Edaphic factors related to the growth of lodgepole pine in Montana

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EDAPHIC FACTORS RELATED TO THE GROWTH
OF LODGEPOLE PINE IN MONTANA

by

J.R.B. Holmes
B.S.F. Montana State University
1959

Submitted in partial fulfillment of
the requirements for the degree of
Master of Science
in Forestry

MONTANA STATE UNIVERSITY
1960

Approved by:

Chairman, Board of Examiners

Dean, Graduate School

Date

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INTRODUCTION

The management of forest stands is dependent on the productivity of the lands which support them. The quantity of timber which may be grown on an area is dependent on the quality of the site. Site has been defined as the sum of the effective conditions under which a tree or tree community lives (21), and also in terms of productivity, the size of a crop that can be produced in a given time (3).

Because of the natural tendency of lodgepole pine (Pinus contorta Dougl.) to reproduce in dense stands, most of the stands in Montana are overstocked, and to some degree stagnated, and are not suitable for site determination in the usual manner. Therefore, some other method must be devised by which lodgepole pine sites can be evaluated.

Purpose of the study: The purpose of this study was to identify certain soil characteristics to determine their influence on the height growth of lodgepole pine. The results of this study may provide basic information leading to the determination of lodgepole pine site quality by soil evaluation.
SILVICS OF LODGEPOLE PINE

General Description: Some taxonomists recognize two varieties of this pine. One form, restricted to low elevations along the Pacific Coast is "shore pine" (Pinus contorta var. contorta). The interior or mountain form is "lodgepole pine" (Pinus contorta var. latifolia).

Since no reliable botanical differences have been found by which the two can always be distinguished, it seems that this pine is morphologically variable, and both forms constitute a single species (17). Recent taxonomic research has lead to the proposal that the species be divided into four sub-species (11). To the writers knowledge this proposal has not as yet been widely accepted.

The Pacific Coast form is a small tree usually 25 to 30 feet high and 12 to 18 inches in diameter at maturity. The bole is often contorted and of little commercial value.

The interior form is a medium sized tree, 70 to 80 feet high and 15 to 30 inches in diameter at maturity. This form has the greater commercial value throughout the range of the species, and is the subject of this study.

Growth Characteristics: In view of the greater commercial importance of the interior form, all discussion in the following text will be related to this form.

Lodgepole pine is a prolific seeder, often producing fertile seed before it is ten years old. Heavy cone crops

2.
are produced at one to three year intervals, but the cones may remain closed for many years with little loss of seed viability (40). These serotinous cones accumulate on the trees and supply great quantities of seed following fire or cutting.

These cone characteristics enable lodgepole pine to completely occupy sites which would normally be stocked by other species. Frequently stocking in lodgepole pine stands is so dense that stagnation occurs. This tendency toward stagnation presents one of the most serious problems in the management of lodgepole pine stands.

Lodgepole pine is shade intolerant, and is exceeded in this respect only by western larch among its main associates. In spite of its pronounced intolerance, it can maintain itself in extremely dense stands for as long as 80 to 100 years (40).

Ecology of the species: Lodgepole pine may be grouped into two ecological categories: 1. subclimax stands, and 2. seral stands (40).

1. Subclimax stands: These stands, usually initiated by fire, are maintained by natural and artificial factors other than climate, usually fire or soil water relationships. These stands may have occupied the sites for so long that they could be considered climax. Stands of this kind are generally isolated from seed supplies of species with the natural potential for replacing them (40).
2. Seral stands: In these stands, the presence of an appreciable amount of reproduction of other species and the mixed composition of the understory indicate that lodgepole pine is but a temporary occupant of the site. These stands are generally in close proximity to seed sources of species which can replace them (40).

Range of the Species: Lodgepole pine is widely distributed throughout western North America. Figure I shows the geographical distribution of the species.

The Coastal form is restricted to elevations from sea-level to 2,000 feet. The interior or mountain form may be found at elevations from 1,500 feet to 11,500 feet (17).

Biotic associations: Merriam (28), identifies lodgepole pine with the Canadian life zone, where it is a major timber species of the Cascade, Sierra, and Rocky Mountain ranges.

At the lower limits of its altitudinal range, lodgepole pine is found in association with ponderosa pine (Pinus ponderosa), Douglas-fir (Pseudotsuga menziesii var. glauca), and western larch (Larix occidentalis).

At middle elevations it is found associated with western larch, Douglas-fir, western white pine (Pinus monticola), aspen (Populus tremuloides), and Jeffrey pine (Pinus jeffreyi).

At the upper limits of its altitudinal range it is found in association with Engelmann spruce (Picea engelmannii), subalpine fir (Abies lasiocarpa), white bark pine (Pinus albicaulis), red fir (Abies magnifica), limber pine (P. flexilis).
GEOGRAPHICAL RANGE OF LODGEPOLE PINE (40).

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A wide variety of subordinate vegetation can be found associated with lodgepole pine stands, a list of the vegetation encountered in this study will be found in Appendix II. The five subordinate plants most frequently encountered on the sample plots are, in order of frequency of occurrence:

Vaccinium (Vaccinium sp.), Pinegrass (Calamagrostis rubescens), Spiraea (Spiraea sp.), Beargrass (Xerophyllum tenax), and Arnica (Arnica sp.).

Although no attempt was made to correlate the presence of these subordinate plants with site quality, the possibility that such a correlation exists should not be overlooked in future studies.
ECONOMIC IMPORTANCE

Lodgepole pine occupies the third largest area, 14.8 million acres, of any tree species found in the western United States. The four Rocky Mountain States - Montana, Idaho, Wyoming, and Colorado contain 80 percent of this acreage. Montana has 4.7 million acres, 31.8 percent of the total. The Montana acreage supports a total volume of 6.9 billion board feet of saw timber, or approximately 1.5 thousand board feet per acre (27).

Lodgepole pine is one of the best softwoods, comparing favorably with ponderosa pine and western white pine for lumber, pattern stock, etc. The use of lodgepole pine for lumber is sixteen times greater today than it was in 1933, and further increase can be expected with the development of better logging and manufacturing techniques (27).

The use of lodgepole pine for pulp has increased from a national total production of 9 thousand cords in 1946, to 132 thousand cords produced by the Rocky Mountain region alone in 1952. Montana's contribution to the 1952 total was 129 thousand cords. In 1956, Montana produced 99 thousand cords of lodgepole pine pulpwood (27).

In 1955, over 200 thousand lodgepole pine poles were treated and used for telephone and rural electric lines (27).

The main problem in the utilization of lodgepole pine is its small size. This problem should be minimized with the advent of improved edge-gluing and laminating processes.
REVIEW OF THE LITERATURE

The productivity of forest land is governed by many factors and combinations of factors. Soil conditions, effective precipitation, insolation, competition between members of the plant community, and physiographic features, as well as other factors, all share in the control of site quality. Some of these, either singularly, or in combination with others have been found to have a pronounced effect, while still others have been found to exert very little influence.

As this paper is primarily concerned with soil-site relationships most of the literature reviewed deals with the effect of soil conditions on the growth of plants and trees; the following is a brief review of past work in this field.

Soil texture: Haig (16) found the texture of the A horizon to be a good indicator of site quality. The best Douglas-fir sites were found on medium textured soils (15), and Holtby (24), found that ponderosa pine grew best on soils with a high content of fine material.

In a study involving the brown, weakly podzolized soils of Connecticut, Haig (16), found that the silt plus clay (material below 0.05 mm. in size) content of the subsurface horizons materially affected the growth of forest trees. Productivity increased as the silt plus clay content increased up to a point, then decreased as the content increased further. Coile (10), found that the depth to the B horizon, 8.
where the silt plus clay would be concentrated, is directly related to site quality.

**Soil depth:** In two studies, one dealing with the growth of yellow poplar (1), the other with black locust (2), Auten found soil depth to be an important growth controlling factor. He determined that bedrock found within twenty four inches of the surface indicates poor sites for black locust due to the poor water holding capacity of the profile. A profile depth of less than twenty four inches over a hard packed substratum was conducive to poor site conditions for yellow poplar.

Gaiser (13), and Lemmon (25), found that site quality increased with increased depth to a moisture impermeable subsoil and consequent increased depth of rooting.

Soils with deep A horizons have been found most productive for white oak (14), and most of the southern pines (10).

**Soil Moisture:** Soil moisture has been termed the dominant factor controlling site quality (41).

In a study designed to correlate Douglas fir site quality with certain soil factors, Hill and his associates found that soils which have clay pans impeding soil moisture penetration to lower horizons are relatively nonproductive (22). Bates (4), found that under conditions of low soil moisture, the concentration of the soil solution became so great that the uptake of nutrients by the trees was impeded.
Soil drainage: Soil drainage has been found to have a varied influence on site quality.

Auten (2), found that poor drainage, indicated by mottling above fourteen inches, was conducive to poor black locust and black walnut sites. Wilde (42), however, states that glei horizons found deep in the profile indicated accessible ground water and subsequently good sites, providing aeration was not limited.

Soils with imperfect internal drainage were found to be ideal for the growth of loblolly pine (13), but the quality of yellow poplar sites increased as drainage improved (1).

Soil fertility: Little success has been achieved in the United States in the attempt to correlate forest soil fertility with site quality (1,16). However, the instances where fertility factors have proven significant in this country, coupled with the findings of investigators abroad, indicate that the chemical complex of the soil must be considered a possible site controlling factor in soil-site investigations.

Soil reaction has been found closely related to the production and quality of alfalfa in New Jersey. The per acre production increased five times as the pH of the soil was raised from 5.1 to 6.7 (5). While carrying out fertility investigations on a number of Oklahoma soils Harper (18), found that the available phosphorus content dropped rapidly when the soil pH was reduced below 6.2.

Mitchell and Chandler (30), found a definite correla-
tion between the site quality for certain deciduous trees of
the northeastern United States and the nitrogen content of
the leaves of the trees occupying the sites. They also es-
stablished a correlation between radial stem growth and avail-
able nitrogen in the soil. In Australia, Stoate (39), discover-
ed a serious nutrient deficiency in forest plantation soils.
He determined the main deficient elements to be nitrogen,
phosphorus, and zinc, and eliminated the deficiency symptoms
shown by the trees by applying fertilizers containing these
elements.

Chapman (9), has shown that an increase in the soil
nitrogen supply produces a definite height and diameter
growth response in many forest tree species. He measured the
growth rates of several forest tree species grown at various
distances from a stand of black locust. The closer the trees
were to the black locust the better was their growth. He
attributed this growth increase to the nitrogen supplying
ability of the black locust.

Young (43), Richards (33), and Boomsma (6), found
phosphorus deficiencies in soils of pine plantations in
Australia resulting in reduced growth rates of the young
pines. In all cases the deficiencies were corrected, and
improved growth rates achieved through the use of phosphate
fertilizers. Heiberg and White (20), corrected a potassium
deficiency in forest soils of northern New York, and increased
the growth rate of the trees growing there through the add-

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12.

Application of a commercial potassium fertilizer to the soil.

Olson (31), working with forest soils in Kansas, examined the soils under chlorotic oak and pine stands. He found the chlorosis to be the result of iron and manganese deficiencies. Iron, manganese, cobalt, and boron deficiencies were found to be the cause of reduced growth rates of young pines in Australian plantations. The condition was corrected by treating the soil with compounds containing these elements (19).

Reports of the successful use of commercial fertilizers to increase growth rates of forest trees have come from all parts of the world. To really elaborate on the subject of forest fertilization is well beyond the scope of this paper, but the reader is urged to read the collection of abstracts on the subject in "Forest Fertilization" by D.P. White, and A.L. Leaf, published by Syracuse University, College of Forestry, 1956.

**Mensurational Studies:** Lodgepole pine presents much different mensurational problems than do other forest tree species. It would therefore be somewhat impractical to apply the results from work in other species to lodgepole pine problems.

The field of stand factor-site quality study in lodgepole pine has received little attention to-date. Past studies, although limited in number, indicate that stand density closely controls volume and height growth (26,38).
The Intermountain Forest and Range Experiment Station of the U.S. Forest Service is currently establishing permanent plots to study the effect of various stand factors on lodgepole pine growth. Some of the mensurational data from their work has been incorporated into this study.

Conclusions: From the results of past work it is evident that site investigations would not be complete or conclusive unless both stand and soil factors were considered. From a soils standpoint the physical properties may be expected to give the best correlations with tree growth, but it would not be practical to totally ignore the chemical aspects.

In spite of the fact this is primarily a soil-site study, stand factors such as age, tree diameter, and stand density must be included in order to properly apportion the gross effect of all factors considered.
Figure II shows the location of the seventy seven sample plots used in the study. These plots, scattered from the Coram district in the north, to the Phillipsburg area in the south, and from the Polson area in the west, to the White Sulphur Springs-Monarch areas in the east, were taken in pure, even aged lodgepole pine stands. The range of stand ages was from 22 years to 96 years. The plot locations were chosen by Mr. David Tackle of the Intermountain Forest and Range Experiment Station, Missoula Research Center, for use in a lodgepole pine density-growth study. Mr. Tackle and his crew took the mensurational data used in this study.

The plots are in small groups, ranging from two to eight plots per group. Each group includes a range of densities considered to bracket well-stocked conditions. The size of the plots varies with stand density and uniformity; for the most part they are one-tenth acre, or slightly less.

On any one plot the density is uniform over the entire plot area, and the trees have been free from the influence of cutting, and relatively free from fire, disease, and insects during the life of the stand. In some of the older stands evidence of minor fires and insect infestations was found, but the influence of these intrusions on growth has been negligible.
PLOT DISTRIBUTION IN LODGEPOLE PINE TYPE OF MONTANA.

* -- Plot Group
SOILS

During the summer of 1959, soil profiles were examined on seventy seven permanent lodgepole pine plots established by the Intermountain Forest and Range Experiment Station in the field seasons of 1957, 1958, and 1959.

**Soil sampling:** The pit location on each plot was selected as being the most representative of general plot conditions with regard to slope, litter accumulation, surface drainage, surface disturbance, and other observable surface conditions.

A complete profile description, as outlined in the United States Department of Agriculture Soil Survey Manual, Handbook 18, was made for each pit, and included such items as:

1. Identification of horizons.
2. Horizon thickness.
3. Horizon boundary description.
4. Soil color.
5. Soil consistency.
7. Depth of rooting.
8. Percentage volume of stone.
9. Internal profile drainage.
10. Classification of the soil.
11. Bulk density by horizon, where possible.
12. Identification of the parent material.
Soil profile variation: A variety of soil conditions were encountered during the course of the field work. Most of the soils were classified as Brown Podzolic or Gray Wooded, but some showed characteristics of both groups and were considered intergrades.

Modal profile descriptions: A modal profile description characterizes the typical profile for a given soil and wide variation can be expected under field conditions.

1. Brown Podzolic: Thin dark gray A₁ and thin gray-brown, or yellowish-brown A₂ over a brown B horizon which is fluffy, and only slightly heavier than the surface soil. The solum is seldom more than twenty four inches thick.

2. Gray Wooded: Thin organic-mineral A₁ over a light colored, bleached A₂, over a brown, more clayey, blocky, or nuciform B₂, grading into a lighter colored, more friable B₃ or C horizon.

Variations in the Brown Podzolic group: The Brown Podzolic soils examined were, generally, very shallow immature soils which often varied quite markedly from the modal.

Surface horizons: The A₁ horizons, although rarely found, varied from scattered pockets to well defined organic-mineral horizons up to one and one-half inches thick.

The A₂ horizons were sometimes found as mere
gray flecks but in other places were well defined
gray-brown horizons up to two inches thick. All Brown
Podzolic soils examined possessed A₂ horizons.
B horizons: The greatest variation in the Brown Pod-
zolics was found in the B horizons; some were only six
inches deep, typically Brown Podzolic, and could not
be subdivided. Others were nearly two feet deep, typi-
cally Brown Podzolic, and could not be subdivided, as
color, structure, consistency, etc., were uniform
throughout; while still others were up to two feet
deep and could readily be subdivided into B₂₁ and B₂₂
horizons on the basis of color, structure, texture, or
consistency.
Structure varied from very weak fine crumb to moderately
well developed subangular blocky. The variation in con-
sistency was from soft to slightly hard when dry, and
from only slightly sticky to quite plastic when wet.
Texture variation was the least pronounced feature of
the Brown Podzolics. None of the soils were very coarse
textured, and in only one instance was a B₂₂ horizon
found to be remarkably high in clay.
C horizons: In most cases the material in the C horizons
is highly weathered parent material interspersed with
soil closely resembling that of the overlying B.
Parent Materials: In most cases the parent rock was
argillite. In one series of high elevation plots the
parent material was argillite bedrock, while in another series at high elevations it was siltstone and limestone colluvium. Most of the profiles exposed at lower elevations were developing from argillite glacial valley fill, or illuvium, fine sands and gravel.

Variation in the Gray Wooded group: Although fewer Gray Wooded soils were examined, a wider range of variation from the modal was found among them.

Surface horizons: A1 horizons were not always present, but where found, ranged in thickness from thin, almost indistinguishable horizons, to well developed organic-mineral horizons two and one-half inches thick. A2 horizons were always present and varied from mere gray flecks in some instances to well developed horizons ten inches thick.

B horizons: The B horizons were readily subdivided in most cases. The structure of the B21 horizons varied from a fine weak crumb to a weak subangular blocky. Consistency varied from only slightly sticky to very plastic when wet, and from very friable to very hard when dry. The range in structure of the B22 horizons was from well developed blocky with strong clay skins, to moderately well developed subangular blocky. The consistency range was from firm to very hard when dry, and
from slightly plastic to very plastic when wet. Considerable variation was found among those B horizons which could not be subdivided. In one instance where the soil was developing from coarse quartzites the B horizon was very sandy, almost structureless, loose when dry, and non-sticky when wet. In another instance where the parent rock was high in feldsper, and the water table was within eleven inches of the surface, the B horizon was a structureless, water sodden mass, which was very plastic when wet, and extremely hard when dry.

In some of the deeper profiles, a transitional B3 was found. The soil in these horizons was generally quite similar to that in the overlying B2, although not so well developed. The incidence of parent rock was usually quite high but weathering was advanced over that of the underlying C horizon.

C horizons: The C horizon in these soils was usually parent material in the advanced stages of weathering.

Parent materials: Gray Wooded soils were found developing from a variety of parent materials. Coarse textured, almost structureless soils were found developing from almost pure quartzite. Medium textured soils with fine weak crumb to weak subangular blocky structures were found developing from limestone and sandstone colluvium. Several fine textured soils with
well developed blocky structures were found developing from such parent materials as micaceous quartzite, and argillitic materials very high in feldspar.

Variation among the intergrades: In these soils characteristic Brown Podzolic surface horizons were found over characteristically Gray Wooded subsurface horizons. Deep, well developed A₂ horizons characteristic of the Gray Wooded group were found over fluffy, homogeneous B horizons characteristic of the Brown Podzolic group.

The parent materials were usually argillites of various origins from glacial outwash to colluvium.

Laboratory Analyses: A number of analyses were performed on the soil samples collected in the field. A detailed description of the analytical procedures is included in Appendix I. These include: 1. Textural analysis; 2. Moisture retention at field capacity and wilting point; 3. Total nitrogen; 4. Organic matter content; 5. Exchangeable potassium; 6. Exchangeable phosphorus; 7. Soil reaction.
MENSURATION

The mensurational data used in this study were collected by the Missoula Research Center of the Intermountain Forest and Range Experiment Station 1/. The following data were taken in the field using conventional forest measurement devices and techniques:

1. Diameter tally of all trees on the plot by one inch diameter classes.
2. Total height of ten dominant trees on the plot.
3. Stand age, determined as the average of the ages of the ten dominants.
4. Live crown length of the ten dominant trees.

The following data were computed for each plot in the offices of the Missoula Research Center using conventional techniques:

1. Basal area per acre.
2. Average diameter of the dominant trees.
3. Average height of the dominant trees.
4. Stems per acre.
5. Average stand diameter, the diameter of that tree having the average basal area.
6. Ratio of crown length to total height of ten dominant trees.

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1/ Data provided under Supplement #3 to Master Memo of Understanding June 6, 1958 between U.S. Forest Service and Montana State University, Contract No. 12-11-204-1.
MISCELLANEOUS DATA

Other information regarding general plot conditions gathered from the plot sites included:

1. Amount of surface stone.
2. Landform of the general area.
3. Position of the plot on the slope.
4. Percent slope.
5. Exposure.
6. Relief, or surface drainage conditions.
7. A list of the subordinate vegetation in order of abundance.

Table V. shows the minimum, mean, and maximum values for all measurements made.
Table V: Ranges of values of laboratory and field data.

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<th>Maximum</th>
<th>Mean</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height - av. ten dom. (ft.)</td>
<td>74.3</td>
<td>44.3</td>
<td>13.8</td>
</tr>
<tr>
<td>Age - av. ten dom. (yrs.)</td>
<td>96.2</td>
<td>46.5</td>
<td>22.0</td>
</tr>
<tr>
<td>Stems per acre</td>
<td>7360</td>
<td>1610</td>
<td>140</td>
</tr>
<tr>
<td>Diameter - av. ten dom. (ins.)</td>
<td>12.5</td>
<td>6.4</td>
<td>2.3</td>
</tr>
<tr>
<td>Av. crown-hy. ratio dom.</td>
<td>0.962</td>
<td>0.599</td>
<td>0.343</td>
</tr>
<tr>
<td>Percent silt / clay</td>
<td>85.0</td>
<td>56.9</td>
<td>12.0</td>
</tr>
<tr>
<td>Percent clay</td>
<td>43.0</td>
<td>17.4</td>
<td>5.0</td>
</tr>
<tr>
<td>Effective profile depth (in.)</td>
<td>44.5</td>
<td>11.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Total profile depth (in.)</td>
<td>46.5</td>
<td>17.8</td>
<td>5.3</td>
</tr>
<tr>
<td>Av. percent avail. moisture</td>
<td>33.5</td>
<td>17.1</td>
<td>4.0</td>
</tr>
<tr>
<td>Av. percent organic matter</td>
<td>5.2</td>
<td>2.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Av. percent total nitrogen</td>
<td>0.1341</td>
<td>0.0661</td>
<td>0.0186</td>
</tr>
<tr>
<td>Av. exchangeable P. (p.p.m.)</td>
<td>50.0</td>
<td>27.6</td>
<td>12.0</td>
</tr>
<tr>
<td>Av. exchangeable K. (p.p.m.)</td>
<td>78.0</td>
<td>25.7</td>
<td>13.2</td>
</tr>
<tr>
<td>Percent slope of plot site</td>
<td>55</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>Depth abundant rooting (in.)</td>
<td>24.0</td>
<td>13.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Soil pH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface horizons</td>
<td>6.33</td>
<td>5.65</td>
<td>5.00</td>
</tr>
<tr>
<td>B horizons</td>
<td>7.73</td>
<td>6.00</td>
<td>4.54</td>
</tr>
<tr>
<td>C horizons</td>
<td>7.90</td>
<td>6.19</td>
<td>4.58</td>
</tr>
</tbody>
</table>

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The influence of the soil and mensurational factors on site quality was determined by multiple regression analysis. The following is an outline of the factors entering into the analysis.

**Dependent variable:** The logarithm of average height of the dominant trees on the plot: The height of the tree is probably the best expression of growth available to foresters. The logarithm of height was used because it tends to give straight line relationships when plotted against other variables.

**Independent variables:** Seventeen independent variables were included in the initial analysis, they were:

- **X₁** -- Reciprocal of average age of the dominant trees: The reciprocal of age was used because it expresses more realistically the relationship between annual percentage growth increase and stand age. The percentage increase drops as the age increases; the percentage volume increase plotted over age of the stand gives a declining curve (37).

- **X₂** -- Stems per acre: The actual number of stems per acre was entered as an expression of stand density.

- **X₃** -- Average diameter of the dominant trees: Average diameter of the site trees was entered in an attempt to correlate height with diameter when other site factors

25.
were considered.

\( X_4 \) -- Ratio of average crown length of dominants to total height of dominants: Ratios of crown length to total height is a possible replacement for stems per acre as an expression of stand density, and was determined as follows:

\[
\text{Ratio} = \frac{\text{length of live crown}}{\text{total height of tree}}
\]

\( X_5 \) -- Percentage silt plus clay in the E horizon, weighted by the effective thickness of the E horizon. The percentage of fine material in the surficial portion has been found to be an important site quality factor. For the purpose of this study the effective thickness of any one horizon in a profile is defined as:

\[
ET = TT (1 - S/100)
\]

Where:

- \( ET \) = Effective thickness of the horizon.
- \( TT \) = Total thickness of the horizon.
- \( S \) = Percentage volume of stone in the horizon.

\( X_6 \) -- Percentage clay in the E horizons weighted by effective horizon thickness: The fertility and moisture characteristics of these soils should be controlled primarily by the colloidal complex of the E horizon.

\( X_7 \) -- Effective depth to the C horizon: The total effective depth of the profile is the sum of the thicknesses of the effective horizons above the C.
$X_8$ -- **Total depth to the C horizon:** Rather than introduce percentage volume of stone into the analysis, the profile depth, with stone, was used; profile depth, less percentage volume of stone, was entered as $X_7$. The effect of the stone is shown by the comparison of correlation coefficients of each of the two variables on the dependent variable.

$X_9$ -- **Average percent available moisture in effective profile:** The percentage of available moisture retained by each horizon of each profile was determined by the method outlined in Appendix I. An average available moisture percentage was computed for each profile in the following manner:

$$Pr = \frac{(Hd_1)(Hr_1)}{Hd_1} \div \frac{(Hd_2)(Hr_2)}{Hd_2} \div \cdots \div \frac{(Hd_n)(Hr_n)}{Hd_n}$$

Where:

$Pr$ = Average percentage available moisture retained by the effective profile.

$Hd$ = Effective depth of each horizon in the profile.

$Hr$ = Percentage available moisture retained by one horizon in the profile.

$X_{10}$ -- **Average percentage organic matter in the effective profile:** Organic content was determined as outlined in Appendix I, and was averaged for each profile in the same manner as available moisture.
X11 -- **Average percent nitrogen in the effective profile:**
Total nitrogen was determined as outlined in Appendix I and was averaged for each profile in the same manner as available moisture.

X12 -- **Average exchangeable phosphorus in the effective B horizons:** Exchangeable phosphorus was determined as in Appendix I and averaged in the same manner as available moisture.

X13 -- **Average exchangeable potassium in the effective E horizons:** Exchangeable potassium was determined as in Appendix I and was averaged in the same manner as available moisture.

X14 -- **Percent slope of each plot site:** Slope was entered into the analysis as a percent figure. Although slope may influence site in other ways, the primary interest in this study was the effect on surface drainage. Very few of the slopes encountered were steep enough to have much influence in any other manner.

X15 -- **Depth of abundant rooting:** The depth of abundant rooting is an indication of the volume of soil available for root development.

X16 -- **Interaction of reciprocal of age and effective profile depth:** Older trees may be expected to require a greater volume of soil to maintain good growth because of their more extensive root systems. This variable was entered as the simple product of the two factors involved.
X17 -- Interaction of reciprocal of age and available moisture in the effective profile: Older trees may be expected to require more moisture than do younger trees because of their larger crowns, and more extensive root systems. This variable was entered as the simple product of the two factors involved.
RESULTS OF THE STATISTICAL ANALYSIS

The analysis of variance for the initial seventeen variable regression is shown in Table I.

The correlation coefficients of each independent variable with the dependent variable were tested for significance by referring to a table of significance for multiple correlation coefficients. The nine significant variables were regrouped for a second regression analysis.

The independent variables chosen for this second analysis were: $X_1, X_2, X_3, X_4, X_9, X_{10}, X_{11}, X_{16}, X_{17}$. The analysis of variance for this nine variable regression is shown in Table II.

A regression equation including four mensurational variables, three soil variables, and two interactions between soil variables and the reciprocal of age was derived from this final analysis; the equation takes the form:

$$Y = b_0 + b_1X_1 + b_2X_2 + \ldots + b_nX_n,$$

and is presented as follows:

$$Y = 1.71830 - 4.91000 X_1 - 0.00024 X_2 + 0.04296 X_3$$
$$- 0.55580 X_4 - 0.02227 X_9 + 0.06020 X_{10} + 2.84800 X_{11}$$
$$+ 0.80130 X_{16} + 0.14950 X_{17}$$

As is shown by the $R^2$ value - Table IV - this equation explains 90 percent of the height variation found in the sample data. Only 3.6 percent of the variation is explained by the variables which were dropped in the second analysis; 6.4 percent of the variation is due to error.

30.
Table I: Analysis of variance for the seventeen variable regression.

<table>
<thead>
<tr>
<th>Source of Variance</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Variance</th>
<th>Sample &quot;F&quot;</th>
<th>Table &quot;F&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>R17</td>
<td>178.83</td>
<td>17</td>
<td>10.52</td>
<td>50.10</td>
<td>1.80 *</td>
</tr>
<tr>
<td>Error</td>
<td>12.32</td>
<td>60</td>
<td>0.21</td>
<td></td>
<td>2.30 **</td>
</tr>
<tr>
<td>Total</td>
<td>191.15</td>
<td>77</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* - 5% point
** - 1% point

Table II: Analysis of variance for the nine variable regression.

<table>
<thead>
<tr>
<th>Source of Variance</th>
<th>Sum of Squares</th>
<th>Degrees of Freedom</th>
<th>Variance</th>
<th>Sample &quot;F&quot;</th>
<th>Table &quot;F&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>R9</td>
<td>172.03</td>
<td>9</td>
<td>19.11</td>
<td>91.00</td>
<td>2.04 *</td>
</tr>
<tr>
<td>R8</td>
<td>6.80</td>
<td>8</td>
<td>0.85</td>
<td>4.05</td>
<td>2.11 *</td>
</tr>
<tr>
<td>Error</td>
<td>12.32</td>
<td>60</td>
<td>0.21</td>
<td></td>
<td>2.85 **</td>
</tr>
<tr>
<td>Total</td>
<td>191.15</td>
<td>77</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* - 5% point
** - 1% point
Table III: Correlation coefficients of the independent variables with the dependent variable.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$ - reciprocal of age -</td>
<td>- 0.741</td>
</tr>
<tr>
<td>$X_2$ - stems per acre -</td>
<td>- 0.526</td>
</tr>
<tr>
<td>$X_3$ - average diameter -</td>
<td>/ 0.809</td>
</tr>
<tr>
<td>$X_4$ - crown-height ratio -</td>
<td>- 0.668</td>
</tr>
<tr>
<td>$X_5$ - available moisture -</td>
<td>/ 0.249</td>
</tr>
<tr>
<td>$X_{10}$ - percentage organic matter -</td>
<td>/ 0.259</td>
</tr>
<tr>
<td>$X_{11}$ - percentage nitrogen -</td>
<td>/ 0.203</td>
</tr>
<tr>
<td>$X_{16}$ - recip. of age X effective depth</td>
<td>- 0.339</td>
</tr>
<tr>
<td>$X_{17}$ - recip. of age X available moisture</td>
<td>- 0.259</td>
</tr>
</tbody>
</table>

Table IV: $R^2$ values showing proportion of sum of squares of dependent variable explained by each source of variance.

\[
\begin{align*}
R_{17}^2 &= \frac{178.33}{191.15} \times 100 = 93.555 \% \\
R_9^2 &= \frac{172.03}{191.15} \times 100 = 89.997 \% \\
R_6^2 &= \frac{6.80}{191.15} \times 100 = 3.557 \% \\
R_{16}^2 &= \frac{12.32}{191.15} \times 100 = 6.445 \%
\end{align*}
\]
DISCUSSION OF THE RESULTS

The results of this study show that nine measurable factors are significant in the measurement of site quality for lodgepole pine in Montana. The correlation coefficients depicting the association of each variable with height will be found in Table III.

As would be expected, there is a direct relationship between the height of a tree and its age. In Table III it will be noted that the correlation coefficient for age is negative, this is because the reciprocal of age rather than age itself was used in the analysis.

The height growth of lodgepole pine is inversely related to stand density. Both density factors, stems per acre, and ratio of crown length to total height, have negative correlation coefficients, indicating a decrease in height growth as the stand density increases. This height decrease is probably a result of severe competition for moisture and nutrients; the competition increases as stand density increases. This inverse relationship is in agreement with the results from other lodgepole pine studies (26,38).

The direct relationship between tree height and tree diameter is much closer than was expected at the outset, although some direct correlation was expected. This relationship has the highest correlation coefficient of any of the relationships investigated.
The amount of available moisture retained by the soil profile is directly and significantly related to the height growth of the trees it supports. As mentioned in the discussion on stand density, the supply of available moisture is undoubtedly limited in the lodgepole pine areas investigated; therefore, the growing conditions for the trees involved improves directly with the increase in the amount of available moisture retained by the soil profile.

Organic matter and total nitrogen are both significant height controlling factors. Organic matter has the highest correlation coefficient of the two, because it is not only the greatest source of nitrogen, a significant factor in itself, but it has a marked influence on the moisture holding capacity of the soil as well.

The direct significance of total nitrogen, one of the most essential nutrients, is not surprising. Although many of our forest soils may not be deficient in available nitrogen, the results of the nitrogen investigations discussed in the review of the literature indicate that the best growth can be expected where the supply is greatest.

A significant inverse relationship is shown between height growth and the interaction of age and the effective depth of the soil profile. The relationship is inverse, and not direct as one would expect, because the reciprocal of age was used. The significance of this relationship may lie in the fact that as trees get older and larger, their height
growth becomes more dependent on the amount of soil available for root development.

The use of reciprocal of age was responsible for the inverse, rather than direct, relationship between height and the interaction of age and available moisture in the effective soil profile. The fact that this variable is significant indicates that the height growth of older trees, with more fully developed crowns and root systems, is more dependent on the moisture holding capacity of the soil profile than is the height growth of younger trees.
SUMMARY AND CONCLUSIONS

Soil and stand information was gathered from seventy-seven plots in the lodgepole pine type of Montana. The study, although primarily a soil-site investigation, included certain stand factors in order to obtain and apportion the gross effect contributed by all the factors considered important in the measurement of site quality for lodgepole pine.

A multiple regression analysis using height as the dependent variable, and seventeen soil and stand factors as independent variables revealed that only nine of these factors were significantly related to height growth. A second analysis was carried out using only the nine significant independent variables. A regression equation was formulated which represents the relationship between tree height and these nine soil and stand factors. This nine variable equation explains ninety percent of the variation in tree height encountered in the study.

Table III shows the correlation coefficients of each of the significant variables with tree height. The four stand variables (reciprocal of age, stems per acre, average diameter of dominants, and the ratio of crown length to total tree height) show greater individual significance than do the three soil variables (percentage total nitrogen, percentage organic matter, and available moisture) or the two interactions (effective profile depth X reciprocal of age, available moisture X reciprocal of age).

36.
A more reliable test of significance would have been a "t" test on the regression coefficients in the nine variable regression, unfortunately the regression program available to us at the Montana State College Computer Laboratory did not provide the intermediate information necessary to carry out this test.

In conclusion, the significance shown by some of the soil and stand factors in the control of height growth, indicates that future site investigations in the lodgepole pine type would produce more accurate results if a soils-mensurational approach were used.

The site evaluation formula presented in this paper is not intended as a working tool, but as a foundation upon which future investigations into lodgepole pine site quality may be based.
APPENDIX I

METHODS OF ANALYSIS

Soil sampling was carried out in the months of June, July, and August, 1959. Analyses were begun in September and completed in December of 1959. All analyses were done in the soils laboratory of the Montana State University School of Forestry, and included:

Textural analysis: A fifty gram portion of each soil sample was placed in a dispersing cup with ten ml. of sodium metaphosphate and approximately one hundred ml. of tap water. The samples were allowed to stand overnight to obtain aggregate dispersion. At the end of the eight hour dispersing period the samples were placed in the receptacle of a standard milkshake mixer and stirred for ten minutes to complete the dispersion. At the conclusion of the stirring the samples were transferred to one-liter soil cylinders, a Bouyoucos soil hydrometer was put in the suspension, and the volume brought up to one liter with tap water.

The suspension were allowed to stand until their temperatures equalled room temperature; the textural analysis was then carried out by the standard Bouyoucos method (7,8).

Moisture retention: Each soil sample was tested for moisture retention at field capacity (one-third atmosphere of pressure) and wilting point (fifteen atmospheres of pressure) using the equipment and procedures outlined by Richards (34). The difference between percentage retention at field capacity and
percentage retention at wilting point was considered the percentage of available moisture retained by each soil.

**Total nitrogen:** The total nitrogen content of each soil was determined by the standard Kjeldahl method as outlined by Russel (36), and modified for use in the Montana State University School of Forestry soils laboratory by the author (23).

**Organic matter content:** The organic matter content of each soil sample was determined colorimetrically by modification of Schollenberger's wet combustion method (36). A standard curve was constructed by preparing solutions of known organic content, using anhydrous dextrose (C₆H₁₂O₆) as the organic agent.

**Exchangeable Phosphorus:** The soil samples from the P horizon of each profile were tested for exchangeable phosphorus by the method outlined by the author (23), and using a Lumetron photoelectric colorimeter.

The extraction of the phosphorus was accomplished using a hydrous sodium acetate-glacial acetic acid extracting solution. Ammonium molybdate was used as the precipitating agent, the characteristic blue color of the molybdate-phosphate complex was developed by employing stannous chloride as the reducing agent.

**Exchangeable potassium:** The soil samples from the P horizons were analyzed for exchangeable potassium by colorimetric methods as outlined by the author (23).
The same extracting solution was used for the phosphorus determination. Cobalt-nitrite was used as precipitating agent, and the turbidity of the solutions was measured in terms of light transmission employing a Lumet photoelectric colorimeter.

Soil reaction: The pH of each soil sample was determined by a Beckman glass electrode pH meter, model H-24. Detailed procedures for use of the instrument.
APPENDIX II
SUBCUTINATE TUBERHOLES

The following is a list of the subcutoines encountered on the plot sites; they are listed in order of frequency of occurrence.

<table>
<thead>
<tr>
<th>Scientific Name (sp)</th>
<th>Common Name (c5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vaccinium sp.</td>
<td>Vaccinium</td>
</tr>
<tr>
<td>Calamagrostis rubescens</td>
<td>Fine grass</td>
</tr>
<tr>
<td>Spiraea sp.</td>
<td>Spiraea</td>
</tr>
<tr>
<td>Xerophyllum tenax</td>
<td>Beargrass</td>
</tr>
<tr>
<td>Arnica sp.</td>
<td>Arnica</td>
</tr>
<tr>
<td>Berberis sp.</td>
<td>Creeping holly</td>
</tr>
<tr>
<td>Arctostaphylos uva-ursi</td>
<td>Kinnikinnick</td>
</tr>
<tr>
<td>Rosa sp.</td>
<td>Wild rose</td>
</tr>
<tr>
<td>Pseudotsuga menziesii</td>
<td>Douglas fir</td>
</tr>
<tr>
<td>Pachystima myrsinites</td>
<td>Pachystima</td>
</tr>
<tr>
<td>Lupinus perennis</td>
<td>Lupine</td>
</tr>
<tr>
<td>Amelanchier alnifolia</td>
<td>Service berry</td>
</tr>
<tr>
<td>Ceanothus sp.</td>
<td>Ceanothus</td>
</tr>
<tr>
<td>Linnaea borealis</td>
<td>Twinflower</td>
</tr>
<tr>
<td>Picea engelmanni</td>
<td>Engelmann spruce</td>
</tr>
<tr>
<td>Juniperus sibirica</td>
<td>Ground juniper</td>
</tr>
<tr>
<td>Chimaphila umbellata occidentalis</td>
<td>Pipsissewa</td>
</tr>
</tbody>
</table>
Subordinate vegetation (Cont').

<table>
<thead>
<tr>
<th>Scientific Name</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Populus tremuloides</td>
<td>Aspen</td>
</tr>
<tr>
<td>Salix sp.</td>
<td>Willow</td>
</tr>
<tr>
<td>Rubus parviflorus</td>
<td>Thimbleberry</td>
</tr>
<tr>
<td>Larix occidentalis</td>
<td>Western larch</td>
</tr>
<tr>
<td>Physocarpus sp.</td>
<td>Ninebark</td>
</tr>
<tr>
<td>Fragaria sp.</td>
<td>Wild strawberry</td>
</tr>
<tr>
<td>Trillium sp.</td>
<td>Trillium</td>
</tr>
<tr>
<td>Ribes sp.</td>
<td>Ribes</td>
</tr>
</tbody>
</table>
REFERENCES CITED


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43. Young, H.E. 1948. The Response of Loblolly and Slash Pines to Phosphate Manures. Ed. J. Am. For. Soc. 5: 77-105. (Forest Fertilization Anniv. 46.)

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