmann (1949), as cited by Coile (1952), presented data showing that stand density, organic matter content of the surface soil, and the product of the depth of the A horizon and organic matter content influenced height growth of ponderosa pine.

Holtby (1947) found in a localized area in southeast Washington that the soil texture 6 inches beneath the surface was a fairly reliable indicator of site quality for ponderosa pine. Knudsen (1950) in his studies cited by Coile (1952) wrote that the only soil property found to be correlated with site index of slash pine was the nature of the subsoil as reflected in its imbibitional water values.

Lutz and Chandler (1946) try to designate significant factors of the soil affecting plant growth. Valmari (1921) found that site quality in Finland imporves with increases of nitrogen and calcium in the upper soil horizons. Lutz and Chandler (1946) stated that structure is one of the most important physical properties of soil. They noted that texture or any other single soil characteristic seldom determines site quality. During years of low precipitation, growth was best on soils with the deepest A horizons. These authors present several generalities concerning the relation of texture to site quality:

1. Loam soils are generally more favorable than coarse sands or heavy clays.
2. Deep coarse sands usually support poor forest stands.
3. Layers of fine textured material in lower horizons may compensate for coarse-textured surface layers.
4. Very heavy clay soils may inhibit regeneration and subsequent growth.

5. Rocks or stones in heavy soils may be a decided advantage by causing increased temperature and penetration of water and air. Quantities of rock up to about 20% of the soil volume may be desirable.

In the Pacific Northwest McArdle and Meyer (1930) observed that the most rapid growth and the largest yields of Douglas-fir occurred on deep, well-drained sandy loam soils. Mount (1952) found site index of spruce in Maine to decrease as the total depth of the A horizon increased and as the imbibitional water value of the A horizon increased. Pearson (1931) relates the best growth of forest types in the Southwest to sandy and gravelly soils, placing texture ahead of chemical composition, especially in the growth of seedlings. Toumey (1947) stated that there was no direct relation between site-class of Scotch pine and amounts of chemical nutrients in the soil. From investigation of various sites he found a progressive increase in the amount of fine particles from the poorest to the best sites and concluded that the physical character of the soil, especially the water-retaining capacity, was of particular importance in determining site quality.

Turner (1937) found soil features influencing available water seemingly to be more influential than any others in determining the rate of growth of loblolly pine in the southeastern states. Young et. al. (1950) found that as the site index in white pine stands decreased the depth of the A horizon and the percent stones in the B horizon increased.

Soil Moisture

Some investigators feel the crucial factor in tree growth is the soil moisture regime. Bates (1927) stressed that soil moisture occupies the position of prime importance as a controllable factor of tree growth in forestry. Cheyney (1942) pointed out that soil moisture exerted a direct influence on tree growth mainly through the water holding capacity of the soil. Smith and Bajzak (1961) found that the optimum moisture regime is associated with highest average site index and concluded that the best indicator of site index among individual variables was the moisture regime. Lutz and Chandler (1946) noted that site quality usually improved where there was increasing amounts of available soil moisture. Wilde (1958) pointed out that the ground water table located at a suitable depth, such as four feet, provided an abundant supply of moisture which was highly beneficial to tree growth.

The various studies mentioned above tend to indicate that the factors of soil texture, depth of surface soil, soil moisture (mainly expressed as the water holding capacity of a soil), and possibly the organic matter content of the surface soil are strongly correlated to resulting site quality. These variables, therefore, should be included in any future projects conducted to determine site quality evaluation.

Soil Influences on Lodgepole Pine

Studies in lodgepole pine growth are not as numerous and extensive as those having been conducted in some other tree species. A large portion of the lodgepole pine research is being undertaken in Canada. The Canadian Department of Mines and Resources (1949) published a bulletin which stated lodgepole pine made its best growth in deep, moist, well-drained loam as pure even-aged stands.

Horton (1958b) noted that the most unproductive sites for lodgepole pine lay at the two extremes of moisture conditions, the very dry site and the very wet site. On each of these sites restrictive rooting could be noticed with evident slow stem growth.

Illingworth and Arlidge (1960) delineated specific forest types. The most important type was found on a "fresh" but well-drained site. This type was of main concern as it supported the best stands of pine in the Northern Rocky Mountain Region. The various site types in descending order of productivity followed a moisture gradient from mesic to xeric.

Investigators involved with tree growth stress the importance of the soil. Kerr (1913) mentions that he found yellow pine and lodgepole pine making their best growth on sandy or gravelly soil. Mason (1915a) noted that lodgepole pine is not exacting in its soil requirements though it does best on deep, "fresh", well-drained agricultural land. He also states limestone soils are apt to be too dry to enable the tree to make normal growth. Mason (1915b) also states that the tree is not fastidious as to soil if there is enough moisture present. Anderson (1959) did not find a single independent factor to be significantly related to site index, but he did find that on a north aspect the independent variables of available moisture at an 18 inch soil depth, percent slope, and available moisture capacity at a two to four inch soil depth were the most important in influencing site quality.

Preston (1942) found the number of ectotrophic mycorrhizae on the "more sterile site" for any given age approximately double that on the better site, indicating a strong inverse correlation between the number of mycorrhizae and soil fertility. Smithers (1956) described forest site quality as the sum total effect of a number of factors which influence forest growth capacity. These factors included soil variation, moisture conditions, and climatic factors. Tarrant (1953) stated lodgepole pine was best adapted to sites with a steady supply of moisture. Thompson (1929) had noticed that a rocky site with shallow soil was in many places very restrictive to growth. Smithers (1956) indicated that as the "fine-textured soil layer" became shallower the height growth of lodgepole pine decreased.

From the few site quality investigations involving lodgepole pine the factors of soil texture and plant available moisture appear to be of major significance. Studies with other tree species have resulted in similar relationships. Emphasis must be placed on these two variables for site quality evaluation besides stressing the need for more comprehensive investigation. The following project attempts to initiate or provide a basis for more comprehensive investigation.

Chapter III

METHODS AND MATERIALS

Field work was carried out during the summer of 1961. The laboratory and statistical analysis were completed during the fall and winter of 1961-62.

Preliminary Planning

The two variables of aspect and climate were not investigated. The study was limited to an east aspect; thus, differences in tree height due to indigenous conditions of various aspects were not involved. Variability in tree development caused by climatic variations will be reduced to the minimum by delineating an area of uniform macroclimatic conditions. These conditions presumedly existed because the study area was limited to 1000 feet in length and 300 feet in width.

Variables. After considering all possible tree growth-envoronment interactions and excluding certain factors by reducing their variability (in order to limit confounding), the following factors were chosen for study:

Percent slope

Slope position

Depth of solum (depth of soil to C horizon)

Percent exposed rock at the soil surface pH for A and C horizons

Soil moisture percentages (1/3 and 15 atmosphere tensions) for A and C horizons

Percentages of sand, silt, and clay in A and C horizons

Bulk densities (weight of oven dry soil/volume soil occupied) in A and C horizons

Potential plant available moisture (bulk density times percent moisture times soil depth) in A and C horizons

Percent rock greater than 5 millimeters in the soil profile to a depth of 12 inches into the C horizon

The methods for collecting these variables will be covered under the field procedures.

Experimental Design. Specific criteria was used for selecting the study area. This criterion is as follows: (1) the stand must be composed of pure evenaged lodgepole pine 15-20 years old, (2) slope direction must be between the azmith readings of 60 to 120 degrees, (3) the topography must be such that three adjacent plots each 0.75 chains square could be superimposed on the same slope position, (4) a slope must be of sufficient length to permit establishment of plots on six slope positions with a minimum distance of 0.75 chains between plots, and (5) the horizontal dimensions must not exceed 15 chains in length and 5 chains in width.

A stratified random sampling design was employed with the six positions each representing a treatment and each of the three plots per position representing replications. An additional position on the ridge was included but due to the small area available only one plot could be established on this position.

Description of Study Area

Location. The study area is adjacent to the South Fork of Panhandle Creek (see figure 1). The location is the northwest portion of the southeast ¼, Section 5, Township 10 North, Range 74 West, 6th Principal Meridian Boulder baseline. It is about 8 miles northwest of Redfeather Lakes, Colorado.

The Panhandle Creek drainage of North Central Colorado encompasses approximately 12,000 acres as stated by Black et. al. (1959). The drainage is almost entirely timbered. The western half of the drainage is national forest land and the eastern half is a checkerboard pattern of private-national forest ownership. Approximately 1,000 acres of forested land was burned in 1939 with reproduction becoming established 3-5 years after the burn. Many charred trees are still standing with several located on the study area. As a result of the fire a layer of charcoal one-half to three inches in thickness covers the soil's surface.

Climate. Long cold winters and cool summers prevail. Weather Bureau statistics from Red Feather Lakes, Colorado show maxima-minima mean ranges for May of $30.6^\circ - 55.6^\circ$ F and a July range of $43.9^\circ - 76.6^\circ$ F with a mean annual temperature of 38.1° F, U.S. Dept. of Commerce (1953). Mean precipitation figures for the spring months show April and May receiving the highest amounts, 3.08 and 2.58 inches respectively. July receives a mean precipitation of 1.44 inches. Yearly precipitation averages 18.55 inches with mean

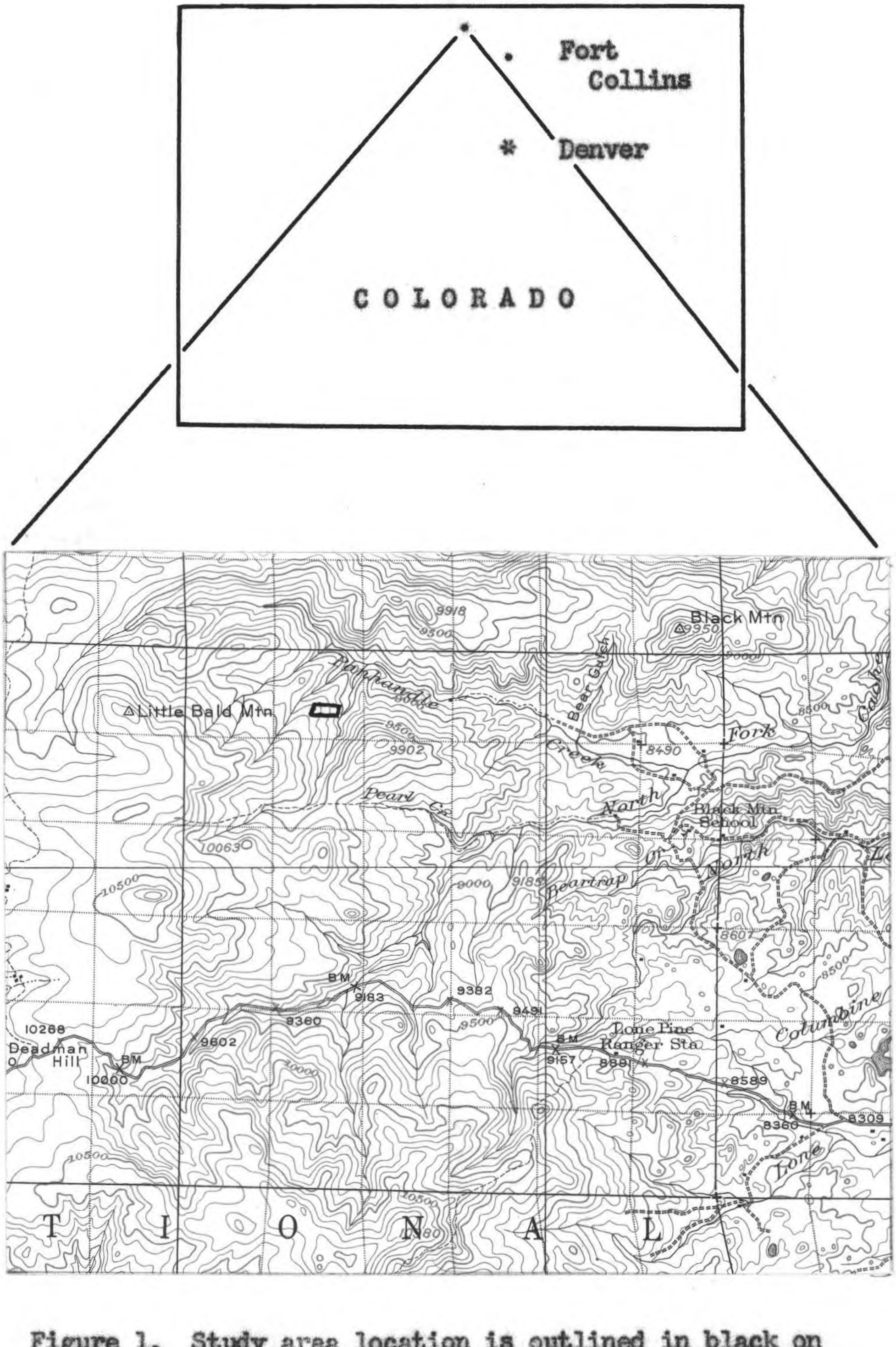

Figure 1. Study area location is outlined in black on the map. Scale: One inch equals two miles, approximately.

annual snowfall totaling 131.7 inches. A characteristic feature of the climatic conditions is the occurrence of almost daily thunder storms during late spring and throughout the summer months.

The Redfeather Lakes station is located at an elevation of 8,227 feet, approximately 750 feet lower than the study area. Recognizing this altitude difference and a distance of 8 miles, it is probably quite safe to assume that mean temperatures will be slightly lower, snowfall slightly greater, and yearly precipitation values slightly higher.

Topography. The Panhandle Creek watershed ranges in elevation from 8,500 feet at the eastern extreme to about 10,000 feet on the western edge. Terrain is very steep and most of the area is inaccessible by car. Elevation of the study area reaches about 9,150 feet on the ridge top with its lower extreme around 9,000 feet. The area has an east aspect with an average azimuth reading of 100 degrees, an average for the 19 plots.

Soils. Soils on the study area are developing on the Silver Plume granite formation, Lovering and Goddard (1950). This formation is somewhat finer textured and is a younger batholith than the Pikes Peak granite, a more abundant formation. Most of the Silver Plume granite is pinkish gray in color, medium-grained slightly porphyritic biotite granite, composed chiefly of pink and gray feldspars, smokey quartz and biotite with muscovite being present in some facies. The percentage of biotite varies from place to place. Soil development appears slight. The soil could be classified in the azonal soil category. There does not appear to be any areas of impeded water drainage. The presence of willows, Salix spp., at several locations does tend to indicate an abundant supply of water.

Vegetation. Vegetation found in the study area can be divided into two groups: (1) associated tree species and (2) lower vegetation. Those tree species besides lodgepole pine found on the study area were subalpine fir (Abies lasiocarpa (Hook) Nutt.), common juniper (Juniperus communis L.), quaking aspen (Populus tremuloides Michs.), and at slope bottom adjacent to the creek a few mature Engelmann spruce (Picea engelmannii Parry). These trees were scattered throughout the study area. Aspen was the most numerous and often occurred in small pure stands. The lesser vegetation varied from place to place and was never dense. The more obvious genera and species noted were Arctostaphylos ura-ursi Adans., Artemisia frigida L., Berberis repens L., Symphoricarpos albus Duhamel., Carex spp., Rosa spp., Vaccinium spp., and a few grasses.

The number of lodgepole pine trees per acre varied from 570 trees to 3300 trees. This represented spacing from approximately 8.5 feet by 8.5 feet down to 3.5 feet by 3.5 feet. Plots having few trees generally had trees quite evenly spaced. The ground cover (lesser vegetation on an observational basis) varied from 5 percent near the ridge top to about 60 percent near the bottom of the slope (see figures 2,3, and 4 for views of study area, absolute top position and bottom position).

Injurious Agents. The presence of dwarfmistletoe (Arceuthobium americanum Nutt.) and a stem rust (Cronartium spp.)

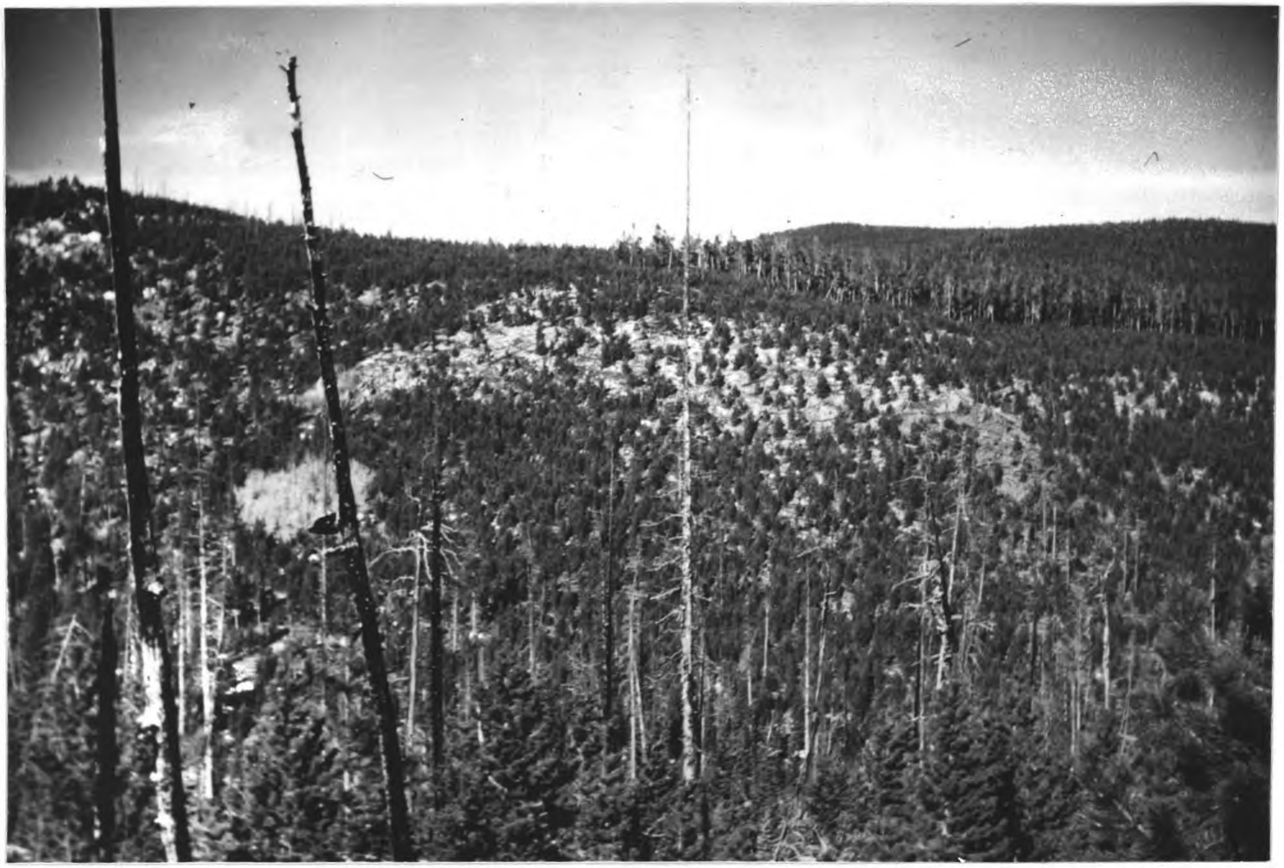

Figure 2. View of study area from opposite ridge. Plots were located on the slope seen directly in the center of the picture.

Figure 3. Looking north from southern extreme of absolute top position.

Figure 4. Looking north from southern extreme of bottom position.

were noted, but only slight infection seemed evident. There appeared to be a light infestation of the stand by the lodgepole pine terminal weevil (Pissodes terminalis Hopk). In general, the stand as a whole was relatively free of disease and injurious insects.

Field Procedures

The plots were established by using a staff compass, two chain tape, and an Abney hand level. Wood stakes were used to mark plot boundaries and plot centers. Each position was aligned as accurately as possible to conform to the topographic relief. Resulting plot arrangement is shown in Figure 5. The plots are drawn to scale with distances between positions representing actual ground measurements but not correcting for percent slope (percent slope readings were recorded).

Collection of Tree Samples. Selection of trees representing site productivity was one of the most critical points of the entire study. The following criteria were used to select those trees which sould best represent site quality: (1) trees must be included in dominant or codominant height classes, (2) trees must be free of disease and insect damage, (3) trees must be of good form (excurrent with no unusual shape), and (4) tree spacing must be within the range of 3 feet by 3 feet to 6 feet by 6 feet (to alleviate the influence of spacing on growth.)

It was decided to randomly select from these qualified trees, 4 trees per plot. The average height of these four trees was presumed to be the best estimate of site quality for the plot.

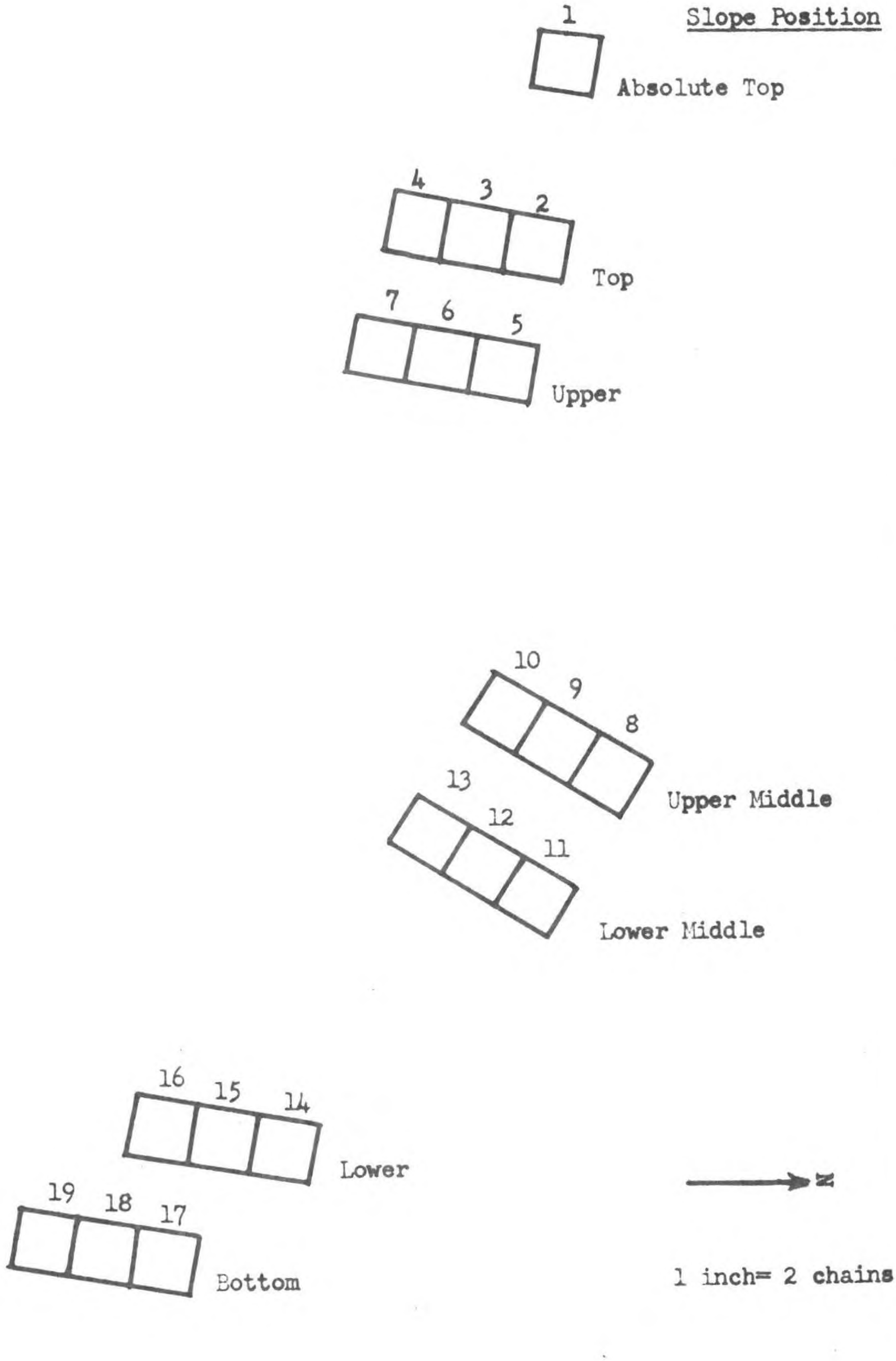

Figure 5. Field plot layout.

Munn, Hoerner, and Clement's (1947) tables of random numbers were used for making the selections. Selected trees were cut at ground level, limbed, and returned to the laboratory (see figures 6 and 7.)

Collection of Soil Samples. Soil samples were taken from a pit dug at the center of each plot (see figures 8 and 9). The soil profile was thus exposed, facilitating the description of the soil horizons. Procedures outlined in the Soil Survey Manual by the Soil Survey Staff (1951) were followed for describing the horizons. In the field a weak B horizon was described and considered to be a transition zone to the C horizon; thus, an A-C soil profile was evaluated. Samples of the soil horizons for each plot were taken and brought to the laboratory for more detailed tests.

Bulk density measurements were made in the field on the A and C horizons. Undisturbed soil was removed from the specified horizon and placed in paper sacks. By using a Volumemeasure (an instrument sold by Soiltest Inc. of Chicago, Ill.), the volume that the undistrubed soil had occupied was determined. The excavated soil was taken back to the laboratory for drying and for removal of rock material greater than 2mm in diameter. Bulk density readings represented the weight of oven dry soil less than 2mm in diameter over the volume this soil had occupied before it had been disturbed.

Qualitative Observation. Several other important factors were measured on each plot. The rise in feet per chain on each plot was determined with a topographic Abney. The percent exposed

Figure 6. Ground-line tree stump after cutting. This was taken on the bottom position, note ground cover.

Figure 7. Trimmed trees taken from study area.

Figure 8. Soil pit exposing the soil profile on the absolute top position.

Figure 9. Soil pit exposing the soil profile on the bottom position.

rock per plot was estimated by comparing the amount of 4mm square (or greater) exposed rock surfaces to charts representing specific percent area coverage. The actual slope direction for each plot was measured with a staff compass and recorded. The average slope direction for the 19 plots was about S 80 E.

Laboratory Procedures

Tree Measurements. Standard stem analysis techniques for developing tree height over tree age growth curves were followed. There was some slight variation in this procedure. The usual method for determining the actual age of the tree for a particular cross section is to count all the annual growth rings on each cross section and subtract this number from the age of the tree. In the present study one-half year was subtracted from the age calculated in this manner before plotting on the graph. The inner-most growth ring, from which this one-half year was subtracted, does not represent the precise point at which height and diameter increment are initiated or cease for a particular growing season. Therefore, giving this inner growth ring an age of one-half year results in more accurate height over age growth curves. All cross section measurements were made at one foot intervals along the stem starting from the ground line.

Diameter measurements were recorded for ground level and were determined for one-half the tree's height. Measurements were made to the nearest one hundreth of an inch. These diameters were obtained to determine whether any correlation existed between tree form and slope position. Tree form was expressed by a form factor that was found by dividing the tree diameter at half the height of the tree by the diameter at ground level.

Soil Tests. Mechanical analysis of soils by the hydrometer method as described by Bouyoucos (1936) was followed. Fifty grams (oven dry weight) of soil less than 2mm in diameter from each horizon were tested. A 10ml solution of Calgon and distilled water, in the proportion of 61 grams Calgon per 200ml distilled water, was added to the 50 gram soil sample. This mixture was allowed to stand for a 12 hour period thus permitting sufficient time for the soil to slake and to soak. Each sample was stirred for five minutes in the dispersing cup recommended by Bouyoucos (1936). The hydrometer readings were corrected for temperature in the usual manner.

Soil reaction (pH) was measured with a Beckman pH meter. A soil to water ratio of one to one by weight was used.

Soil moisture tests were made in the Colorado State University Agronomy Department laboratory during the late summer of 1961. The quantity of water held by soils between the field capacity, (approximately 1/3 barometric tension), and the permanent wilting point, (approximately 15 barometric tension), represents the available water capacity of a soil. Available water is that water which can be extracted from the soil by living plants. Measurement of field capacity and wilting point followed the procedure described by Richards (1949). Field capacity was obtained by saturating about 25 grams of soil contained in a rubber band about one-half inch high for a period of 12 hours and then placing the sample upon a porous ceramic plate. The plate was then placed in a pressure cooker in which air pressure could be accurately adjusted and measured. A pressure differential of one-third atmosphere was then applied across the plate until the soil moisture obtained an equilibrium with the porous plate as determined by cessation of flow. This took about 24 hours. Soil moisture was then determined in the conventional manner by oven drying at 105 C.

The wilting point was obtained by following essentially the same procedure. Instead of using a ceramic plate and pressure cooker, the saturated soil samples were put on a pressure membrane and placed within a pressure cell. Fifteen atmospheres of pressure (about 220 pounds per square inch) were applied across the membrane and equilibrium moisture percentage determined.

The available water determined in preceding paragraphs was weighted (standard procedure) for use in multiple regressions. The available water (percent moisture) was multiplied by the appropriate bulk density readings and by the appropriate soil depth. The actual depth of the A horizon (in this case the solum)was used, but a constant depth of twelve inches was used on each plot for the C horizon because the depth to substratum or parent rock could not be determined.

Office Procedures

After completing all the field and laboratory measurements, the tree growth curves were drawn. By constructing growth curves for each individual tree, appropriate ages and heights could be read directly from these curves and an average growth curve could be drawn. Tree heights by one-foot increments were plotted over age for the curve. The average age for each height was determined arithmetically. Figure 10 shows the average tree growth curve for plot number 5. Straight lines were drawn between points with little loss of accuracy because of the short distance between intervals on the tree stem. Average tree heights for each plot were read from these graphs at six different points: present, three, six, nine, twelve, and fifteen years in the past.

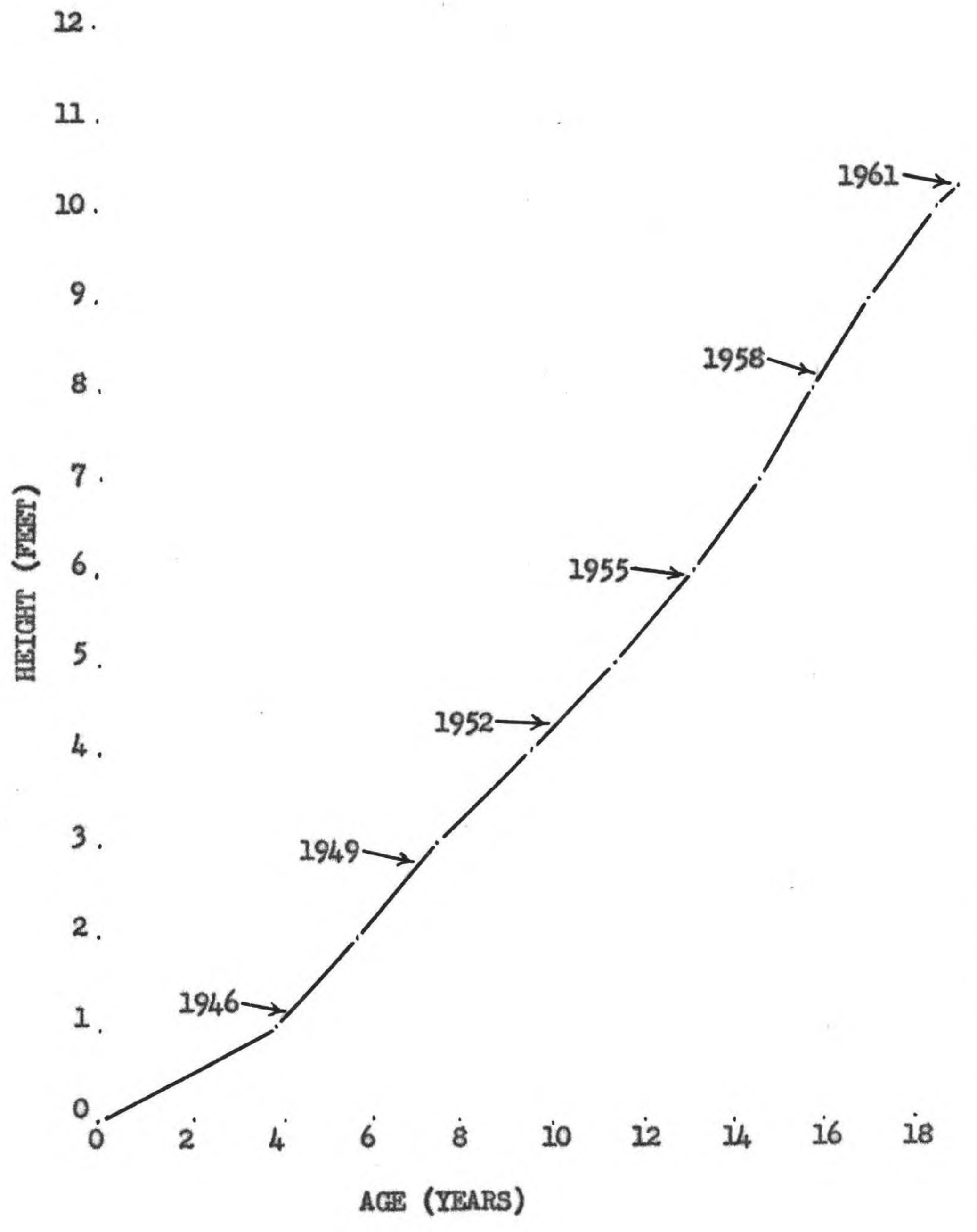

Figure 10. Growth curve for average tree on plot number 5.

Chapter IV

ANALYSIS OF DATA

Any specific site-tree growth relationships determined from the data must mainly be limited to the study area. Statistical analysis of the data appeared to be the most fruitful approach for determining site-tree growth correlations.

Correlations between Tree Development and Topographic Position

Before presenting any relationships the meaning of slope position must be further clarified. In the methods chapter several positions were described. These positions represented an initial attempt to stratify the entire area into three parts, the lower slope area, the middle slope area, and the upper slope area. However, because of the topographic relief, seven positions were defined. These positions represented segments of the study area and were named according to their approximate physical location on the slope. Figure 2 5 shows the arrangement of positions and ? the method of numbering and naming the position from the top of the ridge to the slope bottom. Each position contained 12 trees. Before any statistical tests were made three average tree heights for each position were read from appropriate tree growth curves. Position one contained only one plot but 12 representative trees had been chosen and these trees had been randomly placed into 3 groups. The forest occupying the study area was a pure evenaged stand of lodgepole pine. Individual trees ranged in age from 18-20 years. The average age of the stand was 18.9 years. A comparison of tree heights on each position according to respective ages, 18, 19, or 20 years, disclosed that height differences were not directly related to age. Tree height data found in Appendix A was used in the initial analysis.

Analysis of Variance Tests. An average height difference of 1.5 to 2.0 feet between positions might be assumed to represent an important variation. Differences of this amount or greater were found between the several slope positions. Significance of these differences was tested by the analysis of variance. An analysis of variance test was made with slope positions considered as treatments and with three groups of four trees each considered as a replication. A statistically significant difference in height was found between positions at the 99% level, but no significant difference in height was evident between replications (see table 1). Eighty-four trees were used in this analysis. On the basis of this finding a similar analysis of variance test was run just using the average tree heights. A significant difference in tree height at the 99% level was found between positions, but no significant difference in tree height was found between replications at the 99 or 95% level (see table 2).

In order to study the growth and development of the trees throughout their life, tree heights read from the growth curves for the average trees in past years were tested by analysis of

TABLE 1.—ANALYSIS OF VARIANCE FOR TESTING INDIVIDUAL TREE HEIGHTS BY POSITION AND BY REPLICATION*

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	"F" Ratio
Total	83	289.40	-	-
Between tree groups	20	177.46	-	-
Replications	2	0.29	0.15	1
Positions	6	153.35	25.56	12.91**
Interaction	12	23.82	1.98	1.11
Residual	63	111.94	1.78	-

*This the first analysis and involves 84 trees collected from the study area.

**Significant at 99% level (6/12)

TABLE 2.—ANALYSIS OF VARIANCE FOR TESTING AVERAGE TREE HEIGHTS PER PLOT BY POSITIONS AND BY REPLICATIONS*

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	"F" Ratio
Total	20	44.26	-	-
Replication	2	0.07	0.04	1
Position	6	38.30	6.38	13.02**
Residual	12	5.89	0.49	-

*This the second analysis and involves 21 average trees from the study area.

**Significant at the 99% level (6/12)

variance. A separate analysis was made for each of the five three-year intervals in the tree's life. Figure 10 shows the growth curve for plot number five. Average tree heights by position for 1958, three years ago, were tested by analysis of variance and a significant difference in tree height between positions at the 99% level was evident. This was repeated for average tree heights in 1955, 1952, 1949, and 1946. Statistically significant differences in tree height were determined between positions during each of these years at the 95% level.

Tukey's Test. Since significant differences were found in tree height between positions, Tukey's test as given in Snedecor (1957) was employed to determine between which positions this difference occurred. Of the 21 possible differences 8 significant differences were noted. Statistical difference at the 5% level (false conclusion 5 times out of 100) existed between position one and positions two, four, five, six, and seven and also between position seven and positions two, three, and four (see table 3).

TABLE 3.--RESULTS OF TUKEY'S TEST AS MODIFIED BY SNEDECOR

Position	Mean of $Y(\bar{y})$	1 $\bar{y}$-9.15	3 $\bar{y}$-10.98	2 $\bar{y}$-11.31	4 $\bar{y}$-11.68	6 $\bar{y}$-12.35	5 $\bar{y}$-12.64	7 $\bar{y}$-13.78
7	13.78	4.63*	2.80*	2.47*	2.10*	1.43	1.14	-
5	12.64	3.49*	1.66	1.33	0.96	0.29	-	-
6	12.35	3.20*	1.37	1.04	0.77	-	-	-
4	11.68	2.53*	0.70	0.37	-	-	-	-
2	11.31	2.16*	0.33	-	-	-	-	-
3	10.98	1.83	-	-	-	-	-	-
1	9.15	-	-	-	-	-	-	-

*A difference greater than D=1.98 (a product of the standard error of the mean, $S_{\bar{x}}$, and a factor Q) is significant at the 5% level

Correlations between Tree Height and the Environmental Variables

The results of the tests just completed indicate that height differences do exist between positions. Several specific environmental variables cause these differences to occur.

Selection of Variables. The ten variables listed in the previous chapter were considered for possible correlations to tree height development. The next step was to set aside those variables indicating no apparent relationship to tree growth. Scatter diagrams were drawn to analyze relationships. The independent factor (environmental variables) was plotted on the abcissa or x axis while the dependent factor (tree height) was plotted on the ordinate or y axis. Of the ten different variables six of them independently expressed a definite linear relationship to tree height. Two other variables appeared to have a relationship of lesser magnitude. The six variables were: slope position, percent exposed rock at the soil's surface, elevation change per chain, potential plant available water in the C horizon, bulk density of the C horizon, and the average percent silt plus clay for the profile.

Each of the variables had been plotted as an independent factor but due to interactions between the variables these graphs did not denote their true influence. A very strong interrelationship between the variables does exist, but each variable still does have its own independent effect.

Multiple Linear Regression. Multiple linear regressions were used in attempting to evaluate relationships and influences of the six environmental variables. To insure a more valid regression and permit equal weighting of one soil sample to an average tree delineated by four trees, only four of the twelve trees representing position one were used. The regressions were calculated on an IBM 1620 computer. Nineteen plots each containing representative samples of the six variables associated with an average tree height were tested. Basic data can be found in Appendix B. Six multiple linear regressions were run. The first regression, tree height in 1961, is of major concern and most of the discussion will be concerned with it. The other five regressions each used the same environmental factors. The only difference was that each dependent y variable represented the average tree height per plot for the specific year(1946, 1949, 1952, 1955, 1958, or 1961) that was tested. Appendix B shows the actual factor headings as they were applied in the regressions.

The results of the regression involving the six variables and the tree heights for 1961 produced significant information (see Appendix C). The "F" ratio for the 1961 regression was 6.53 with 6 and 12 degrees of freedom. This was significant at the 99% level. "R" square, the coefficient of determination, was calculated as 0.7655, or stated another way 76.55% variability of the tree height was accounted for by the six variables. The relative importance of each of the six variables in relation to y can partially be determined by comparing their regression coefficients. To avoid unequal variation in x the standard partial regression coefficients were calculated as stated in Snedecor (1957). The variables were then ranked according to their relative contribution to the regression.

The variables were ranked as follows: (1) slope position, (2) percent exposed rock, (3) Potential plant available water (4) elevation change per chain (5) bulk density and (6) average percent silt plus clay.

Statistical significance of the regression coefficients was tested by checking the calculated "t" value from the regression in a "t" table, at the 95% level and with 12 degrees of freedom, and the result was that only one coefficient was found to be significant. This coefficient was for variable x_2, slope position. A confidence interval for this coefficient was calculated.

$$\text{Confidence Interval} = \pm\, t_{95} \sqrt{\text{variance coefficient}}$$

$$C\ I = \pm\, 2.179 \sqrt{\text{variance coefficient}}$$

$$C\ I = \pm\, 0.37871$$

$$\text{Regression Coefficient for } x_2 \pm\ C\ I = 0.38793 \pm 0.37871$$

Answers for the completed regressions can be found in Appendix C.

The first four variables in the ranking still contribute significantly to the regression when the last two variables are removed. The sums of squares due to regression for the variables of average silt plus clay and bulk density were determined. An analysis of variance test was calculated to see if these two variables in combination contributed significantly to tree height variation in the first regression (see table 4). "F" was found to be less than one. This was not significantly different at the 95% level. Next the sums of squares due to regression for average silt plus clay and bulk density (x_4 and x_5) were subtracted from

TABLE 4.--ANALYSIS OF VARIANCE TABLE TESTING THE EFFECT OF THE VARIABLES OF AVERAGE PERCENT SILT PLUS CLAY AND BULK DENSITY ON TREE GROWTH FOR THE REGRESSION

Source	Degrees of Freedom	Sums of Squares	Mean Squares	"F" Ratio
Sums of Squares due to Regression - Tree Height with Average Percent Silt plus Clay and Bulk Density	2	3.302	1.651	<1
Residual	16	27.733	1.733	-
Total	18	31.036	-	-

TABLE 5.--ANALYSIS OF VARIANCE TABLE TESTING THE INFLUENCE OF THE VARIABLES x_1, x_2, x_3, and x_6 INDEPENDENT OF x_4 and x_5 on y*

Source	Degrees of Freedom	Sums of Squares	Mean Squares	"F" Ratio
Sums of Squares due to Regression - y with x_1, x_2, x_3, and x_6	6	23.758	3.960	6.529
y with x_4 and x_5	2	3.302	1.651	-
y with x_1, x_2, x_3, and x_6	4	20.457	5.114	8.432**
Residuals	12	7.278	0.607	-
Total	18	31.036	-	-

*x_1 = Elevation change per chain
x_2 = Slope position
x_3 = Exposed rock
x_4 = Average silt plus clay
x_5 = Bulk density
x_6 = Potential plant available water
y = Average tree height by respective plot

**Four variables still contribute significantly to regression after removing variables x_4 and x_5

the six variable multiple regressions, 1961. This resulted in an analysis of variance including the first four variables x_1, x_2, x_3, and x_6. "F" was found to be 8.43. This was statistically significant at the 99% level (see table 5).

A prediction equation can be developed from the multiple regression.

$$\text{1961 Regression } \hat{y} = \text{constant} + b1\ x1 + b2\ x2 - b3\ x3 + b4\ x4 - b5\ x5 - b6\ x6$$

$$\hat{y} = 12.241 + .019\ x1 + .388\ x2 - .060\ x3 + .003\ x4 - .182\ x5 - .991\ x6$$

The predicted tree height $\hat{y}$ was calculated for each plot. Data from Appendix B was used in this calculation. Symbols used in the prediction equation are clarified in Appendices B and C. The average deviation was calculated from these values for the entire study area. The average deviation is equal to the numerical sum of individual differences between actual tree heights and predicted tree heights over the sum of the predicted tree heights times 100 to convert to a percent. The average deviation was 3.91% with a range of 0.08 percent to 11.17 percent.

Results of multiple regression for specific past tree heights can be found in Appendix C. The "F" ratio for each regression was checked in Snedecor (1957). The "F" ratios for regressions in 1952, 1955, 1958, and 1961 were significant at the 99% level while 1946 and 1949 were significant at the 95% level. The coefficients of determination 1946-1958 were .616, .660, .747, .795, and .802; an increasing trend with increasing age.

Prediction equations for the 1946-1958 regressions follow:

$$1958 \text{ Regression } y = 8.300 + .001\, x_1 + .428\, x_2 - .048\, x_3 + .009\, x_4 + .994\, x_5 - 1.063\, x_6$$

$$1955 \text{ Regression } y = 6.366 - .003\, x_1 + .398\, x_2 - .041\, x_3 + .001\, x_4 + .696\, x_5 - .677\, x_6$$

$$1952 \text{ Regression } y = 2.600 - .004\, x_1 + .294\, x_2 - .017\, x_3 + .029\, x_4 + .712\, x_5 - .460\, x_6$$

$$1949 \text{ Regression } y = .042 - 1.109\, x_1 + .198\, x_2 - .003\, x_3 + .038\, x_4 + 1.211\, x_5 - .510\, x_6$$

$$1946 \text{ Regression } y = -\, .327 - .005\, x_1 + .062\, x_2 - .001\, x_3 + .026\, x_4 + .298\, x_5 - .133\, x_6$$

The predicted tree heights y was calculated for each plot. Data from Appendix B was used in the calculation. The average deviation was then determined for each regression. They were 1958 - 4.53%, 1955 - 6.19%, 1952 - 10.21%, 1949 - 9.62% and 1946 - 12.05%.

As stated before only six variables appeared to have clear-cut relationships to height growth for the present but two other variables did show a slight relationship. On this basis, and hoping to improve the coefficient of determination, the two variables of depth of the solum (new x_4) and potential plant available water in the A horizon (new x_5) replaced the bulk density and the average silt plus clay. Ranking by the standard partial regression coefficient indicated which variables contributed most significantly to the regression equation. Variables x_4 and x_5 in the original regression contributed the least and were then replaced by the two new variables. The "F" ration, R square, and the system of ranking by order of importance were, for all practical purposes, the same as the original regression.

Chapter V

DISCUSSION AND CONCLUSION

After studying and interpreting the results of the data, including the statistical analysis, certain conclusions have been reached. These conclusions will be discussed and explained in the following sections and will result in recommendations for future study with the main purpose of developing workable site quality classification schemes for this region.

Tree Height and the Topographic Position

The initial analysis of variance confirmed the field observation that actual tree height differences existed between various portions of the slope. The analysis of variance involving average tree heights substantiated the assumption that differences in tree growth are adequately expressed by average tree heights. This facilitates the development of site quality criteria based on site index values applicable to various slope locations.

Tukey's test, which included all possible comparisons between slope position means, essentially established three subdivided areas within the study area. These three areas, as noted by the test results, could be grouped into the top portion, the middle portion and the bottom portion. There was a gradual transition from one grouping to the next. The top portion included positions 1, 2, and 3; the middle portion included positions 4 and 5; the bottom portion included positions 6 and 7. Statistical differences between positions mainly followed these three groupings.

The analysis of variance tests showed that specific variations in tree heights occurred between ridge top and slope bottom. Tukey's test pointed out between which specific slope positions tree height differences were statistically significant. Position one was statistically different in tree height from Positions two, four, five, six, and seven. Position seven was statistically different in tree height from positions one, two, three and four.

Tree Height and the Environmental Variables

Six of the ten variables measured in the field appeared to be related to tree height. These six factors were:

1. Slope position
2. Percent exposed rock
3. Potential plant available water in the C horizon
4. Elevation change per chain
5. Bulk density in C horizon
6. Average percent silt plus clay for the profile

These variables, represented by x's, were used in multiple linear regressions with tree heights represented by y. These six factors contributed significantly in all six regressions.

Interpreting the 1961 Regression

The "F" test for this regression was significant at the 99% level, thus emphasizing that these six factors contributed significantly to the regression. The coefficient of determination indicated that 75% of the tree height variability was accounted for by these variables. The prediction equation accounted for a very high percentage of the actual tree height. This can be seen by the very low average deviation which was less than 4 percent. This percentage value is well within limits used in the field of forestry for acceptable volume tables and site index curves.

Slope Position. Slope position was found to be the most important factor influencing tree height differences. After checking the "t" square values for each variable (1/12), slope position was the only variable found to be significantly related to the regression when considered independently. Decreasing site quality was clearly evident when observing several different positions. A definite increase in height occurred from the top position to slope bottom. Lunt (1939) observed that the better site for red pine was on the lower slope where soil was deeper. Soil is generally deeper on the bottom position than on the top positions.

Percent Exposed Rock. The percent exposed rock was rated as being second in importance. The influence of this factor seemed to be related to decreasing tree height when viewing the scatter diagram. In the field an observable direct correlation of increasing percent exposed rock to a decreasing tree height could be seen. Thompson (1929) had noted restricted growth on rocky sites with shallow soil. Excessive rockiness is clearly evident on the absolute top position.

Potential Plant Available Moisture. Potential plant available moisture in the C horizon was of third importance but is probably of greater significance during years lacking sufficient spring and summer rain fall. Toumey (1947), from observation of Scotch pine, felt that the water retaining capacity was particularly important in determining site quality.

Elevation Change Per Chain. The variable of fourth importance was the elevation change in feet per chain. This is actually two-thirds the value of percent slope readings. The average influence of the elevation change per chain reflected an apparent increase in height with this increasing elevation. Turner (1937) noted that slope was highly influencial in determining low site values of mountain soils with slopes greater than 40%.

Bulk Density and Average Percent Silt Plus Clay. The last two variables of bulk density and average percent silt plus clay did contribute to the overall regression, but by statistically removing them from the regression, little was lost. The "F" ratio for the two variables was non-significant at the 95% level. After these two variables were removed the other four variables still contributed significantly to the regression. What this actually means is that the first four variables influence site quality appreciably and that slope position is still the most important factor. Haig (1929), Coile (1935), Coile (1948), and Hicock, et. al. (1931) all had shown silt plus clay alone or in a ratio to be an important factor influencing site quality. Silt plus clay in this study was related to site quality but in a much lesser degree than what previous studies indicate. Soil development on the study area is slight compared to soil development in other areas. Where soil development is more pronounced silt plus clay probably plays a greater role in site quality.

By replacing the last two variables of bulk density and average percent silt plus clay with the next two supposedly important variables, depth of solum and potential plant available water in the A horizon, no change in the regression appeared evident. These two variables probably influence the regression to the same extent as did the two deleted variables. For all practical purposes little emphasis will be placed on these two new variables of depth of solum and potential plant available water in the A horizon.

Interpreting Regressions for 1946-1958

The regressions for 1946-1958 indicate that something is lacking in the prediction of tree heights. The analysis of variance "F" ratio for each regression shows that the six variables contribute significantly to the regressions, but this is not the entire picture. In each preceding regression the variability accounted for by the six variables decreases. After determining the prediction equation, the average deviations were noticeably larger than for the 1961 regression indicating that the equations are not nearly as accurate an estimate of tree height. The larger average deviations indicate that the designated variables do not predict tree height as accurately in past years as they do at present.

After ranking the variables for each regression, the most important variable in each regression was still slope position. The order of importance for each of the other factors varies from one regression to the next, see Appendix C (the largest number in the loss of sums of square for deleted variables is represented by the most important variable).

The variable of climate (held constant and not measured) could be, and probably is, the factor contributing most significantly to variations in tree height through the influence of microclimatic conditions. Variations in temperature, precipitation, and even humidity are very critical factors during earlier years of growth.

Environmental Variables and Site Quality

On the basis of field observation, analysis of variance tests and multiple regressions, several conclusions have been drawn. Tree growth on the study area is appreciably influenced by the six environmental factors of slope position, percent exposed rock, elevation change per chain, potential plant available moisture in the C horizon, bulk density in the C horizon, and the average percent silt plus clay in the C horizon. Bulk density and the average silt plus clay contribute to prediction of tree heights but are of least importance. Most emphasis can be placed upon slope position, percent exposed rock, elevation change per chain and potential plant available water. These four variables do contribute considerably to site quality evaluations as expressed by tree height.

Position of slope was found to be the most critical factor in the study. Differences in tree height are most directly affected by this variable. Tree height differences between slope positions result from a direct interaction of the other environmental variables. Because extreme ranges within some of the environmental variables may be noted under some circumstances, site evaluation of lodgepole pine should not be solely dependent upon slope position. All six variables must be taken into consideration.

Evidence obtained from additional statistical analysis and field work tend to indicate that tree height differences at earlier ages in the tree's development are not as strongly dependent upon the six variables. Other variables may be of greater importance. Microclimatic conditions of temperature, humidity, evaporation, and rainfall associated with specific slope positions, may influence tree growth in the earlier stages.

Suggestions for Further Study

Site quality classification projects should benefit appreciably from this study. The six variables used in the multiple regressions showed excellent relationships to tree growth as can be seen from the accuracy of the prediction equation, especially for the 1961 regression. Reducing the number of variables from six to four was another improvement. These four variables of (1) slope position, (2) percent exposed rock, (3) rise in elevation per chain, and (4) potential plant available water should now be the basis for more intensive study. By slightly modifying collective techniques, measuring procedures, and by expanding the project, a site quality classification scheme is clearly foreseeable.

The variables evaluated in this study resulted in these recommendations:

1. Delineate a study area where more than one aspect can be evaluated.
2. Determine the influences of microclimatic conditions of temperature, precipitation, and humidity on the growth of juvenile lodgepole pine.
3. Measure specifically the environmental variables of percent slope, slope position, potential plant available moisture in the soil profile, percent exposed surface rock, and the average silt plus clay per horizon.

Chapter VI

SUMMARY

This study was conducted to determine significant correlations between the growth of juvenile lodgepole pine and associated environmental factors. Field research was conducted during the summer of 1961 on the South Fork of Panhandle Creek in North Central Colorado. A pure evenaged stand of lodgepole pine 18 to 20 years of age was used for the investigation.

The study area was stratified into seven slope positions with twelve dominant and codominant trees cut within each position. A stem analysis was conducted on each tree with subsequent development of growth curves. Ten environmental factors associated with the sample trees were measured. Scatter diagrams, analysis of variance tests, and multiple linear regressions were employed for analyzing the data during the fall and winter of 1961-1962.

Of the ten variables measured, six of them were selected for use in multiple linear regressions. These six variables were slope position, percent exposed rock, potential plant available moisture in the C horizon, elevation change per chain, bulk density, and percent silt plus clay in the soil profile. Multiple linear regressions were run for the years 1946, 1949, 1952, 1955, 1958, and 1961. Although all six variables were correlated with tree height, bulk density and the average percent silt plus clay were of least importance.

Throughout the entire study the variable of slope position was found to be the most important variable influencing the growth of lodgepole pine. Tree height differences in lodgepole pine are directly correlated with this variable.

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APPENDIX

APPENDIX A

INDIVIDUAL TREE HEIGHTS BY PLOT AND BY POSITION

Plot Number and Position	Tree Height Feet	Plot Number and Position	Tree Height Feet	Plot Number and Position	Tree Height Feet
1a - 1	8.43	6 - 3	13.00	13 - 5	11.20
1a - 1	8.54	6 - 3	10.45	13 - 5	13.05
1a - 1	10.80	6 - 3	9.73	13 - 5	12.57
1a - 1	10.30	6 - 3	11.10	13 - 5	14.01
1b - 1	9.13	7 - 3	10.50	14 - 6	12.23
1b - 1	9.15	7 - 3	10.53	14 - 6	11.24
1b - 1	9.27	7 - 3	13.81	14 - 6	13.40
1b - 1	9.25	7 - 3	11.75	14 - 6	13.01
1c - 1	8.39	8 - 4	13.16	15 - 6	11.40
1c - 1	8.67	8 - 4	13.36	15 - 6	11.73
1c - 1	9.31	8 - 4	11.97	15 - 6	13.00
1c - 1	8.54	8 - 4	12.09	15 - 6	13.08
2 - 2	12.95	9 - 4	12.30	16 - 6	10.38
2 - 2	11.89	9 - 4	13.09	16 - 6	11.69
2 - 2	9.90	9 - 4	9.53	16 - 6	13.49
2 - 2	10.07	9 - 4	9.87	16 - 6	13.51
3 - 2	9.89	10 - 4	11.11	17 - 7	11.45
3 - 2	10.41	10 - 4	11.90	17 - 7	14.80
3 - 2	10.93	10 - 4	9.90	17 - 7	13.14
3 - 2	11.89	10 - 4	11.83	17 - 7	11.20
4 - 2	11.78	11 - 5	11.57	18 - 7	14.41
4 - 2	12.26	11 - 5	13.58	18 - 7	15.32
4 - 2	12.89	11 - 5	13.65	18 - 7	11.30
4 - 2	10.90	11 - 5	11.68	18 - 7	18.47
5 - 3	11.40	12 - 5	9.79	19 - 7	14.40
5 - 3	9.55	12 - 5	14.19	19 - 7	13.61
5 - 3	9.58	12 - 5	12.38	19 - 7	13.57
5 - 3	10.42	12 - 5	13.98	19 - 7	13.71

APPENDIX B

DATA COLLECTED DURING SUMMER 1961 AND USED IN MULTIPLE LINEAR REGRESSIONS

	Environmental Variables						Tree Heights used in Respective Regressions					
Plot	Elevation Change per Chain x1	Slope Position x2	Exposed Rock x3	Average Silt plus Clay x4	Bulk Density x5	Potential Plant Available water x6	First* 1961 y	Second 1958 y	Third 1955 y	Fourth 1952 y	Fifth 1949 y	Sixth 1946 y
No.	Feet	Position	Percent	Percent	wt/vol	Inches	Feet	Feet	Feet	Feet	Feet	Feet
1	1	1	40	34.68	0.84	0.46	8.91	6.82	5.08	3.44	2.26	0.93
2	5	2	15	37.45	1.29	1.24	11.20	8.98	6.80	4.52	2.85	1.19
3	5	2	15	35.57	1.23	1.27	10.78	8.79	6.62	3.90	2.26	0.88
4	5	2	10	45.58	1.01	0.92	11.90	9.28	6.80	4.52	2.52	1.02
5	11	3	25	42.94	1.13	1.37	10.24	8.18	5.90	4.27	2.76	1.05
6	9	3	10	48.93	1.50	2.16	11.07	9.10	7.14	5.10	3.28	1.30
7	11	3	15	26.45	1.31	0.87	11.68	9.50	7.28	4.70	2.73	1.05
8	16	4	30	45.92	0.96	0.88	12.64	10.35	8.00	5.76	3.48	1.45
9	18	4	25	41.49	1.24	0.98	11.19	8.86	6.48	4.31	2.66	1.10
10	21	4	25	43.95	1.02	0.95	11.18	8.70	6.30	4.40	2.75	1.28
11	31	5	25	34.61	1.30	0.80	12.61	10.15	7.45	4.92	2.85	0.93
12	30	5	25	40.32	1.19	1.05	12.58	10.10	7.70	4.84	2.64	0.94
13	28	5	20	37.08	1.10	1.21	12.71	10.16	8.10	5.50	3.36	1.30
14	21	6	7	49.98	1.30	1.37	12.47	10.79	8.72	6.54	4.48	2.00
15	24	6	7	52.64	1.21	1.40	12.30	10.00	7.75	5.42	3.55	1.46
16	22	6	10	38.76	1.20	1.58	12.22	9.84	7.58	5.06	2.80	1.04
17	8	7	2	50.18	1.24	1.70	12.65	10.40	8.16	5.60	3.32	1.62
18	6	7	2	47.60	1.17	1.32	14.88	12.44	9.60	6.46	3.94	1.50
19	6	7	1	34.70	1.26	0.75	13.82	11.90	9.52	6.26	4.00	1.28

*Average tree heights of four trees measured in 1961. This is the most important regression.

APPENDIX C

RESULTS OF THE SIX MULTIPLE LINEAR REGRESSIONS 1946 - 1961

	Variable	No.1 1961	No.2 1958	No.3 1955	No.4 1952	No.5 1949	No.6 1946
Constant 1/		12.241	8.300	6.366	2.600	.042	-.237
Regression Coefficient 2/	x1	.019	.001	-.003	-.004	-1.109	-.005
	x2	.388	.428	.398	.294	.198	.062
	x3	-.060	-.048	-.041	-.017	-.003	-.001
	x4	.003	.009	.001	.029	.038	.026
	x5	-.182	.994	.696	.712	1.211	.928
	x6	-.991	-1.063	-.677	-.460	-.510	-.133
Sums of Square Due to Regression		23.758	23.553	18.966	9.747	4.393	.914
Residual Sums of Square		7.278	5.812	4.877	3.302	2.263	.570
Variance of Coefficient 3/	x1	.001	.001	.001	.001	.000	.000
	x2	.030	.024	.020	.014	.009	.002
	x3	.001	.001	.001	.001	.001	.000
	x4	.002	.001	.001	.001	.001	.000
	x5	4.256	3.340	2.852	1.931	1.323	.333
	x6	.695	.555	.466	.315	.216	.054
Loss in Sums of Squares for Deleted Variable 4/	x1	.254	.001	.006	.015	.089	.016
	x2	3.022	3.685	3.181	1.739	.784	.078
	x3	1.748	1.107	.829	.145	.005	.000
	x4	.003	.032	.000	.324	.542	.258
	x5	.005	.141	.069	.072	.209	.013
	x6	.858	.986	.400	.190	.227	.015
"T" Square	x1	.420	.001	.015	.054	.473	.346
	x2	4.982	7.607	7.828	6.317	4.158	1.164
	x3	2.882	2.286	2.039	.534	.027	.004
	x4	.004	.067	.000	1.177	2.871	5.439
	x5	.008	.290	.170	.263	1.111	.267
	x6	1.141	2.037	.985	.688	1.202	.324

APPENDIX C - Concluded

	No.1 1961	No.2 1958	No.3 1955	No.4 1952	No.5 1949	No.6 1946
Variance	.606	.484	.406	.275	.188	.047
"F" Ratio	6.529	8.104	7.778	5.903	3.883	3.209
Coefficient of Determination 5/	.766	.802	.795	.747	.660	.616

1/ This represents a in the prediction equation

2/ This represents b in the prediction equation

3/ The square root of this times t at 95% level with 12 Degrees Freedom gives the confidence interval for the regression coefficient

4/ These values are similar to the "Beta" coefficient. The variables can be ranked according to their importance

5/ This value multiplied by 100 gives the percent variability accounted for by the six variables in the equation

Abstract of Thesis

GROWTH OF JUVENILE LODGEPOLE
PINE IN RELATION TO SOIL AND SLOPE

The thesis is concerned with determining site-tree growth relationships that exist in pure evenage juvenile stands of lodgepole pine. The study is a basis for developing methods that will eventually predict site productivity.

A pure evenaged stand of lodgepole pine 18 to 20 years in age was chosen for study. Research was limited to an east aspect in this stand. The study area was subdivided into seven positions. Twelve dominant or codominant trees were cut on each position and each tree was subjected to a stem analysis. Three soil pits were dug on each position and soil samples collected from each horizon. A mechanical analysis of the soil was conducted, and soil moisture capacities for each horizon were determined.

A total of ten environmental variables were measured and of this number six variables were found to be highly correlated to the tree height. The six variables were slope position, percent exposed rock, potential plant available water in the C horizon, bulk density in the C horizon, average percent silt plus clay in the soil profile, and elevation change per chain. Analysis of variance tests and multiple regressions were applied to the data. Six multiple regressions using tree heights in 1946, 1949, 1952, 1955, 1958, and 1961 as the dependent variables were analyzed.

Position of slope was found to be the most critical fac-

tor in the study. Differences in tree height were most directly affected by this variable.

Evidence obtained from additional statistical analysis and field work indicated that tree height differences at earlier stages in the tree's development are not as strongly dependent upon the six variables. Other variables may be of greater importance. Microclimatic conditions of temperature, humidity, evaporation and rainfall associated with specific slope positions, may influence tree growth in the earlier stages.

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February 23, 1962.

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