THESIS

SITE-VEGETATION RELATIONSHIPS IN THE MONTANE ZONE OF NORTHERN COLORADO

Submitted by
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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR

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ENTITLED SITE-VEGETATION RELATIONSHIPS IN THE
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BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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A study of this type is of necessity the result of the cooperative efforts of numerous individuals. All have contributed greatly and I would like to express my most sincere appreciation to these people for their aid in completing this study and for their considerable time and interest.

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Chapter I

INTRODUCTION

Ever growing demands are being made upon the natural resources of the western United States. These demands are varied and sometimes conflicting, consequently it is necessary for the land manager to select specific areas to meet specific needs.

Uses in the ponderosa pine (*Pinus ponderosa* Laws.)[1] vegetative type in Colorado include recreation, wildlife, logging, grazing, and numerous others. The timberman and cattleman are oftentimes using the same area and question arises as to which resource, the timber or the forage, should have priority on a particular site. Resolution of this problem is not always a simple task since numerous considerations such as demand for these products and others, cost of management, present productivity, and potential productivity should enter into the final decision.

Little work has been done to determine what kind of situation is superior for ponderosa pine production or for the production of native herbaceous vegetation associated with ponderosa pine. Perhaps the emphasis on management would shift in many areas if research could resolve this question.

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[1] Scientific nomenclature for trees is taken from Preston, R. J., Jr. 1961. North American trees; exclusive of Mexico and tropical United States. 2nd ed. Iowa State University Press, Ames. 395 p. Names for grasses and forbs are according to Harrington, H. D. 1954. Manual of the plants of Colorado. Sage Books, Denver. 666 p.

Objectives

This study deals with the search for site factors which could be measured, independent of the vegetation, and could then be used to determine the suitability of a site for the production of ponderosa pine and native herbaceous vegetation. Evaluation independent of vegetation is important since one may wish to consider burned or denuded areas or convert other existing vegetation that might be present.

The objectives are: to identify the site factors which are important in determining the productivity of an area for both ponderosa pine and native herbaceous species, and to develop a growth prediction equation for ponderosa pine and for native herbaceous vegetation which can be used to determine the site suitability for these two crops.

Definition of terms

The following definitions are those which apply to certain terms as used in this study:

Total height index.-- the average total height measured in feet divided by the average total age of the trees sampled on a plot, multiplied by thirty.

Five year growth index.-- the average length of the previous five years leader growth of sample trees on a given site measured in inches.

Total herbaceous vegetative production (herbaceous production).-- the mean annual yield in pounds per acre of all grasses and forbs present in the clipped plots.

Growth prediction equation.-- an equation developed through stepwise multiple regression analysis and used to indicate the productive capacity of a site for a particular crop.

Percent silt plus clay.-- the percent silt plus the percent clay of a given soil horizon on a dry weight basis.

Inches silt plus clay.-- the sum of the percent silt and the percent clay, multiplied by the bulk density and effective thickness of a given horizon. This value may then be added to similar values for other soil horizons to compute inches of silt plus clay to the desired depth, such as, the C horizon.

Weighted mean percentages (of some soil constituent).-- the sum of the products of the dry weight percentage times the rock and gravel-free horizon thickness for each horizon included, divided by the total rock and gravel-free depth.

Effective depth.-- the rock and gravel-free soil depth computed by multiplying the actual depth by 1.00 minus the percent (decimal) rock and gravel.

Nutrient index (for example: exchangeable calcium index or cation exchange capacity index).-- the amount of a nutrient expressed in milliequivalents (meq.) per 100 grams multiplied by the effective soil depth being considered.

Site or Landscape.-- a uniform land area capable of producing a specific kind and amount of vegetation, and which reacts uniquely to management.

Site index.-- refers to the forester's site index and is the average total height of the dominant trees on a site at some specified base age.

Site suitability.-- the relative productivity of a site with respect to its capacity to produce a crop in question under a defined level of management.

Warm season.-- that period of time between May 1 and September 30.

Cold season.-- that period of time between October 1 and April 30.

Frost-free season.-- that period between the last spring minimum of 32°F or below and the first fall minimum of 32°F or less. This period will be used as an indication of the length of the growing season.

Special note

B. P. Kayastha, graduate student from Nepal, collected data for his thesis problem from the same sites and used the same sample trees as those used in this study. Results of his research will be cited in this thesis since they were utilized in the analysis of data.

Chapter II

REVIEW OF LITERATURE

Investigation of the numerous factors which might influence growth is difficult due to the complex manner in which any one factor acts. Kozlowski (1955) states that a complex of environmental factors (climate, soil, biotic) affect tree growth and that their effects are interacting, interdependent, and reciprocal.

When considering a particular site, the conditions imposed upon the plant in this relatively localized situation are considered to be the sum of the effective factors which influence growth, among which, one or more are dominant. Also, the order of dominance of these various factors may change during the period between the germination of the seed and maturity (Heiberg and White, 1956).

The optimum conditions for growth vary according to the species considered. Billings (1950) noted that within an area having the same climate, physical and chemical soil differences cause differences in pattern and composition of the climax vegetation. Herbage production as well as composition differences between two adjacent areas, both supporting the same species have also been found (Crockett, 1964; Passey and Hugie, 1963). Coile (1948), working in mixed stands of loblolly (*Pinus taeda* L.) and shortleaf (*Pinus echinata* Mill.) pine, found that loblolly pine had a consistently higher site index than shortleaf pine in the study areas.

Soil factors influencing vegetative production

Some of the numerous soil factors which have been found to influence the growth of vegetation will be discussed below under various headings. It is somewhat illogical to discuss the effect of any one factor on production since its influence is measured in combination with other factors, however this means of coverage will reduce repetition.

The reader should note that some items (parent material and organic matter, for example) influence both the physical and chemical soil properties but will be discussed under a single section only.

Physical factors--

The majority of studies encountered which deal with soil-plant relationships indicate that physical soil properties are more commonly the dominating influences on growth.

Bulk density and internal drainage.-- Carmean (1954) found that site quality for Douglas-fir (*Pseudotsuga menziesii* Franco) decreased with increased soil compaction. Trees growing on relatively compact soils had an average site index of 140 feet at a base age of 100 years while the site index for trees on loose soils averaged 200 feet. The author stated that the effect of the compaction was probably related to restricted root development resulting from poor aeration and restricted internal drainage. Auten (1933) noted soils with lower bulk densities had higher water absorption rates and thus better internal drainage characteristics. Later, (1945) the same author found that the depth to tight subsoil (high in clay) was the primary factor influencing site quality of yellow poplar stands in southeastern Ohio. Soils exhibiting a greater depth to tight subsoil and consequent improved internal drainage supported stands of higher mean site index.

An apparent effect on plant composition was noted by Box (1961), who compared four range plant communities in south Texas. He stated that a higher percentage composition of climax grasses were associated with soils of low bulk density and high macro-pore space.

Parent material.-- Numerous soil differences may, at least in part, be attributed to a difference in parent material. Rate of weathering, soil depth, state of maturity, texture, nutrient status, pH, erodability and other factors are related to the material from which a soil is derived (Jenny, 1941).

In investigations of lodgepole pine (*Pinus contorta* Dougl.) growth, Duffy (1964) computed correlations between growth measures and soil factors on three separate parent materials after an analysis of variance showed significant differences between them with respect to productivity, water holding capacity, and nutrient levels. Similarly, Zinke (1958), working with West Coast ponderosa pine and Douglas-fir noted that soils derived from unconsolidated sandstone and recent alluvium gave higher site index values than those derived from serpentine and peridotite.

Rockiness.-- The effect of rock in the profile will depend somewhat on its distribution in the soil and the particular situation encountered. Rock has been noted to reduce tree growth, by decreasing the soil water holding capacity and subsequent productivity, and yet in other instances improve conditions for plant growth.

Relationships between soil and site factors and lodgepole pine growth in Colorado showed site index to be negatively correlated to the percent of surface area occupied by rock. This factor was found to be second only to position on slope in importance of the various factors influencing height growth (Outslay, 1962). Carmean (1954) noted that gravel content of soils reduced their moisture storage capacity and found that Douglas-fir site indices in Washington decreased as gravel content of the soil material above the substrata increased. The effect of a given percentage of gravel appears to be greater in shallow soils than deep soils. For example, at 50 percent gravel (2 mm diameter and over) content site indices averaged approximately 130 feet for soils 15 inches deep and 150 feet for soils 35 inches deep.

Rock is a relatively good heat conductor and in situations where fine textured soils are cold due to high moisture content, the presence of rock may be advantageous. In general, rock content up to 20 percent in heavy textured soils has been regarded as favorable for tree growth (Lutz and Chandler, 1946).

Another effect to be noted is that a layer of relatively coarse material below finer textured material restricts drainage to some degree since upper layers must reach a moisture content above field capacity before movement of the wetting front can occur into the coarser material.

<u>Soil depth</u>.-- Numerous ways of expressing soil depth have

been used by experimenters in correlation studies of vegetation production. These have included depth to C horizon, log depth to C, depth of A horizon, depth to hardpans, depth of moisture penetration, and rock free soil depth (Carmean, 1954; Coile, 1948; Copeland, 1958; and Lemmon, 1955; Myers and Van Deusen, 1960).

Coile (1948) presented data indicating a curvilinear relationship between site index and shallow depths of the A horizon. For both loblolly and shortleaf pine the curvilinearity exists for depths below ten inches. Above ten inch depths the relationship is linear. Coile used the log of site index as the dependent variable in multiple linear regression equations to reduce curvilinearity of this and other relationships. Myers and VanDeusen (1960) found similar relationships with ponderosa pine site index for soil depths (depth to C) below about fifteen inches. However, these investigators used the log of soil depth to reduce curvilinearity.

Forrestall and Gessel (1955) noted that hardpans impede tree root growth thus reducing the amount of growing space in the soil available to the plants. In other studies downward root extension has been found to be limited by bedrock, lime accumulation layers, and strata of loose sand or gravel (Gessel and Lloyd, 1950; Cox, McConnell, and Matthew, 1960). Where moisture storage in the soil is a critical factor, some restricting layers play a dual role by reducing root penetration and soil water holding capacity. Soils less than two feet deep for Douglas-fir and less than one foot for ponderosa pine were such poor environments in the California region that neither produced commercial quality growing stock of the respective species (Zinke, 1958).

In general, the authors cited above found positive correlations between their various measurements of soil depth and tree growth. However, Young (1954) found site index decreased as the depth of the A horizon increased for spruce and pine stands in Maine. Soils supporting pine were well drained, young soils with little B horizon development, while those supporting spruce were, in many cases, heavy textured in the surface, and also exhibited little or no true B horizon characteristics in the subsoil.

Texture.-- Soil texture appears to have more than one effect on vegetation production.

Haig (1929) found that red pine (Pinus resinosa Ait.) site index was highly correlated to the silt plus clay content of the A horizon. Similarly Holtby (1947) noted soil texture measured at a depth of six inches to be a fairly reliable indicator of site quality for ponderosa pine in southeastern Washington.

Hanson and Whitman (1938) studied vegetation-soil relationships on thirty-six grassland areas of the Little Missouri region of western North Dakota. They stated that there appeared to be a correlation between textural heterogeniety and the composition differences in the vegetation, however the authors added that other factors are also related.

In other work, Pawluk and Arneman (1961) dealing with jack pine (Pinus banksiana Lamb.) found silt plus clay content of the soil to be the best single measure of both water holding capacity and cation exchange capacity, each of which was in turn significantly related to tree growth. Apparently the organic matter content was rather low in these soils since the authors stated that with low organic matter content, colloidal clay made up the major portion of the exchange complex.

Soil moisture.-- Numerous investigators have correlated measures of the moisture regime to plant growth. Dix (1958) stated that the most important single factor in determining the kind and number of plants which occupy a given site is soil moisture. Other factors such as slope, exposure, and topography are important only as they influence soil moisture. Similar thinking of researchers in forestry is illustrated by their feeling that the productive capacity of a site for timber is related to factors which provide optimum amounts of available moisture for plant growth over the greatest portion of the growing season (Lemmon, 1955; Pearson, 1918).

Metzger (1935) noted that one might have difficulty in certain climates when seeking soil-plant relationships, in that he found plant yields reflected soil heterogeniety in low moisture supply areas, whereas high moisture supply tended to obscure these soil differences. Nevertheless, investigators have found correlations between such measures as available water holding capacity, moisture equivalent, and imbibitional water value and site productivity (Coile, 1953; Copeland, 1958; and Hickock et al., 1931).

Dahl (1963) found that both depth of moist soil and amount of soil moisture on April 15 were useful indices for prediction of early August grass production in the eastern Colorado sandhills areas.

In correlation studies involving shortleaf and loblolly pine growth, Bassett (1964) used potential evapotranspiration and moisture tension of the top one-foot of soil to obtain a measure of moisture stress for each day of the growing season. The sum of these stress values for this period was then used as an index of productivity and proved to be highly correlated to tree growth.

Pearson (1918) noted another important aspect of soil moisture related to a temperature-moisture interaction. He stated that height growth of ponderosa pine in northern Arizona varied inversely with temperature if there was a moisture shortage. But, where there was abundant moisture, height growth varied directly with temperature.

Chemical Factors--

Concerning the importance of chemical soil relationships, Beadle (1953) stated that in a given soil, nutrient levels and rate of supply determine not only the kind of vegetation but also the structure of the vegetation. Given a uniform climate and physiography, distinct patterns of vegetation will be determined by the concentration of the limiting nutrient. Dix (1958) added that other factors such as salt content also play a significant role in determining composition. (The reader should note again here that most researchers have found physical and moisture relationships to be the dominating influence in plant performance.)

The following studies point out that nutrient deficiencies do exist in certain situations and limit growth of the existing vegetation. Therefore, it is important that they be considered in soil-plant relationship studies.

Nitrogen.-- Hickock et al. (1931), studying young red pine stands, found that the total nitrogen content of the A12 horizon showed a higher correlation with site index than any other factor studied. Forristall and Gessel (1955) noted that total nitrogen content of soils was much higher on the more productive forest areas in northern Washington. Nitrogen content ranged between 7,200 and 8,000 pounds per acre on better producing soils and 3,600 - 4,300 pounds per acre on lower producing soils.

Phosphorus and Potassium.-- Studies of four range plant communities in south Texas by Box (1961) showed that the largest percentage of climax grasses were noted on soils with high phosphorus and potassium content. Box also noted that soils exhibiting the lowest amount of brush cover were highest in potassium. Anderson (1959) studied the relation of environmental factors to height and vigor of lodgepole pine in Colorado and noted that a shortage of phosphorus appeared to be limiting growth but this was not shown to be statistically significant.

Lime.-- As mentioned earlier, one factor which limited ponderosa pine root penetration was a lime accumulation zone. Shallow rooting depth has been shown to be correlated with low site indexes (Cox *et al.*, 1960). Duffy (1964) stratified soils with respect to presence and absence of lime and reported that depth to lime significantly affected height growth in the 60-year age classes of lodgepole pine. In mixed age classes, however depth to lime was not shown to be significantly affecting height growth.

Organic matter.-- There are several properties of organic matter which make its presence in soil quite desirable. Humus exhibits a much higher water holding capacity and cation exchange capacity than clays. The low plasticity and cohesion of organic matter aids in counteracting unfavorable physical soil properties due to excessive quantities of clay through the promotion of soil particle aggregation. Vitamins and hormones are also carried by humus which may at times stimulate both higher plants and microorganisms (Baver, 1956; Buckman and Brady, 1960).

Soil reaction.-- Low pH or soil reaction with subsequent multiple nutrient deficiencies was found to be the cause of vegetation differences between two adjacent sites in the western Great Basin. (Billings, 1950). Altered andesite soils (pH = 4.3) supported scattered ponderosa and jeffrey (*Pinus jeffreyi* Grev. and Balf.) pines with sparse understory vegetation while the other soil (pH = 7.4) underlain by unaltered andesite supported a sagebrush-bunchgrass vegetation. The former was low in nitrogen, phosphorus, and exchangeable bases in comparison to the latter. Storie and Wieslander (1948) found that high producing timber sites in California had a pH of between 5.2 and 6.0 and a large percentage of these contained a subsoil pH of about 5.5. For soils in the Coast Range and Sierra Nevada area the authors state that a pH of 6.5 was approximately the dividing line between timber and non-timber soils and that soils between pH 6.2 and 6.5 produced trees of low commercial quality.

Cation exchange capacity.-- Numerous researchers studying soil-plant relationships sought correlations between exchange capacity and productivity, however relatively few found any evidence that a relationship existed. Forristall and Gessel (1955) reported that higher exchange capacities were associated with the more productive soils in northern Washington. Pawluk and Arneman (1961) correlated site index of jack pine (*Pinus banksiana* Lamb.) with the cation exchange capacity of the A_2 plus B horizons. Site index values at 50 years ranged from 45 to 75 feet for exchange capacities between six and 24 milliequivalents per 100 grams of soil respectively. A plot of the data indicated a curvilinear relationship for lower values of cation exchange capacity.

Landscape characteristics influencing vegetative production

Such factors as slope, aspect, position on slope, and landform are among the more stable factors of the environment and may be important influences upon vegetative composition and production.

Percent slope and topography.-- The percent slope of a site has been found to be negatively correlated to productivity in numerous studies (Lemmon, 1955; Meyers and Van Deusen, 1960; Zahner, 1958; and Zinke, 1958). Zinke noted however, that this correlation was not due to slope alone but was related to soil change with slope increase or decrease. Anderson (1956) stated that as percent slope increased soil depth decreased and vegetative composition changed.

The effect of surface drainage on site index of loblolly pine was investigated by Zahner (1958). Results showed that site indexes were higher on areas of moderate surface drainage (1-2% slope) than on areas of poor (0%) or excessive (3%+) surface drainage. Graphs indicate that excessively drained (3-4%) areas produced better height growth than poorly drained areas.

Results of a study investigating the relation between topography and Douglas-fir site quality by Tarrant (1950) showed that sites having a concave landform had higher site indexes than those with convex landform. Concave sites had a finer surface soil texture, higher soil moisture content, and higher levels of soluble salts, resulting from water movement onto the area rather than away, as was the case for the convex landform.

Position on slope.-- Also negatively correlated with site index in most cases is the topographic position or location of a site with respect to the landform. In general, the greater the distance from the bottom of the slope the lower will be the corresponding site index (Doolittle, 1957; Duffy, 1964; Meyers and Van Deusen, 1960; and Outslay, 1962). An exception to this was noted by Coile (1948) who stratified sites according to topographic position for analysis but later found no difference in site indices attributed to this source.

Elevation.-- The relationship between elevation and site productivity varies with the particular locality. This is illustrated by the following studies.

Lemmon (1955) found that the site index for Douglas-fir decreased with increasing elevation in the Willamette Basin in Oregon. Zinke (1958) noted that in northeastern California the relationship between site index and elevation is influenced by the presence or absence of fog. For Douglas-fir and ponderosa pine outside fog-affected areas, site index increased as elevation increased up to

3,000 feet and then decreased thereafter. Within areas where fog occurred, Douglas-fir site index decreased with increasing elevation.

Aspect or exposure.-- In general, sites on south facing slopes are warmer and drier than those on north facing slopes of the same latitude and altitude (Oosting, 1956). Investigators in soil-plant relationships have noted that significant differences in ponderosa pine height growth occur between different exposures (Meyers and Van Deusen, 1960; Potter and Green, 1964; and Zinke, 1958). Meyers and Van Deusen (1960) incorporated aspect into their equation for predicting site index, but Doolittle (1957), even though recognizing its importance, omitted this variable since he felt other factors (depth of A horizon , position on slope, and percentage of sand in the A horizon) accounted for it indirectly.

Climate.-- With reference to the climate as a whole, Anderson (1962) stated that when the climatic forces operating produce two different soil groups, the respective climax vegetation is different in both kind and amount.

Work done at the Fort Valley Experiment Station in northern Arizona by Pearson (1918) showed that ponderosa pine height growth occurred in the period of lowest precipitation of the year. Because of this, he concluded that growth was mainly dependent upon soil moisture stored from earlier precipitation. The bulk of the precipitation in that area was noted to occur between December and March. However, where two or more inches of precipitation occurred between April and May the affect on height growth was several times greater than the same amount during the December to March period. Where precipitation only occurred in this latter period, height growth was slight.

Most researchers who used precipitation as a factor in predicting tree growth found that the site index increased as precipitation increased (Carmean, 1954, Hill et al., 1948; and Lemmon, 1955). Gessel and Lloyd (1950) and Zinke (1958) however both report decreasing site index relationships with increasing precipitation. In the case of the former, studies in northwestern Washington showed that the site index for Douglas-fir increased for medium and light surface textured soils from 25 to 40 inches mean annual precipitation, but decreased slightly between 40 and 55 inches. Site index of trees on coarse textured soils decreased over the whole range between 25 and 55 inches. The authors suggested that the decreased site index was due to decreased length of growing season associated with a rise in altitude as precipitation increased. Approximately 35-40 inches of moisture was needed to bring all profiles to field capacity, and it was felt that amounts exceeding 40 inches would cause excess leaching. No significant differences in site index between any of the soils was found for 25 inches of precipitation, however the writers felt an increased sample size might have changed this. Zinke (1958) noted that Douglas-fir site index decreased as precipitation increased in fog influenced areas of northwestern California. This was interpreted as a gradual ascent out of the areas of summer fog occurence.

Measurement of tree productivity

Most researchers have used site index as their measure of site quality in soil-plant relationship studies of tree species.

Duffy (1964) indicated that dominant and average height growth of lodgepole pine was predicted with greater accuracy than either basal area or total volume per acre measurements.

Several studies have shown that growth to breast height is quite variable. For this reason a few researchers have experimented with the use of intercept height growth values for various numbers of years above breast height. In a study of juvenile lodgepole pine in Colorado, Anderson (1959) noted that the length of the last three years terminal leader growth was significantly correlated with site index (base age 15 years) but less correlated with site measurements than site index. He recommended using the last five years terminal leader growth to improve this relationship. Wakely and Marrero (1958) measured the five year height growth immediately above breast height as an indicator of site index for longleaf pine (Pinus palustris Mill.) in southern pine plantations. They found this measurement to be rapid and easy to make, and noted that it eliminated variation in tree growth due to planting stock, planting technique, and juvenile injuries. Comparisons with total height measurements showed the intercept more accurately reflected site differences. Heiberg and White (1956) stated that site indexes which reflect more recent performance may be more desirable to the forester than those reflecting past performance. They illustrated their point with two examples. A tree growing in a sandy well drained soil may show poor growth initially but do considerably better later, while a tree in a heavier soil with a restricting layer will do well initially but slow down later.

Competitive relationships between ponderosa pine and herbaceous vegetation

The ponderosa pine zone is composed of areas ranging from dense stands of trees with few understory plants to open parks of principally herbaceous species. Between these two extremes the interrelationships among the herbaceous species and trees become important.

Reproduction--

A continuous supply of ponderosa pine for future use is dependent upon regeneration by natural or artificial means. Reproduction by natural means often fails due to improper climatic conditions and severe competition with understory species where they are present in abundance. Billings (1950) noted this to be the case in his studies in the western Great Basin. However, reproduction and establishment of seedlings does occur throughout the many different sites where ponderosa pine occurs. Potter and Green (1964) found stands of ponderosa pine to be increasing in area in western North Dakota and noted no evidence of decrease. They stated that all sites investigated (pine and grassland) would support this species if moisture conditions were suitable. Similarly, Arnold (1950) noted that ponderosa pine seedlings were invading grassland parks and restocked cutover areas in northern Arizona.

Establishment--

Of the many seeds produced by plants, relatively few find a suitable place in the environment to begin growth and even fewer become established and reach maturity (Gleason, 1964). The duration of the establishment period of trees varies according to the conditions of the environment to which the plant is subjected. Height growth reflects the variable nature of the environment through erratic growth rates usually until the seedling reaches breast height. However, after this time, height growth generally becomes almost uniform and most tree species then exhibit their characteristic growth abilities (Husch, 1956; Bruce and Schumacher, 1950).

Influence of ponderosa pine on herbaceous production--

When the trees are established among the understory species it is appropriate to consider the effects on the herbaceous species as tree growth progresses.

Arnold (1950) found that ponderosa pine seedlings from the 1919 seed crop in Arizona accomplished dominance over herbaceous species after only five years. This was initially accomplished by overcoming root competition for moisture. As growth continued, shading by tree crowns and root competition together caused decreased cover and production of herbaceous plants, which was shared by all species sampled. Cooper (1960) noted similar decreases in herbaceous vegetation production as ponderosa pine canopy cover increased. He developed an equation to express this relationship which indicated that for each one percent canopy cover, herbaceous vegetation decreased linearly at a rate of 21 pounds per acre below that on areas with no pine cover present.

Summary

To summarize, one must conclude that a complex of interrelated factors are operating which influence plant growth. These may be chemical or physical soil properties, climatic influences, or landscape characteristics inherent to a given locality. The relative importance of any single factor, as well as the kind of factors, varies not only between localities in which the investigator may be working, but also between the species he may encounter.

Considering the foregoing, it is evident that in studying soil-plant relationships, one must evaluate as many influences on the plant as possible in order to properly evaluate growing conditions. Most certainly, such studies present a challenge to even the most experienced researchers.

Chapter III

METHODS AND MATERIALS

The study sites selected for investigation extended from the Ansel Watrous Campground in the Cache La Poudre River Canyon, 24 miles from Fort Collins on State Highway 14, upstream to approximately one mile above the Rockwell Ranch in the Little South Fork drainage of the Cache La Poudre River, Larimer County, Colorado (Figure 1). The elevations of these sites vary from 5,860 feet to 8,240 feet. The topography is steep to rolling with rock outcrops commonly occurring on ridge tops and mountain sides.

At lower elevations ponderosa pine grows principally on north-facing slopes and brush or "chaparral" type of vegetation on south slopes; mountain mahogany (*Cercocarpus montanus* Raf.) and bitterbrush (*Purshia tridentata* (Pursh) D. C.) are dominant in the latter areas. Transition at the upper elevations occurs with Douglas-fir (*Pseudotsuga menziesii* Franco) usually occupying north-facing slopes and ponderosa pine the south slopes. Disturbance by fire at these higher elevations may cause replacement of either species by lodgepole pine (*Pinus contorta* Dougl.). On moist areas throughout most of the ponderosa pine zone, one can find stands of quaking aspen (*Populus tremuloides* Michx.), which increase in density by sprouting after disturbance by fire or heavy grazing. Streamside vegetation is dominated by blue spruce (*Picea pungens*

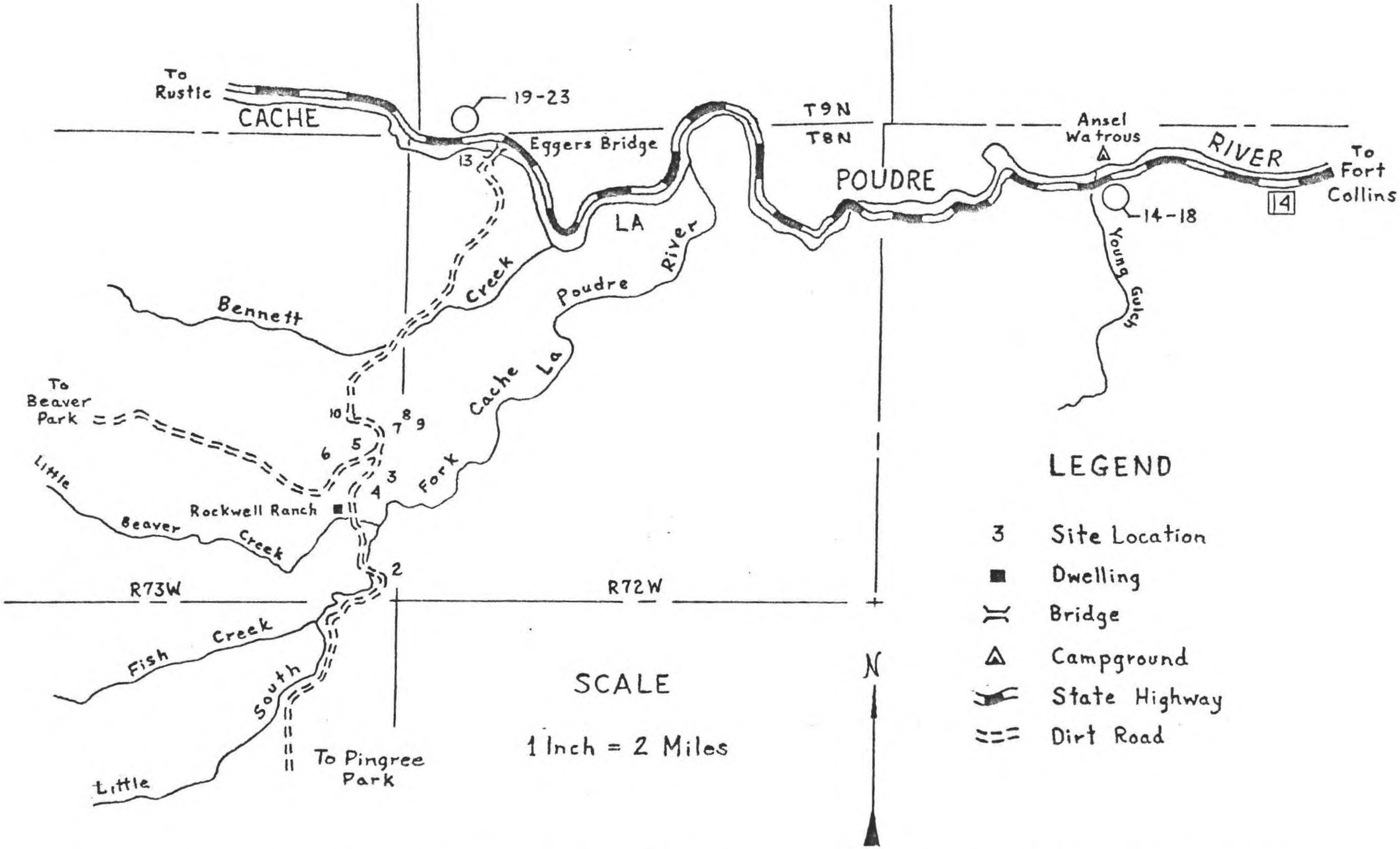

FIGURE 1. Map of a portion of the Cache La Poudre drainage showing location of study sites. Sites are numbered 2 to 10 and 13 to 23.

Engelm.), thinleaf alder (*Alnus tenuifolia* Nutt.), water birch (*Betula occidentalis* Hook.), and thinleaf cottonwood (*Populus angustifolia* James).

The only woody species dealt with in this study was ponderosa pine. The more common grasses included: mountain muhly (*Muhlenbergia montana* (Nutt.) Hitchc.), Idaho fescue (*Festuca idahoensis* Elmer), Spike fescue (*Hesperochloa kingii* (S. Wats.) Rydb.), blue grama (*Bouteloua gracilis* (H.B.K.) Lag.), squirreltail (*Sitanion hystrix* J. G. Smith), junegrass (*Koeleria cristata* (L.) Pers.), Parry oatgrass (*Danthonia parryi* Scribn.), carex (*Carex* spp. L.), needle and threadgrass (*Stipa comata* Trin. and Rupr.), slimstem muhly (*Muhlenbergia filiculmis* Vasey), Kentucky bluegrass (*Poa pratensis* L.) and western wheatgrass (*Agropyron smithii* Rydb.). Forbs and half shrubs included: erigonum (*Erigonum* spp. Michx.), pussytoes (*Antennaria* spp. Gaertn.), goldenpea (*Thermopsis montana* Nutt.), larkspur (*Delphinium* spp. L.), Fendler sandwort (*Arenaria fendleri* A. Gary), lupine (*Lupinus* spp. L.), locoweed (*Oxytropis* spp. D. C.), vetch (*Astragalus* spp. L.), western yarrow (*Achillea lanulosa lanulosa* Keck), fringed sage (*Artemisia frigida* Willd.), and geranium (*Geranium* spp. L.).

All study sites occur on the Idaho Springs geologic formation which is composed of highly metamorphosed sedimentary rocks of pre-Cambian age (Lovering and Goddard, 1950). This formation is the oldest of those occurring in the Front Range of Colorado. Principal constituents are quartz-biotite schists and quartz-biotite-sillimantite schists. Quartzite, quartz schists, and quartz gneisses are also present. Most soils have derived from this material, however, there are indications that upper portions of the study area contain remnants of glacial outwash, which originated at higher elevations in the Little South Fork watershed.

Johnson et al. (1963) divided soils of the montane zone in the Little South Fork of the Cache La Poudre River into five categories: Gray Wooded, Regosol, Lithosol, Chestnut-Chernozem Intergrade, and Chernozem. Preliminary identification of soils described in this study indicates these soils to be from the following great soil groups: Brown and Chestnut (both moderately developed), Lithosol and Regosol.

Climatic data were not collected in this study, however the following data from three weather stations near the study area are presented in an attempt to characterize the conditions spanned by the study sites (Tables 1, 2, 3, 4). Values for the 5-year period and 1964 will be discussed later in reference to production. The 14-year values will be used for comparison purposes.

Hart (1937) found that U. S. Weather Bureau records clearly showed an increase in precipitation with increasing elevation for the Rocky Mountain region. The Estes Park precipitation records (Table 1) do not reflect the above findings, however comparison with other stations of similar altitude indicate that Estes Park precipitation values are below those which are more characteristic of that altitude (John Jones, U. S. Forest Service, verbal statement). Considering this information and

TABLE 1. Warm and cold season precipitation in inches for three weather stations in the proximity of the study area[1]

Station	14-Year (1950-63) Means			5-Year (1959-1963) Means			1964		
(elevation)	Warm Season	Cold Season	Annual	Warm Season	Cold Season	Annual	Warm Season	Cold Season	Annual
Fort Collins (5001 ft.)	9.27 (62%)	5.57 (38%)	14.84	9.56 (61%)	6.11 (39%)	15.67	4.24 (53%)	3.83 (47%)	8.07
Estes Park (7,497 ft.)	9.27 (66%)	4.72 (34%)	13.99	10.55 (71%)	4.31 (29%)	14.86	8.00 (68%)	3.85 (32%)	11.85
Red Feather Lakes (8,365 ft.)	10.06 (59%)	6.94 (41%)	17.00	11.15 (64%)	6.40 (36%)	17.55	7.55 (62%)	4.53 (38%)	12.08

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[1] U.S. Weather Bureau, 1950-1964. vol. 55-69, issues no. 13. sections headed Total Precipitation And Departures From Normal

records reported herein, precipitation in the study area probably does increase with elevation. Average values would be expected to range between 15 to 17 inches annually and 9 to 10 inches during the warm season.

Warm season precipitation is higher than cold season precipitation for all three stations. Comparison of monthly values (Table 2) indicates that Fort Collins is drier during July and August than Estes Park and Red Feather Lakes. May is a wetter month in Fort Collins while September and June precipitation is about the same for all three stations.

TABLE 2. Warm season monthly precipitation in inches for three weather stations in the proximity of the study area[1]

Period	Station	May	June	July	August	September
14-Year[2]	Fort Collins	3.19	1.76	1.38	1.78	1.16
	Estes Park	2.20	1.77	2.05	2.03	1.22
	Red Feather Lakes	2.89	1.57	2.18	2.12	1.30
5-Year[3]	Fort Collins	3.18	1.76	1.52	1.33	1.77
	Estes Park	1.82	2.56	2.06	2.21	1.90
	Red Feather Lakes	3.23	1.98	2.16	1.88	1.90
1964	Fort Collins	1.87	0.54	1.04	0.45	0.34
	Estes Park	1.43	1.03	3.25	1.40	0.89
	Red Feather Lakes	1.47	1.85	1.24	1.78	1.21

[1] U. S. Weather Bureau, 1950-1964. vol. 55-69, issues no. 13. sections headed Total Precipitation And Departures From Normal

[2] 1950-1963

[3] 1959-1963

Temperature generally decreases approximately three degrees F. with each 1000 feet increase in elevation (Oosting, 1956). Weather

TABLE 3. Warm season mean maximum and minimum monthly temperatures in degrees F. for three weather stations in the proximity of the study area[1]

Period		May		June		July		August		September	
		Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
14-Year[2]	Fort Collins	69.2	42.4	80.0	50.1	85.8	55.7	84.0	54.1	76.2	44.8
	Estes Park	62.5	34.6	73.4	40.9	78.1	45.3	76.6	44.5	70.6	37.4
	Red Feather Lakes	59.0	31.9	70.6	38.9	77.0	43.8	75.1	43.8	68.9	37.6
5-Year[3]	Fort Collins	70.3	42.6	80.7	51.2	86.3	55.6	84.7	54.6	74.3	45.3
	Estes Park	63.7	35.2	73.6	41.1	77.9	44.3	77.2	44.9	69.4	38.6
	Red Feather Lakes	60.9	33.4	71.5	41.0	77.4	44.4	75.5	45.4	66.5	38.0
1964	Fort Collins	72.1	43.7	77.0	50.4	89.0	58.8	82.1	51.9	76.1	43.2
	Estes Park	63.5	32.2	69.5	40.2	80.6	46.9	76.0	44.5	70.7	36.0
	Red Feather Lakes	58.3	33.0	65.7	38.5	80.1	49.5	71.8	43.7	66.2	36.5

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[1] U. S. Weather Bureau, 1950-1964. vol. 55-64, issues no. 1-12. sections headed Daily Temperature.

[2] 1950-1963

[3] 1959-1963

Bureau records (Table 3) indicate that this is very nearly the case in the study area.

From reported data, the length of the frost-free season would be expected to range between 70 to 145 days from the upper to the lower elevation study sites respectively (Table 4). In Fort Collins this period begins in early May and ends in the latter part of September. The season extends from late May to early September at Estes Park and from early June to late August at Red Feather Lakes.

TABLE 4. Frost-free season length for three weather stations in the proximity of the study area[1]

Period	Fort Collins	Estes Park	Red Feather Lakes
14-Year (1950-1963)	145	97	70
5-Year (1959-1963)	150	93	79
1964	138	73	69

[1] U.S. Weather Bureau, 1950-1964. vol. 55-69, issues no. 13. sections headed Temperature Extremes And Freeze Data

An increase in precipitation, coupled with a decrease in temperature leads one to surmize that the soil moisture regime improves as elevation increases. However, the decrease in the length of the frost-free season associated with this improvement in the soil moisture regime makes interpretation of possible benefit to plant production complex.

Experimental design

Due to the large number of variables involved in this type of study a combination of scatter diagrams, correlation analyses and stepwise multiple linear regression analyses was used.

Under the assumption that the important factors related to vegetation production vary with changes in productivity, study sites were selected to obtain a wide and continuous range of productivity for both the woody and herbaceous vegetation. Each site was inspected for uniformity of topography and soils. A soil auger was employed for soil inspection where lack of rocks would permit. An elevation range of about 2300 feet was spanned by the study sites to obtain a range of precipitation and temperature.

In all cases but one, landscapes supporting both ponderosa pine and native herbaceous vegetation were selected, thus facilitating productivity measurements of both on the same site. Shrubby vegetation areas were avoided to eliminate their competitive effect. Relatively young ponderosa pine stands (average age 28-58 years, Kayastha, 1965) of moderate to low density were chosen to avoid the between-tree competition, which would cause confounding in productivity correlations. Tree heights were several feet taller than breast height and were assumed to be growing in the early pole stage of their growth curves. Growth above breast height has been shown to be representative of growing ability of other species (Husch, 1956).

Two ponderosa pine plantations, established during Civilian Conservation Corps activity, were utilized. Five different sites were located in each of the two plantations. This afforded trees of very nearly the same age on different sites at different elevations. One plantation is located immediately south of the Ansel Watrous campground (Figure 2) and the other is located approximately one-tenth

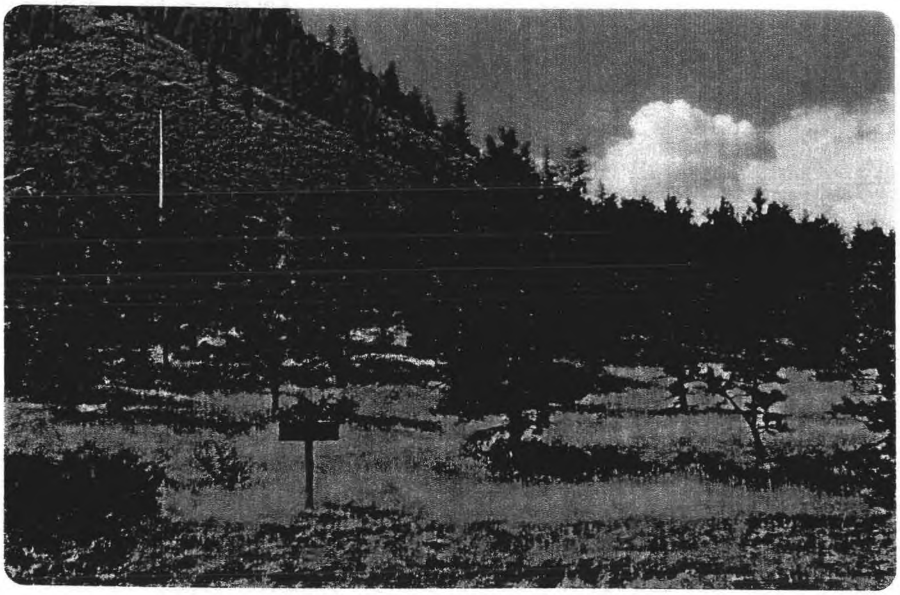


FIGURE 2. General view of a portion of the plantation across from the Ansel Watrous campground. The sign indicates ponderosa pine planted in 1920.

of a mile East of Eggers bridge (Figure 1) on State Highway 14. Both plantations are adjacent to the highway.

Collection of Data

Sites were located and data collected during the period June to mid-September, 1964.

Ponderosa pine production.-- In a companion study, Kayastha (1965) measured 5-year (1954-1963) growth index, total height and total age of three sample trees on the study sites. Five-year growth was obtained by counting the nodes (usually lateral branch whorls) back five years from the node at which the 1964 growth was initiated and measuring this length with a steel tape. This time interval was verified by severing the main stem and counting annual rings. Total age was found by counting annual rings at ground level. Total height was measured from ground level to upper node using a steel tape. One of the objectives of Kayastha's study was to determine which measure of tree growth, 5-year growth index or total height index, was better correlated with physical soil factors. Results of his work have been utilized in this study in order to choose the proper dependent variable for the ponderosa pine growth prediction equation.

Herbaceous vegetative production.-- Due to the short duration of this study herbaceous production could be measured for one growing season only. Five two-foot by four-foot plots were located on each site at points which were felt, through observation, to be representative of the average productivity and yet sampled the range of productivity present also. Wire cages were used to protect plots from being utilized or disturbed by animals. Past grazing use was assumed to have a small effect on plant production since sites were in moderate to light use areas. Annual and perennial plant materials produced on each plot were collected by clipping to ground level at approximately the end of the growing season. Clippings were placed in paper sacks, air dried, and weighed. In placement of the cages, care was taken to stay as far away from the influence of tree roots as possible and still obtain representative productivity values for the site being investigated.

Soils investigation.-- A standard soil description was made according to procedures outlined in the Soil Survey Manual (U. S. Dept. Agr., 1951). Soil samples for laboratory analysis were obtained from the horizons described. Photographs of the soil profile (Figure 3) and general view at each site were taken.

In the soil description, horizon thicknesses were measured with a steel tape graduated in inches. The percent gravel (2 mm. - 3 in. diameter) and rock (3 in. +) by volume was estimated for each horizon. Moist and dry colors were obtained by comparison with a Munsell soil color chart. Field textures were obtained by rubbing. Structural type and degree of development was determined by comparison with previously observed laboratory samples. Tests for presence of carbonates were made by applying 1N hydrochloric acid to soil horizons and noting the amount of effervescense. Abundance and type of roots in each horizon was noted. The consistence of the soil in dry, moist, and wet condition was estimated.

Bulk density measurements were made for each major soil horizon. The vertical face of the profile was cut into horizontally

FIGURE 3. Soil pit at site 17. Note the lime accumulation horizon at a depth of two feet.

to expose the desired horizon, and a soil sample was carefully extracted vertically from an undisturbed portion of the horizon using a knife to loosen the soil, and a kitchen spoon to remove it. Volume of the samples was determined with a Soiltest volumeasure (Figure 4). Soil samples were placed in soil moisture cans to avoid spilling and contamination in transport. Samples were then oven dried, and bulk densities were computed.

Chemical analyses were performed by the Soil Testing Laboratory at Colorado State University. Methods used were those outlined by the U. S. Department of Agriculture (1954) and Olsen et al. (1954). Analysis included available P_2O_5 and K_2O, organic matter, pH, conductivity (soluble salts), carbonates, water soluble (w.s.) sodium, w.s. potassium, w.s. calcium, w.s. magnesium, exchangeable (exch.) sodium, exch. potassium, exch. calcium, exch. magnesium, and cation exchange capacity. From these data total water soluble cations (sum of w.s. Na, K, Ca, Mg), exchangeable hydrogen (C.E.C. - total exch. cations), percent base saturation (100 x meq. exch. cations / C.E.C.), and exchangeable sodium percentage (100 x exch. Na / C.E.C.) were calculated.

Mechanical analyses of the samples were performed following, in major detail, the procedure described by Bouyoucous (1936) employing the hydrometer method. Two modifications of this procedure were made. Samples were allowed to soak in sealed flasks containing distilled water and Calgon solution for one week. Samples were occasionally mixed by shaking to aid the dispersion of soil particles. Also, a blank solution lacking only the soil was prepared. Hydrometer

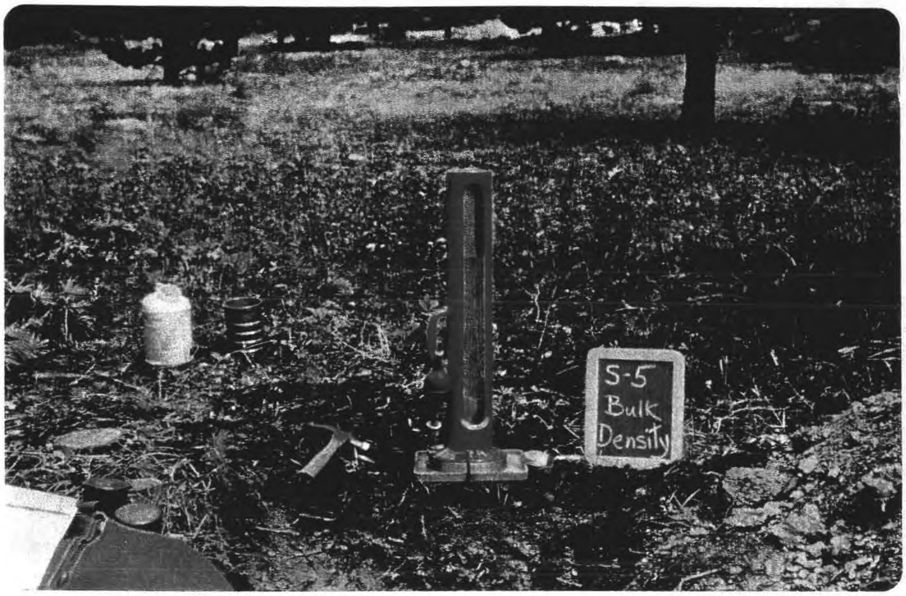


FIGURE 4. View of the Soiltest volumeasure used to determine the volume of soil material extracted for use in bulk density computations.

readings of this solution were used to correct for the presence of Calgon. The same hydrometer was used for all readings.

Measurement of landscape characteristics.-- The percent slope of each site was determined by use of an Abney level. The position of the site was estimated as the percentage of the distance between the top and bottom of a given slope on which the site was located, the bottom being zero percent.

Aspect was found by using a compass and finding the azmuth bearing from true north when the zero degree mark was pointed in the direction the site faced.

Sites were plotted on U. S. Geological Survey topographic maps and elevations recorded.

General observations.-- Field observation was made of items which might influence plant growth but could not be readily evaluated quantitatively. These included, where appropriate, description of landform (concave, convex), character of the soil surface (wavy, smooth, gravelly, compact, etc.), notation of rock outcrops, notes from road cuts as to nature of substrata and soil variability, rodent activity, and presence of ashes evident in the soil from past fire damage.

In addition, observations as to the time of initiation of growth of ponderosa pine relative to grasses and forbs were made.

Chapter IV

ANALYSIS AND PRESENTATION OF DATA

Analysis of the data was divided into two phases. The first phase (correlation analyses) was concerned with the determination and selection of site factors which were significantly correlated with production values, and the second (regression analyses) was the determination of growth prediction equations utilizing the variables selected in the first phase.

Due to the large number of computations necessary for determining the correlation coefficients (r) and the multiple linear regression equations, the computer facilities of the Department of Mathematics and Statistics at Colorado State University were used. To efficiently utilize these facilities, it was necessary to pair all data in the correlation phase. This meant that in order to obtain r-values between site factors and both ponderosa pine and herbaceous vegetation production, the timber-only production plot had to be eliminated from this portion of the analysis.

Correlation analyses

At the outset of this phase of the analysis, results from Kayastha's (1965) study were utilized to make proper choice of the dependent variable for the ponderosa pine growth prediction equation and for correlation purposes. His research concerned determination of the influence of soil depth and texture on ponderosa pine growth.

Two dependent variables were chosen for his correlation analyses: total height index and 5-year growth index. Results showed that the 5-year growth index was highly correlated with soil factors but no significant correlations were found using total height index. Hence, this measure of ponderosa pine productivity was adopted for use in the growth prediction equation as the dependent variable.

As for the independent variables, Kayastha found that the depth of the A horizon was significantly correlated with 5-year growth index ($r = 0.467$) while the depth to the C horizon was not ($r = 0.142$). The correlation with depth of the A horizon was improved by using the effective depth of the A horizon ($r = 0.559$), and still further improved by using the $\log_{10}$ of the effective depth of the A ($r = 0.614$). The log of effective depth was used because a scatter diagram indicated a possible curvilinear relationship. Also used as independent variables were percent sand, percent silt plus clay and inches of silt plus clay for the A and the A plus B horizons where present. All the above variables have been included in this study with the exception of the depth of A and depth to C variables.

From studies reviewed in chapter two and Kayastha's work it was apparent that some independent variables lend themselves to various methods of expression.

<u>Methods of expression of independent variables</u>.-- It should be pointed out that where changing a variable involves merely adding or multiplying by one or a series of constants, the r-value remains the same. A constant is useful however, in simplifying the numbers with which one is dealing. For example, in the case of organic matter content, which is generally expressed in pounds per acre,

values were quite large and dividing by 1000 facilitated ease of handling.

Textural measures, which are usually reported as percentages were also expressed in inches for the silt-plus-clay variable. Thus, one obtains a measure of the amount of silt-plus-clay as well as its relative proportion in the soil.

The organic matter content, more commonly expressed as a percentage, was also computed for correlation in terms of pounds per acre. To accomplish this, the approximation that there are two million pounds of soil per acre-six-inches was used (Buckman and Brady, 1960). The number of pounds of soil per acre-inch was found and then multiplied by the effective depth of the applicable horizon. Horizon values were then summed to obtain a figure for the overall depth that was desired.

Aspect (degrees from North) was handled in the following fashion. Since South and West-facing slopes are generally warmer, it was decided that the change in temperature from cooler to warmer was more rapid from North to West to South than from North to East to South. A proportional relationship between temperature and aspect was assumed from North to East to South. On the other hand, it was assumed that temperature increased much more from North to West than from West to South. Because this gradient was unknown, three curves, each with a different radius, were used to adjust aspect values for the North to West to South directions (Figure 5). The actual aspects in this range (N. to W. to S.) were assigned adjusted values from each of the three curves. The adjusted values

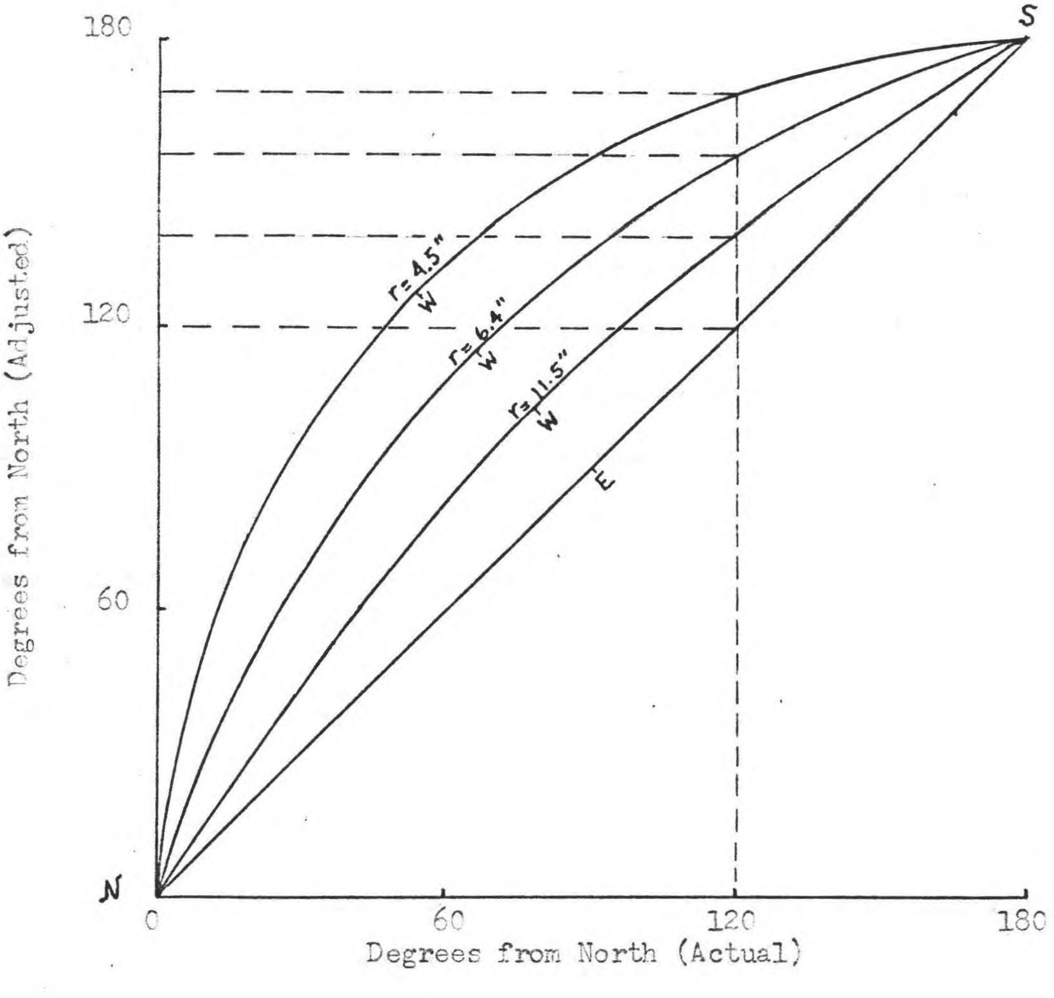


FIGURE 5. Figure showing curves used to determine the adjusted aspect from actual values.

from a given curve were used with unadjusted aspects for the North to East to South directions as a variable for correlation computations. As a result, three different sets of values for aspect were used.

Laboratory values for P_2O_5 and K_2O were reported in pounds per acre-six-inches (pounds per 2 million pounds). These values were converted to pounds per acre-inch, multiplied by the effective depth of the horizon, and values for horizons summed where appropriate.

Exchangeable cations and exchange capacity are generally reported as milliequivalents per 100 grams of soil. Used as such, these values do not reflect the amount of cations available to the plant for a given depth of soil. Therefore, these values were weighted by the effective thickness of their parent horizon and the resulting values summed for the depth desired.

Other variables were expressed in conventional units such as percentages or weighted mean percentages.

Units means and ranges of factors used in the correlation analyses are shown in tables 5, 6 and 7. Some quantities were not used in the correlation analyses because of their lack of variability. These included water soluble Na, K, Ca, Mg; total water soluble cations; exchangeable sodium percentage; soluble salts; and exchangeable Na and K (Table 5). Only five of the sites investigated exhibited a lime accumulation horizon in the soil profile. Because no measure of depth to lime could be assigned to soils on the remaining sites, this variable was eliminated from the correlation and regression phases of this study.

Correlation coefficient values for the remaining site factors

TABLE 5. Mean and range of chemical soil factors considered for correlation analyses

Factor	Units	Mean	
P_2O_5 in A	lbs./A.	47	4 - 172
P_2O_5 to C	lbs./A.	57	4 - 172
K_2O in A	lbs./A.	584	260 - 1558
K_2O to C	lbs./A.	796	260 - 1558
C.E.C. Index of A[1]	meq. in./100 g.	86	37 - 235
C.E.C. Index to C	meq. in./100 g.	139	37 - 247
Exch. Ca Index of A[2]	meq. in./100 g.	69	24 - 196
Exch. Ca Index to C	meq. in./100 g.	112	24 - 336
Exch. Mg Index of A	meq. in./100 g.	17	6 - 57
Exch. Mg Index to C	meq. in./100 g.	24	11 - 57
Total Exch. Cation Idx. of A	meq. in./100 g.	96	39 - 256
Total Exch. Cation Idx. to C[3]	meq. in./100 g.	152	39 - 383
Surface pH	--	6.9	6.3 - 7.8
Organic Matter in A	1000 lbs./A.	72.2	20 - 161
Organic Matter to C	1000 lbs./A.	85.6	20 - 161
Organic Matter in A	Weighted Mean %	2.7	0.4 - 5.9
Organic Matter in Surface Horizon	Percentage	3.2	0.7 - 7.3
Base Saturation in A	Weighted Mean %	93	71 - 100
Base Saturation to C	Weighted Mean %	95	82 - 100
W.S. Sodium a.h.[4]	meq./100 g.	0.01	0 - 0.02
W.S. Potassium a.h.	meq./100 g.	0.01	0 - 0.04
W.S. Calcium a.h.	meq./100 g.	0.04	0.01 - 0.24
W.S. Magnesium a.h.	meq./100 g.	0.04	0.01 - 0.22
Tot W.S. Cations a.h.	meq./100 g.	10.9	5.5 - 38.1
Exch. Sodium a.h.	meq./100 g.	0.18	0.09 - 0.20
Exch. Potassium a.h.	meq./100 g.	0.41	0.16 - 0.78
Exch. Sodium % a.h.	Percentage	1.92	0.6 - 3.4
Conductivity a.h. (Soluble salts)	mmho./cm.	0.2	0.2 - 0.4

[1] Cation exchange capacity index of the A horizon

[2] Exchangeable calcium index of the A horizon

[3] Total exchangeable cation index for soil material above the C horizon, including hydrogen

[4] Water soluble sodium, all horizons

TABLE 6. Mean and range of physical soil factors and landscape characteristics considered for correlation analyses

Factor	Units	Mean	Range
Elevation	Feet	7200	5860 - 8240
Aspect	(adjusted)		
4.5 inch radius	Degrees from N	108	0 - 180
6.4 inch radius	Degrees from N	101	0 - 180
11.5 inch radius	Degrees from N	95	0 - 180
Slope	Percentage	15	4 - 35
Position on Slope	Percentage	50	0 - 95
Rock and Gravel in A	Wtd. Mean %[1]	11	2 - 40
Rock and Gravel to C	Wtd. Mean %	13	2 - 31
Effective Depth of A	Inches	9	4 - 27
Log_{10} Effective Depth A	--	0.893	0.602 - 1.431
Sand in A	Wtd. Mean %	67	57 - 79
Sand to C	Wtd. Mean %	66	52 - 79
Clay in A	Wtd. Mean %	12	7 - 19
Clay to C	Wtd. Mean %	14	8 - 22
Silt plus Clay in A	Wtd. Mean %	33	21 - 43
Silt plus Clay to C	Wtd. Mean %	34	21 - 48
Silt plus Clay to C	Inches	7	3 - 15

[1] Weighted mean percentage

TABLE 7. Mean and range of vegetative production data

Quantity	Units	Mean	Range
Mean Annual Herbaceous Production[1]	lbs./A	945	456 - 2820
Mean 5-Year Growth Index	inches	34	11 - 48

[1] Includes annual and perennial species

and both 5-year growth index and total herbaceous production were obtained (Tables 8, 9, 10, 11). However, all combinations of correlations between site factors were not obtained due to the large number necessary. A number of intercorrelations were obtained concerning some of the soil-plant relationships.

Selection of variables for regression analysis.-- Only those variables which were significantly correlated with productivity values at the 5 percent (r greater or equal to 0.39 for 17 d.f.) levels were selected for possible inclusion in the prediction equation (Tables 8, 9, 10, 11). All available intercorrelation values were found from combinations determined by the computer. These were arranged in tabular form to see the various relationships to each other (Tables 12, 13).

For those variables correlated with ponderosa pine production, percent silt plus clay to the C, percent sand to the C, and percent clay to the C had approximately the same correlation coefficients as the same factors computed for the A horizon. Since significant depth correlations were found only with the A horizon (Kayastha, 1965) it was felt that a prediction equation which concentrated soil measurements on a single horizon (A) would be easier to use in the field. The intercorrelation between these textural variables were quite high, indicating that the quantities were similar. Therefore, variables concerned with the soil were restricted to the A horizon.

The correlation between the percent silt plus clay and the percent sand in the A horizon (-.997) indicates a nearly perfect inverse relationship. This should be expected since the percent sand

TABLE 8. Correlation coefficient values between 5-year growth index and physical factors of the sites[1]

Factor	Units	Correlation Coefficient (r)
Elevation	Feet	0.39*
Aspect	(adjusted)	
4.5 inch radius	Degrees from N	0.17
6.4 inch radius	Degrees from N	0.25
11.5 inch radius	Degrees from N	0.33
Slope	Percentage	-0.66**
Position on slope	Percentage	0.14
Rock and Gravel in A	Weighted Mean Percentage	-0.13
Rock and Gravel to C	Weighted Mean Percentage	-0.11
Effective Depth of A	Inches	0.56**
Log_{10} Effective Depth A	--	0.61**
Sand in A	Weighted Mean Percentage	0.46*
Sand to C	Weighted Mean Percentage	0.48*
Clay in A	Weighted Mean Percentage	-0.41*
Clay to C	Weighted Mean Percentage	-0.51*
Silt plus Clay in A	Weighted Mean Percentage	-0.47*
Silt plus Clay to C	Weighted Mean Percentage	-0.48*
Silt plus Clay to C	Inches	-0.11

[1] Timber-only production plot omitted

* Significant at the 5 percent level

**Significant at the 1 percent level

TABLE 9. Correlation coefficient values between 5-year growth index and chemical factors of the sites[1]

Factor	Units	Correlation Coefficient (r)
P_2O_5 in A	lbs./A.	0.26
P_2O_5 to C	lbs./A.	0.13
K_2O in A	lbs./A.	0.34
K_2O to C	lbs./A.	-0.03
C.E.C. Index of A[2]	meq. in./100 g.	0.24
C.E.C. Index to C	meq. in./100 g.	-0.37
Exch. Ca Index of A[3]	meq. in./100 g.	0.11
Exch. Ca Index to C	meq. in./100 g.	-0.35
Exch. Mg Index of A	meq. in./100 g.	0.35
Exch. Mg Index to C	meq. in./100 g.	0.03
Total Exch. Cations of A	meq. in./100 g.	0.16
Total Exch. Cations to C	meq. in./100 g.	-0.34
Surface pH	--	-0.34
Organic Matter in A	Thousand lbs./A.	0.12
Organic Matter to C	Thousand lbs./A.	-0.11
Organic Matter in A	Weighted Mean Percentage	-0.46*
Surface Organic Matter	Percentage	-0.37
Base Saturation in A	Weighted Mean Percentage	0.28
Base Saturation to C	Weighted Mean Percentage	0.21

[1] Timber-only production plot omitted
[2] Cation exchange capacity index of the A horizon
[3] Exchangeable Calcium index of the A horizon
*Significant at the 5 percent level

TABLE 10. Correlation coefficient values between herbaceous production and physical factors of the sites

Factor	Units	Correlation Coefficient (r)
Elevation	Feet	0.48*
Aspect	(adjusted)	
4.5 inch radius	Degrees from N	0.32
6.4 inch radius	Degrees from N	0.34
11.5 inch radius	Degrees from N	0.35
Slope	Percentage	-0.41*
Position on Slope	Percentage	-0.04
Rock and Gravel in A	Weighted Mean Percentage	0.28
Rock and Gravel to C	Weighted Mean Percentage	0.14
Effective Depth of A	Inches	0.67**
Log_{10} Effective Depth A	--	0.66**
Sand in A	Weighted Mean Percentage	0.07
Sand to C	Weighted Mean Percentage	0.12
Clay in A	Weighted Mean Percentage	0.10
Clay to C	Weighted Mean Percentage	-0.10
Silt plus Clay in A	Weighted Mean Percentage	-0.07
Silt plus Clay to C	Weighted Mean Percentage	-0.17
Silt plus Clay to C	Inches	-0.38

* Significant at the 5 percent level
**Significant at the 1 percent level

TABLE 11. Correlation coefficient values between herbaceous production and chemical factors of the sites

Factor	Units	Correlation Coefficient (r)
P_2O_5 in A	lbs./A.	-0.05
P_2O_5 to C	lbs./A.	-0.14
K_2O in A	lbs./A.	0.49*
K_2O to C	lbs./A.	0.24
C.E.C. Index of A[1]	meq. in./100 g.	0.78**
C.E.C. Index to C	meq. in./100 g.	0.23
Exch. Ca Index of A[2]	meq. in./100 g.	0.64**
Exch. Ca Index to C	meq. in./100 g.	0.23
Exch. Mg Index of A	meq. in./100 g.	0.79**
Exch. Mg Index to C	meq. in./100 g.	0.59**
Total Exch. Cations of A	meq. in./100 g.	0.71**
Total Exch. Cations to C	meq. in./100 g.	0.27
Surface pH	--	0.12
Organic Matter in A	Thousand lbs./A.	0.64**
Organic Matter to C	Thousand lbs./A.	0.48*
Organic Matter in A	Weighted Mean Percentage	-0.18
Organic Matter in Surface Horizon	Percentage	-0.15
Base Saturation in A	Weighted Mean Percentage	0.28
Base Saturation to C	Weighted Mean Percentage	0.21

[1] Cation exchange capacity index of the A horizon

[2] Exchangeable calcium index

*Significant at the 5 percent level

**Significant at the 1 percent level

TABLE 12. Correlation coefficient values (r) among site factors which were significantly correlated with 5-year growth index

Symbol	Site Factor	1	2	3	4	5	6	7
1	Log_{10} Effective Depth A							
2	Percent Silt plus Clay in A	-.533**						
3	Percent Silt plus Clay to C	-.567**	.892**					
4	Percent Sand in A	.527**	-.997**	-.889**				
5	Percent Sand to C	.554**	-.919**	-.930**	.919**			
6	Percent Clay in A	-.181	.412*	.428**	--	--		
7	Percent Clay to C	-.407*	.544**	.694**	--	--	.874**	
8	Percent Slope	-.550*	--	--	--	--	--	--
9	Elevation	--	--	--	--	--	--	--
10	Percent O.M. in A	.566**	-.577**	.383	--	--	.115	.239

* Significant at the 5 percent level
**Significant at the 1 percent level
--Not computed

TABLE 13. Correlation coefficient values (r) among site factors which were significantly correlated with herbaceous vegetative production

Symbol	Site Factor	1	2	3	4	5	6	7	8	9
1	Effective Depth A									
2	Log_{10} Eff. Depth A	.952**								
3	Percent Slope	-.465*	-.550**							
4	O.M. in A (lbs./acre)	--	.579**	-.286						
5	Elevation	--	--	--	--					
6	K_2O of the A	--	--	--	--	-.009				
7	C.E.C. Index of A	--	.763**	--	--	--	--			
8	Exch. Ca Index of A	--	.623**	--	--	--	--	.890**		
9	Exch. Mg Index of A	--	.746**	--	--	--	--	.856**	.758**	
10	Total Exch. Cation Index of A	--	.665**	--	--	--	--	.943**	.986**	.826**

* Significant at the 5 percent level
**Significant at the 1 percent level
--Not computed

is calculated as 100 minus the percent silt plus clay. Because the two were so closely related the percent silt plus clay variable was eliminated. Snedecor (1956) stated that when two independent variables which might be used in a regression equation are highly correlated ($r = 0.95$), elimination of one should be considered.

No intercorrelation was computed between percent sand and percent clay, however the r-value between silt plus clay and clay (0.412) would indicate that these are much less related than silt plus clay and sand. Hence the percent clay was retained for inclusion in the prediction equation.

The weighted mean percent organic matter was eliminated from use as an independent variable. Correlations with nutrient indexes showed that the measure of organic matter expressed in pounds per acre was a more desirable expression since it reflected levels of exchangeable cations while the percent organic matter did not.

Percent slope was inversely correlated with the log depth of the A but the r-value (-.550) was not high and both were included for prediction purposes.

Although no intercorrelations between elevation and other variables were determined by the computer, this factor was included because of the importance of the change in temperature and precipitation associated with changes in elevation.

For the variables significantly correlated with herbaceous production (Table 13), only two were eliminated from use in the prediction equation. The first, $\log_{10}$ effective depth of the A horizon, was eliminated because effective depth of the A horizon gave a better correlation with production and only one soil depth measure was needed. The other factor eliminated was total exchangeable cation index of the A horizon. This quantity is nearly the same as the C.E.C. index of the A. The former is a sum of the exchangeable cations, determined individually, including hydrogen (which is C.E.C. minus the sum of the exchangeable Ca, Mg, Na, and K). The latter is a single determination of the total cation exchange capacity. Since the C.E.C. index was somewhat better correlated with herbaceous production, it was chosen for inclusion in the equation rather than the total exchangeable cation index.

It should be noted that even though the C.E.C. index was highly correlated with the exchangeable calcium and magnesium indexes, these values represent different measurements. The C.E.C. index is a measure of the magnitude of the exchangeable ion complex, while the exchangeable Ca and Mg indexes are a measure of what is held on the complex. All three were included as factors for the computation of the growth prediction equation.

A correlation coefficient between 5-year growth index and herbaceous vegetation production of 0.347 was found. This is not a statistically significant value, however its possible implications will be mentioned in the discussion chapter.

Simple linear regression equations were computed for both kinds of vegetation and the variables selected for the multiple regression equations (Figures 7 - 19).

Regression analyses

The model assumed for both the regression equations follows that for multiple linear regression given by Snedecor (1956) for fixed X-values:

$$Y - a + B_1 (X_1 - \bar{X}_1) + B_2 (X_2 - \bar{X}_2) + e$$

where a and B are the parameters we wish to determine, e the error made in estimating Y, X the independent variable, $\bar{X}$ the mean of X, and Y the dependent variable. B-values are referred to as partial regression coefficients.

The stepwise multiple linear regression method of computation of regression parameters was used in this study. In this procedure the independent variables are selected in an orderly fashion according to their relative importance in prediction of the dependent variable. The X-variable most correlated with Y is chosen first and a regression equation along with an r-value is computed. The next variable selected is that which is most correlated with the remaining variation in Y after that accounted for by the previous X has been removed. A new regression equation is computed, utilizing both the selected X-variables, and a multiple correlation coefficient (R) is also calculated. The procedure continues in a similar fashion until all the X-variables have been included in the regression equation. As each new variable is added to the equation, new partial regression coefficients are computed for the previously selected X-variables which are different from those computed in foregoing steps. The sign of one or more partial regression coefficients may change with addition of new variables, also. Each X-variable in the equation may gain or lose importance in its predictability of Y, according to the manner in which a new variable changes the previous regression equation. Thus, the order of importance of X-variables, generally assigned by the relative magnitude of their individual regression sum of squares, may change as new variables are added (Snedecor, 1956).

The stepwise procedure does not necessarily result in the best equation for prediction of Y. However, it does allow the investigator to evaluate the importance of a given variable at any point in the procedure should he decide to eliminate one or more. To obtain the best possible relationship, all combinations of X-variables and their regression with Y would be required, and this is beyond the scope of the study.

The ponderosa pine prediction equation.-- Included in the information in the computer output is a correlation matrix of the variables used in the prediction equation (Table 14). It should be noted that at this point, the data from the site producing only ponderosa pine entered into the values reported. This one site changed the correlation coefficient values between 5-year growth index and the weighted mean percent clay and elevation variables enough to make them non-significant. However, these two variables were close to the non-significant level previously. As for the other variables, the r-value for slope remained essentially unchanged while the $\log_{10}$ effective depth of the A and the weighted mean percent sand in the A were improved slightly.

TABLE 14. Correlation matrix of factors used in the regression equation for prediction of 5-year growth index

Symbol	Site Factor	1	2	3	4	5
1	5-Year Index					
2	Log_{10} Effective Depth of A Horizon	.64**				
3	Percent Sand in A	.48*	.55**			
4	Percent Slope	-.65**	-.53**	-.49*		
5	Percent Clay in A	-.35	-.11	-.34	.19	
6	Elevation	.36	.35	.29	-.76**	-.32

* Significant at the 5 percent level
**Significant at the 1 percent level

The positive correlations of variables 2, 3, and 6 with 1 indicate individually that as these values increase, the 5-year growth index increases. Similarly, for variables 4 and 5, as these factors increase, 5-year growth index decreases.

Four intercorrelations were significant: log eff. depth A versus sand in the A, log eff. depth A versus percent slope, percent sand in the A versus percent slope, and percent slope versus elevation.

The regression equation using all 5 independent variables for prediction of 5-year growth index was as follows:

$$Y = 79.1305 + 13.6308\ X, -0.01286X_2 -0.7346X_3 -0.8505X_4 -0.0038X_5$$

where: X_1 = $\log_{10}$ effective depth A, X_2 = weighted mean percent sand in the A, X_3 = percent slope, X_4 = weighted mean percent clay in the A, and X_6 = elevation.

The numerical coefficients of the X-variables represent the partial regression coefficients and the constant is the Y intercept.

The multiple correlation coefficient of the equation was $R = 0.81$, and the coefficient of determination R^2 was 0.66. R^2 indicates the percent (as a decimal) of the variability of Y accounted for by the regression equation. A test of the equation using the statistic F showed that it was significant at the one percent level.

The amount of the total sum of squares accounted for by each independent variable immediately upon entering the regression equation is a measure of the importance of this variable at that time and may be tested (Table 15). Variables are shown in order of selection in the stepwise procedure.

TABLE 15. Multiple coefficients of determination, regression sum of squares, and F-values for variables at their initial appearance in the regression equation

Variable	R^2 (including previous variables)	Regression sum of squares after previous variables	F-value
Slope	0.423	519.59	13.17**
Log eff. depth A	0.540	143.87	4.32
Percent clay in A	0.591	63.72	2.03
Elevation	0.654	78.52	2.78
Percent sand in A	0.661	7.32	0.25

**Significant at the 1 percent level

The only significant contributor to the regression equation in the stepwise process was slope. However, log eff. depth A was almost significant at the five percent level (tabled F = 4.45).

The R^2 - values indicate that the variability accounted for by adding factors to the equation steadily increased, and these increases would seemingly justify additional factors except in the case of percent sand since the latter accounted for an additional 0.7%, whereas the previous three collectively added 23.1% to that accounted for by the slope factor alone.

The order of the variables in table 15 is also the order of importance based on their contribution to the total regression sum of squares at the final step in the stepwise procedure. Due to the change in the regression equation when the percent clay variable entered the equation, elevation became more important than percent clay. However, after subsequent steps had been completed, elevation then assumed lesser importance. The analysis of variance of the final regression equation illustrates this point (Table 16).

The degree to which variables change in importance from their initial entrance into the regression to the final regression is illustrated by contrasting the regression sum of squares for each variable in tables 15 and 16. In the latter case there are three significant contributors to the total regression sum of squares: slope, log eff. depth A, and the percent clay in the A horizon. Elevation is significant at the 10% level. The contribution of the percent sand to the regression sum of squares is quite small even though it was initially significantly correlated to 5-year growth index. The percent clay and elevation, which were not initially significantly correlated to 5-year growth index, at this point assume a good deal more importance in their contribution to the regression than the percent sand.

TABLE 16. Analysis of variance of the final regression equation for ponderosa pine production using 5 independent variables

Source	Degrees of Freedom	R^2 for each	Sum of Squares	Mean Squares	F-value
Slope	1	0.259	318.95	318.95	10.71**
Log eff. depth A	1	1.152	186.98	186.98	6.28*
Percent clay in A	1	1.135	166.03	166.03	5.58*
Elevation	1	1.106	129.92	129.92	4.36
Percent sand in A	1	0.009	11.14	11.14	0.37
Sub-total Regression	5	0.661	813.02	162.60	5.46**
Residual	14	--	416.77	29.76	--
Total	19	--	1229.79	--	--

* Significant at the 5 percent level
**Significant at the 1 percent level

The herbaceous vegetation prediction equation.-- A correlation matrix of site factors used in this equation is presented in table 17. The correlation values are unchanged from the original ones obtained in the correlation analysis, since no data was added.

A portion of the intercorrelations weave an interesting pattern. Variables concerned with nutrients are significantly correlated with effective depth partially due to the manner in which they were computed. The individual nutrient measurements and C.E.C. Index are also highly correlated with the organic matter content.

TABLE 17. Correlation matrix of site factors used in the regression equation for prediction of herbaceous production

Symbol	Site Factor	1	2	3	4	5	6	7	8
		...........Correlation	Coefficients	(r)...........					
1	Herbaceous Production								
2	Effective Depth of A Horizon	.67**							
3	Percent Slope	-.41*	-.48*						
4	Organic Matter in A	.64**	.63**	-.29					
5	Elevation	.48*	.28	-.76**	.40*				
6	K_2O in A	.49*	.89**	-.28	.65**	-.01			
7	Exch. Mg Index of A	.79**	.77**	-.38	.75**	.33	.70**		
8	C.E.C. Index of A	.78**	.85**	-.35	.85**	.25	.85**	.86**	
9	Exch. Ca Index of A	.64**	.68**	-.35	.80**	.27	.69**	.76**	.89**

* Significant at the 5 percent level
**Significant at the 1 percent level

All these correlations are positive as are the correlations of each with herbaceous production. These are quite logical relationships and show no inconsistencies.

The correlation between slope and elevation (-.76) implies a decreasing slope with increasing elevation. General knowledge of the study area would not confirm this relationship. This indicates that the sites were not representative of the study area in this respect.

The regression equation for herbaceous vegetation with variables ranked in order of importance in the final regression equation was as follows:

Y (mean annual herbaceous production) =

-1279 (regression constant)

+ 17.56 X_1 (cation exchange capacity index of the A horizon)

+ 15.55 X_2 (exchangeable magnesium index of the A)

- 0.9785 X_3 (K O in the A)

- 3.629 X_4 (exchangeable calcium index of the A)

- 6.180 X_5 (organic matter in the A)

+ 0.1915 X_6(elevation)

+ 10.48 X_7 (percent slope)

+ 18.36 X_8 (effective depth of the A).

The multiple R was 0.918 (sig. at the 1 percent level) and the multiple R^2 was 0.843, indicating that 84.3% of the total variability of Y was accounted for by this equation.

The order of selection of variables in the stepwise process from first to last was different (Table 18) from the final order of importance shown above.

TABLE 18. Multiple coefficients of determination, regression sum of squares, and F-values for variables at their initial entrance into the regression equation

Variable	R^2 (including previous variables)	Regression sum of squares after previous variables	F-value
Exch. Mg index of A	.624	4,037,030	28.51**
Elevation	.672	355,690	2.77
C.E.C. Index of A	.723	291,033	2.48
K_2O in A	.757	270,955	2.54
Org. Matter in A	.792	250,131	2.62
Exch. Ca index of A	.834	170,973	1.92
Percent slope	.841	43,095	0.46
Eff. depth of A	.843	17,117	0.17

**Significant at the 1 percent level

In the stepwise process, only the exchangeable magnesium index of the A was a significant contributor to the regression sum of squares at the time of entrance into the regression equation.

The R^2-values increased from 0.624 initially to 0.843 in the final step. The last two variables, slope and effective depth, collectively added only 0.9% to the previous R^2-value while the previous five variables added 21.0% to the percent accounted for by exchangeable magnesium alone.

An analysis of variance of the final regression equation showed that the regression sum of squares accounted for by each variable changed from that accounted for upon entering the equation and thus the R^2-value for each changed also. Each variable was again tested (Table 19).

TABLE 19. Analysis of variance of the final regression equation for herbaceous production using 8 independent variables

Variable	Degrees of Freedom	R^2 for each	Sum of Squares	Mean Squares	F-value
C.E.C. Index of A	1	.470	3,030,457	3,030,457	30.06**
Exch. Mg Index of A	1	.093	601,568	601,568	5.97*
K_2O in A	1	.082	525,642	525,642	5.21*
Exch. Ca Index of A	1	.067	434,322	434,322	4.31
Org. Matter in A	1	.066	428,517	428,517	4.25
Elevation	1	.038	246,746	246,746	2.45
Percent Slope	1	.016	100,751	100,751	1.00
Effective Depth of A	1	.011	65,021	65,021	0.67
Sub-total Regression	8	.843	5,436,024	679,503	6.74**
Residual	10	--	1,008,142	100,814	--
Total[1]	18	--	6,444,166	--	--

[1] The total degrees of freedom is one less than inthe ponderosa pine analysis since there was one less site investigated for herbaceous production

* Significant at the 5 percent level

**Significant at the 1 percent level

The reader should note that in the final regression equation, the first three variables were significant in their contribution to the regression sum of squares. The next two are close to significance at the 5% level (tables F = 4.96) and are significant at the 10% level.

Confidence intervals for the regression equations

A confidence interval was computed for both equations at the mean values of all X-variables in each equation. For the ponderosa pine equation, the probability of the true equation value (where the whole population would be used) being bracketed by the interval: the predicted Y ± 2.6 inches (± 7.6% of the mean of Y), was 95 percent. For the herbaceous production equation, the probability of the true equation value being bracketed by the predicted Y ± 162 lbs./A. (± 17% of the mean of Y) was also 95 percent.

Chapter V

DISCUSSION

Studies of this kind not only yield equations for predicting production, they give insight to soil-plant relationships in the natural environment. The discussion of the influence of factors related to plant growth is based on the results of correlations computed in both the correlation and regression analyses. These are two dimensional relationships as opposed to the six and nine dimensional relationships described by the regression equations. Difficulty arises in interpretation of relationships between site factors and production in these regressions because of the numerous interactions which exist among variables. To study a single factor in the equation and its effects on production would require varying it and interrelated variables while holding others constant at various levels. The influence of the factor on production would change accordingly. One must consider also, that a devised set of values may not even exist in nature. If maximum and minimum X-values are substituted into the two prediction equations developed in this study the resulting values are contradictory. For the ponderosa pine equation the maximum site values yield a much lower calculated growth index than the minimum values while the reverse is true for the herbaceous production equation. This indicates that the maximum or minimum X-values are apparently not an appropriate set for substitution into the equations.

The signs of the relationships between some X-variables and productivity computed in the correlation analysis were noted to be different from those in the regression equations. The signs of elevation and percent sand were different in the ponderosa pine equation, as were K_2O, exch. Ca, organic matter, and slope in the herbaceous production equation. As indicated previously, the relationships in the equation could change markedly if other X-variables were included in the equation (Snedecor, 1956). This illustrates another difficulty in interpretation from equations.

In contrast, a strong point in favor of using correlations is that their relationship to production was studied under the influence of all other factors, and their values were obtained from real situations.

Correlation analyses

In correlation work one must avoid implications of cause and effect relationships between any two variables since the investigator is merely measuring associated values under similar conditions.

There is a considerable difference in the kind of soil factors related to productivity of ponderosa pine and the herbaceous vegetation. Tree growth in the study area has been shown to be related principally to physical soil factors rather than chemical ones. This is consistent with work done by Coile (1948), Carmean (1954), Lemmon (1955) and others. Chemical factors have, however, been shown to influence plant growth in other studies of tree species (Hickock et al., 1931; Forristall and Gessel, 1955). Herbaceous vegetative production, by contrast is primarily related to chemical soil factors. The importance of soil chemical properties on the composition and structure of herbaceous vegetation was pointed out by Beadle (1953) and Box (1961).

From field observations it was noted that ponderosa pine rooted principally below a dense layer of grass and forb roots but this rooting zone was relatively close to the surface. Moderate amounts of grass roots do occur in the pine rooting region also. The large number of lateral roots on the trees would indicate that these are probably dominating the uptake of nutrients and moisture (Figure 6).

Since no dense stands of ponderosa pine were included in the sampling, it may be that nutrient competition is relatively small in such situations and physical soil factors are those that are important to production. It would be unrealistic to think that nutrients are not important to trees in these situations and would not be of more importance at higher stocking rates. Duffy (1964) noted however, that high stocking levels and large age differences may obscure the effect of soil and landscape characteristics on tree growth. Billings (1950) has also pointed out that ponderosa pine may be able to withstand low nutrient levels by utilizing a greater volume of soil than that used by shrubs and grasses.

An indication of the success of the sampling procedure was the correlation between 5-year growth index and herbaceous production ($r = 0.347$). The value though not significant indicates by its

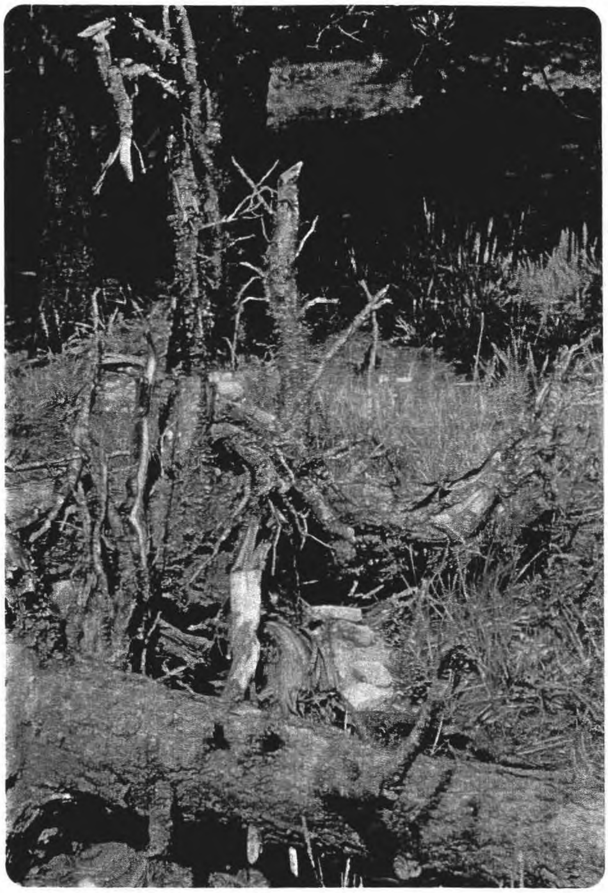


FIGURE 6. View of two overturned ponderosa pine trees with root system exposed. Note the large proportion of lateral roots.

positive sign that the measurement of grass production was not made in an area influenced by tree growth. A negative sign would indicate lower herbaceous production with a higher 5-year growth index. Also, the positive sign might indicate that to some degree, an area of better production of ponderosa pine may also be a superior location for grass and forb production.

Correlations and ponderosa pine growth.-- The depth of the A horizon seems most important to ponderosa pine growth. This is to be expected in view of the discussion on rooting habits above. Coile (1948) also noted the depth of the A horizon to be more important to production of loblolly and shortleaf pines than the depth to the C horizon. He concluded that heavy B horizons limited root penetration, thus restricting the amount of soil material from which the trees could draw moisture and nutrients. Little difference was found between textures of A and B horizons in the soils described in this study. Therefore it would not appear that the conclusions drawn by Coile would be applicable in this case.

Considering the textural relationships to production it was found that the percent sand was positively correlated with growth while inches of silt plus clay showed no correlation. Kayastha (1965) suggested that ponderosa pine growth in the study area is dependent on moisture from light summer rains. Since sandy textures are associated with rapid infiltration rates and low water holding capacity, deeper penetration would be expected. This deeper penetration would then aid in lowering evaporation losses. Inches of silt plus clay, in contrast, is apparently related to storage of moisture which in this case seems to be of much less importance than infiltration. Observations as to the time of initiation of growth seems to indicate that cool-season grasses and early growing forbs may begin growth approximately one month before ponderosa pine and thus early growing grasses and forbs may depend more on moisture storage. It should be pointed out here also, that the largest percentage of the annual precipitation does occur during the warm season. This would appear to be advantageous to the pine. Pearson (1918) observed that April and May precipitation of two inches or more in northern Arizona was more effective in terms of growth than the same amount occurring in the December to March interval. The latter was the period of major precipitation in that area.

The negative relationship between percent slope and 5-year growth index is related to the foregoing in that the greater the slope, the higher would be the amount of surface runoff resulting from precipitation and hence, the amount of infiltration would be lower. This reduced infiltration would then be reflected in lower height growth. The negative correlation of slope with the log effective depth of the A would agree with the findings of Zinke (1958) who noted that as slope increased, soil depth decreased.

The effect of an increase in precipitation and a decrease in temperature with an increase in elevation seems to be an increase in ponderosa pine growth for the range spanned by the study sites (5,860' to 8,240'). Zinke (1958) found that in areas not influenced by fog, Douglas-fir site index in northeastern California increased with elevation up to 3,000 feet but decreased thereafter. The plot of 5-year growth index against elevation indicates that growth may increase with elevation but this increase may become increasingly less at upper elevations (Figure 7). A positive straight line relationship was assumed for the correlation and regression calculations, however the scatter of points suggests curvilinearity. Pearson (1918) indicated that where moisture was abundant, height growth varied directly with temperature, however where there was a shortage of moisture, height growth varied inversely with temperature. Lower temperatures at higher altitudes in the study area may limit growth even though the moisture supply is more favorable than at lower altitudes. In contrast, growth at lower altitudes may be limited by a shortage of moisture. Initial data from a study now in progress suggests that the date of initiation of ponderosa pine leader growth in the study area may be two weeks or more later at 8,000 feet than at 5,800 feet. The cessation of leader growth appears to occur at approximately the same time. Thus, considering the moisture, temperature, and growing season influences, it would appear that moisture limits growth at lower altitudes but low temperatures and consequent shorter growing season length limit growth at higher altitudes.

Correlations and herbaceous production.-- Slope and elevation appear to reflect their influence on grass and forb production in a similar fashion to 5-year growth index. In this case however, the plot of elevation and herbaceous production appears to be more linear (Figure 8). This may indicate a lower threshold temperature for the growth process of grasses and forbs.

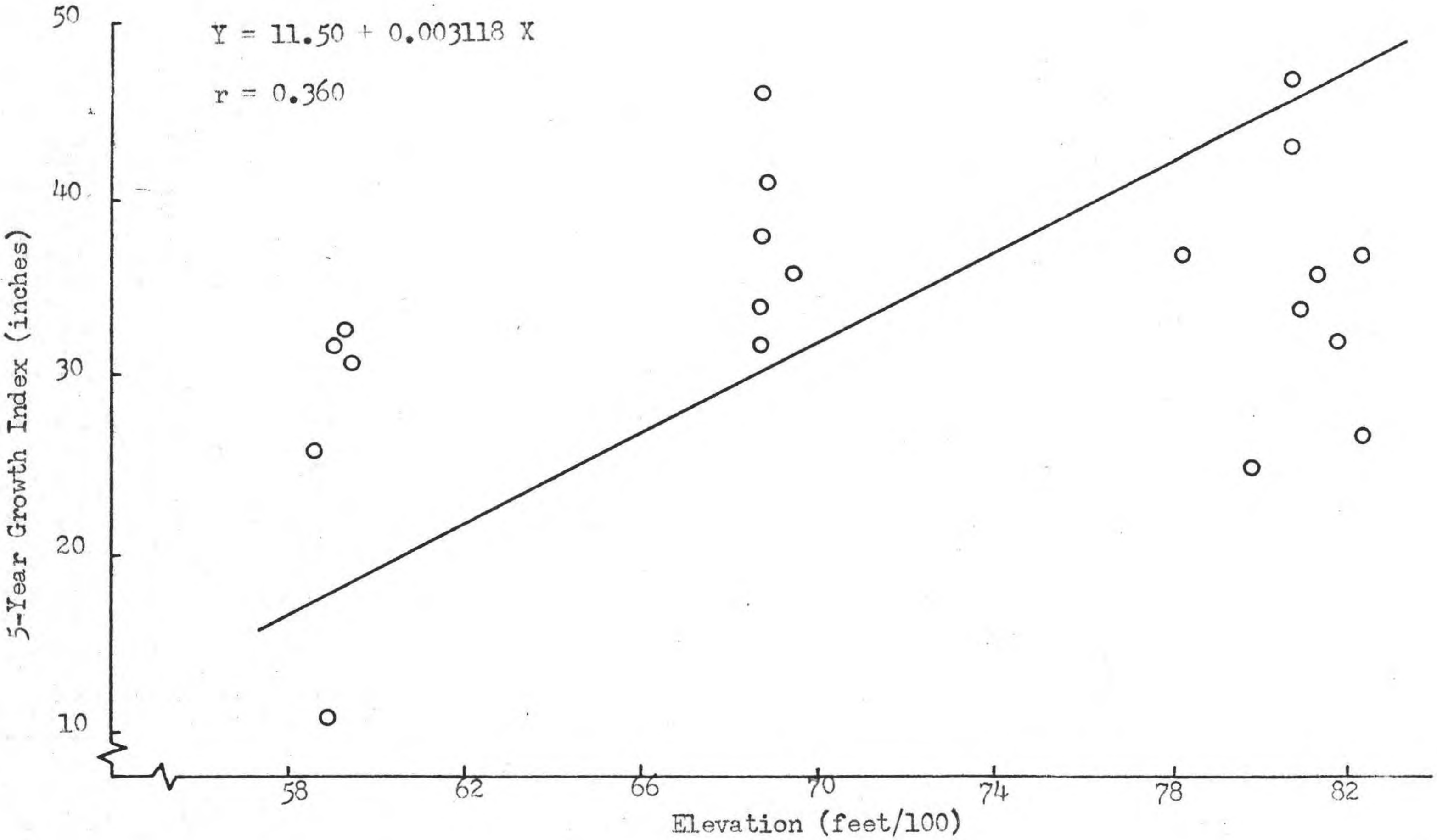


FIGURE 7. Regression of 5-year growth index against elevation.

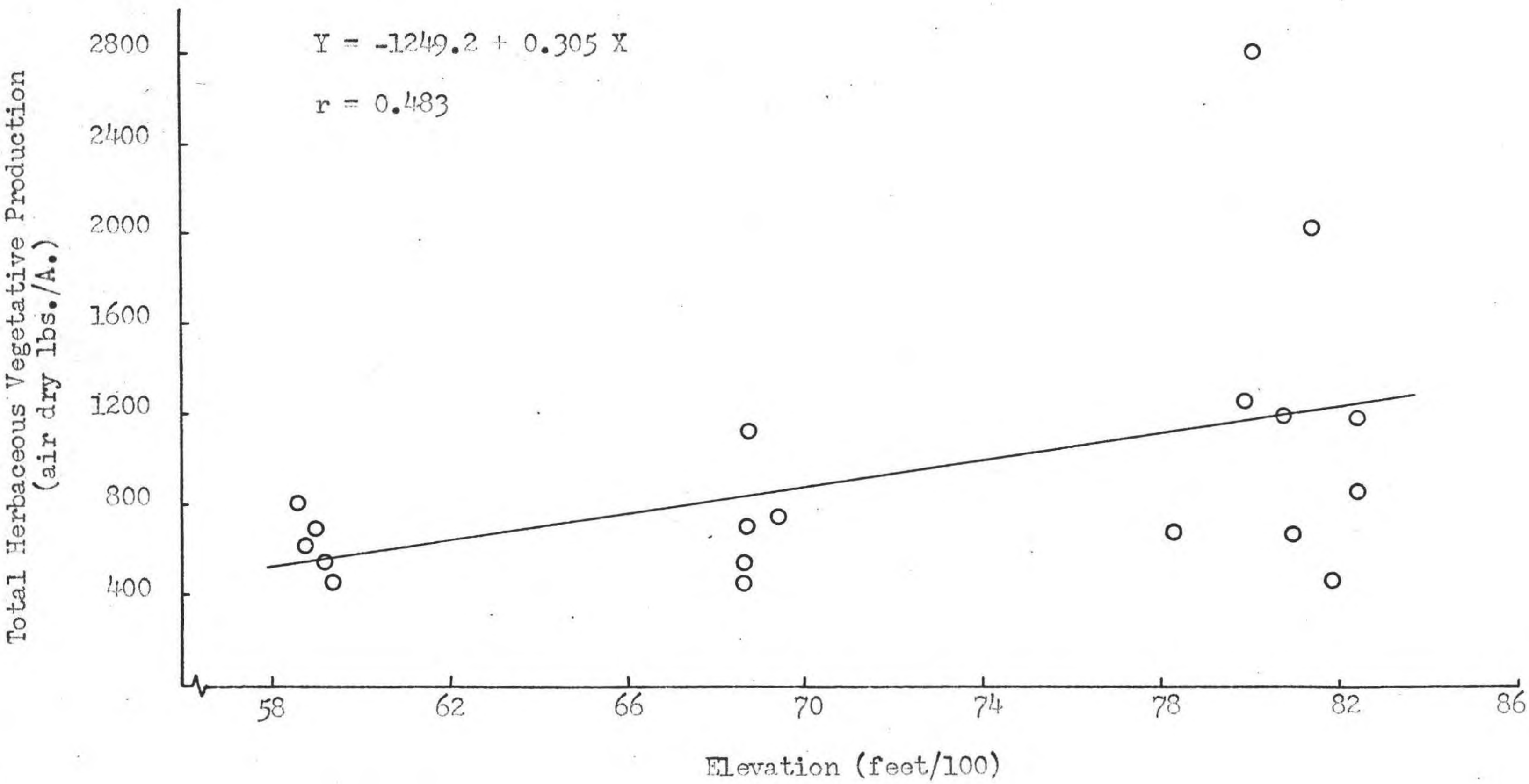


FIGURE 8. Regression of total herbaceous vegetative production against elevation.

The amount of organic matter in the A horizon was highly correlated with nutrient variables (Exch. Ca and Mg indexes, K_2O, C.E.C. index) in the A horizon but poorly correlated with the same variables computed to the C horizon. In contrast, both the percent clay and percent silt plus clay were very poorly correlated with nutrient levels in the A and to the C horizon. This would indicate that the A horizon, which is high in organic matter, isthe important horizon for storage of nutrients, particularly in view of the relatively low amounts of silt and clay present in these soils. Thus, shallow rooting by all species would appear to be advantageous from the standpoint of obtaining nutrients held on the exchange complex associated with the organic matter. The high water holding capacity of organic matter should also favor the growth of herbaceous species since the major amount of rooting appeared to occur in the A horizon.

Interpretation of the influence of nutrient variables is complicated by the manner in which the nutrient indexes were computed. Since each is weighted by effective depth, a portion of the correlations must be attributed to depth. This is probably the reason that the soil depth variable was selected quite late in the stepwise procedure in developing the herbaceous production equation. It was noted that the nutrient indexes were better correlated to the herbaceous production than effective depth alone, and hence, one would conclude that nutrient competition probably exists between herbaceous species in the study area.

It is difficult to avoid weighting nutrient values in some fashion by depth since using laboratory analysis figures (meq./100 g.) do not reflect the amount of soil from which a plant may draw nutrients. If amounts on a volume basis are used, depth enters into the computations also; thus it is simpler to weight values with depth alone initially.

Regression analysis

The regression equations developed in this study may at first seem impractical for use in the field. Although the cost of determining chemical factors is somewhat high, future demands on forage and timber supplies will make such costs feasable for the land manager. Soil surveys, which are becoming more available, will yield a portion of the necessary chemical and physical information needed. Hence the use of an equation is more realistic than one might at first imagine.

The writer does not propose that these equations are in a form to be used in the field because of the relatively small number of samples involved. The basic approach is believed to be sound and it is felt that the equations could be improved by the addition of more site data to the level that field use would be practical.

Ponderosa pine growth prediction equation.-- The variables which significantly (95%) contributed to the final regression sum of squares (percent slope, $\log_{10}$ effective depth of the A, weighted mean percent clay in the A) will require the following data collection to permit calculation of these variables for prediction:

1. measurement of the depth of the A horizon or subhorizons of the A and an estimate of the rock and gravel percentage

of each to obtain the effective depth,

2. measurement of the percent slope of the site with an Abney level,
3. obtaining a sample, or samples if there are subhorizons, of the soil material in the A horizon.

Sample sites are generally located on an aerial photograph or map of some nature, and thus, location of the sites on a topographic map will yield a value for the evaluation variable.

In the laboratory a mechanical analysis will be necessary to determine the relative amounts of sand, silt and clay. Since the percent sand is available as well as the percent clay the data necessary for computation of values for both of these variables can be calculated. Thus, even though the elevation and percent sand variables were not significant contributors to the regression equation, the data necessary for use in the equation is easily obtained. Since these two added variables will increase the accuracy of the prediction equation, they should be used.

The limits of the confidence interval computed at the mean of all the X-variables are the smallest for the equation at the 5-percent level. Thus, the accuracy of the equation is highest at these values on the basis of samples taken in this study. How the equation will work in the field remains to be seen from actual use.

Herbaceous production equation.-- In development of this equation the variables were not in the same order of importance in the stepwise procedure and the final regression equation. Apparently, the entrance of new X-variables changed the regression to such a degree that each assumed somewhat different relationships to the other in the prediction of Y as the stepwise procedure progressed.

It would seem that those factors which significantly contribute to the regression equation at least 90 percent of the time (significant at the 10% level) should be used for prediction purposes. These would include the first five variables as listed in decreasing importance to the final regression equation (Table 19). All are concerned with the nutrient regieme (C.E.C. index, exch. Ca. and Mg. indexes, K_2O content and organic matter content) of the A horizon.

The following field work to collect the necessary soil samples and measurements for computation of these quantities would be necessary:

1. measurement of the depth of the A horizon or subhorizons and estimation of the percent rock and gravel content of each to calculate the effective depth,
2. collection of a soil sample for laboratory analysis of each subhorizon, where present, of the A horizon.

With results from the laboratory analysis, computation of the X-variable values can be made. Since effective depth of the A is measured for use with other variable values, this X-variable should be included in the prediction equation. The remaining factors, slope and elevation, can be easily obtained, as indicated previously, for the ponderosa pine equation and all the quantities of the final equation may be used. Using all variables improves the predictability of the herbaceous production equation, and since there is so little difference between obtaining the necessary information for five variables and eight variables it would seem that using all eight is more appropriate.

As in the ponderosa pine prediction equation, the confidence interval indicates the best the equation will predict on the basis of the samples taken, and trial use in the field will show its actual reliability.

Question arises upon comparing the confidence intervals of the two equations as to why the ponderosa pine equation will predict closer to the true value of production. The ponderosa pine equation accounts for only 66 percent of the variation of Y compared to 84 percent in the herbaceous production equation. This may be explained by considering the variability of Y in both cases. The coefficient of variation (C.V.) of Y for the ponderosa pine equation is 23.7 percent while the C.V. for herbaceous production is 63.3 percent. From these values it is evident that the study sites spanned a wider range of productivity of grass and forb production than of ponderosa pine production. Therefore, one may conclude that evaluation of a multiple linear regression by considering the multiple coefficient of determination (R^2) will be misleading if this value is not considered with a confidence interval or the coefficient of variation of Y.

In order to compare the results of this study with others in which prediction equations have been used, several studies are cited. Meyers and Van Deusen (1960) used soil depth, slope, aspect, and position on slope for sites on igneous parent material in the Black Hills of South Dakota to predict site index within eight percent ($R^2 = 83\%$) of actual values at the mean site index of ponderosa pine. For limestone derived soils in the Black Hills, slope position and soil depth variables predicted values within seven percent ($R^2 = 78\%$) of actual values at the mean site index. Carmean (1954) used soil depth, bulk density, and gravel content as variables in prediction equations for Douglas-fir site index for several different parent materials. The difference between predicted and actual values varied between 5 and 15 percent of actual. Duffy (1964) reported R^2-values only for his various lodgepole pine prediction equations; they varied between 0.58 and 0.75. Of the studies reviewed dealing with forage production, only one prediction equation was encountered. Dahl (1963) used the depth of moist soil on April 15 in a simple linear regression to predict grass yields by August 7. He reported an R-value of 0.797, but did not indicate what the magnitude of the error of prediction might be.

Comparison between precipitation and temperature data for the years that productivity was sampled in this study and 14-year means, led to the following conclusions:

1. For the ponderosa pine prediction equation, the precipitation values and frost-free season length for the 5-year growth period were somewhat above average while monthly temperatures were very nearly the same. Thus, it may be expected that predicted 5-year growth indexes may be slightly above average.
2. For herbaceous production, 1964 precipitation and the frost-free season length were below average, and temperatures, though variable, appeared to be slightly above average. Predicted production in this case would therefore be expected to be below average.

Recommendations for further study

Before actual use of the equations can be made by the land manager, it would be desirable to make improvements in the equations and check their predictability in the field. More sample site data should be added to that evaluated herein. This increase in the number of sites should in itself reduce the variance of the production values and improve the accuracy of the equations. Added information would also refine the theoretical relationships discussed herein between soil factors, landscape characteristics and plant production. A desirable factor to add to future investigations would be the measurement of actual amounts of moisture available to plants during the growing season. This could be done for soil horizons or for fixed depths. Current production through the growing season could be measured at the same time to observe growth trends with moisture availability.

In some cases, correlations between productivity measurements and values of site factors computed to the C horizon were significant as well as the same factor computed for the A horizon. This indicates that the B horizon is also functioning in some fashion in soil-plant relationships and should be investigated and evaluated.

An effort was made in this study to use sample trees which were in the early pole stage of height growth. It would be desirable therefore to check the growth rates of older trees against the predicted equation values. Information gained would indicate the range of tree ages for which prediction is of tolerable accuracy.

Basic research work is needed to determine the nutrient requirements of important native species. Billings (1950) found that results related to the nutrient regime are difficult to interpret without such information. The same problem was encountered in this study.

Chapter VI

SUMMARY

As demands upon the natural resources increase, the resource manager must seek to determine which areas have the highest potential for producing specific crops. These areas will then be subjected to intensive management practices since they can yield the most for the time and money invested.

The ponderosa pine vegetative zone in Colorado is one which supports many uses. These include logging and grazing. A means of predicting the yield of these crops from soil and landscape characteristics has not been developed for this area of the country. The objectives of this study, were to identify those site factors important in determining the productivity of an area for both ponderosa pine and the associated native herbaceous vegetation, and to develop a growth prediction equation, utilizing these factors, for each of these two crops. These equations can be used to determine the suitability of a site for production of ponderosa pine and native herbaceous vegetation.

The study area was located in Larimer County, Colorado. Twenty study sites were established in portions of the Cache La Poudre River watershed which support both ponderosa pine and native herbaceous vegetation. Under the assumption that the important factors related to growth vary with changes in productivity, study sites were selected to obtain a wide and continuous range of productivity for both the ponderosa pine and herbaceous vegetation.

Production of herbaceous vegetation on each site was sampled by clipping five 2-foot by 4-foot plots at the end of the 1964 growing season. Kayastha (1965) used the same sites in a companion study and found that 5-year growth index was a measure of ponderosa pine growth which reflects site differences. Therefore, this quantity was used as the measure of ponderosa pine production in this study.

A soil description was made at each site and soil samples from each horizon were obtained for mechanical and chemical analyses. Samples for determining bulk density were also taken. The percent slope, aspect, position on slope, and elevation of sites were determined. Chemical analyses were performed which included pH, K_2O, P_2O_5, organic matter, carbonates, cation exchange capacity, exchangeable and water soluble Na, K, Mg, and Ca. Mechanical analyses of soil samples were made to determine the relative percentages of sand, silt, and clay in each.

Quantities measured in the field or in the laboratory which showed little or no variation were omitted. Other quantities were expressed in terms of actual amounts (for example: inches, lbs./A.) or relative amounts (percentages) or both. Values of these quantities were computed for the A horizons and to the C horizons. Results of these computations yielded independent variables for the growth prediction equations.

To determine which of the numerous potential independent variables were significantly related to production measurements, simple correlation coefficients (r) were computed between each variable and productivity measurements of the two crops.

The effective depth of the A horizon was found to be better related to production than the effective depth to the C, therefore, soil-related variables used in the prediction equation were restricted to the A horizon. Where two expressions of a quantity were both related to production, the one with the lowest r-value was eliminated from use in the prediction equation. Variables which were related to different quantities, but were also intercorrelated, were not eliminated.

A fixed multiple linear regression model was assumed for each of the growth prediction equations. Computer facilities were used for the development of these expressions by a stepwise multiple regression process. Results, with independent variables listed in decreasing order of contribution to the regression sum of squares were as follows:

for the ponderosa pine equation--

Y (5-year growth index) = :

+79.13 (regression constant)

-.7346 X_1 (percent slope)

+13.63 X_2 ($\log_{10}$ effective depth of the A horizon)

-.8505 X_3 (weighted mean percent clay in the A)

-.0038 X_4 (elevation)

-.0129 X_5 (weighted mean percent sand in the A) for the herbaceous vegetation equation--

Y (mean annual herbaceous production) = :

-1279 (regression constant)

+17.56 X_1 (cation exchange capacity index of the A horizon)

+15.56 X_2 (exchangeable magnesium index of the A horizon)

-.9786 X_3 (K_2O in the A)

-3.629 X_4 (exch. Ca index of the A)

-6.180 X_5 (organic matter in the A)

+.1916 X_6 (elevation)

+10.49 X_7 (percent slope)

+18.36 X_8 (effective depth of the A).

The multiple coefficient of determination (R^2) for the ponderosa pine prediction equation was 0.66 and the R^2-value for the herbaceous vegetation prediction equation was 0.84.

A confidence interval was computed at the mean of all X-variables in the two equations. For the ponderosa pine equation, the probability of the true equation value (where the whole population would be used) being bracketed by the interval: the predicted Y ± 2.6 inches (± 7.6% of the mean of Y) was 95 percent. For the herbaceous production equation, the probability of the true equation value being bracketed by the predicted Y ± 162 lbs./A. (± 17% of the mean of Y) was also 95 percent.

Interpretation of the relationships between individual variables and production were made from the results of correlation computations. Herbaceous production and 5-year growth index are apparently related to different kinds of soil factors. Physical soil factors are correlated with ponderosa pine growth while chemical soil factors are correlated to herbaceous production. Both production measures were related to slope and elevation.

Observations of the rooting of ponderosa pine and the herbaceous species indicate that many of the pine roots occur in the upper portion of the soil but below a dense surface layer of grass and forb roots. Moderate amounts of grass and forb roots occur in the pine rooting zone. Although all rooting is not restricted to the A horizon, the strong correlations between production and the effective depth of the A indicate that the upper portion of the solum is of primary importance to growth. This theory is strengthened by the low r-values obtained between production and expressions of soil depth to the C horizon.

The percent sand was positively correlated with 5-year growth index but negatively correlated with variables related to silt and clay. This seems to indicate that ponderosa pine is more dependent upon penetration of moisture than storage. Precipitation occurs in the form of light thunderstorms during the warm season and will penetrate deeper in coarser textured soils. Hence moisture will reach the ponderosa pine rooting zone more often in these soils.

Early growing grasses and forbs appear to begin growth before ponderosa pine and thereby reduce stored moisture. This is another indication that ponderosa pine may depend principally on warm season precipitation.

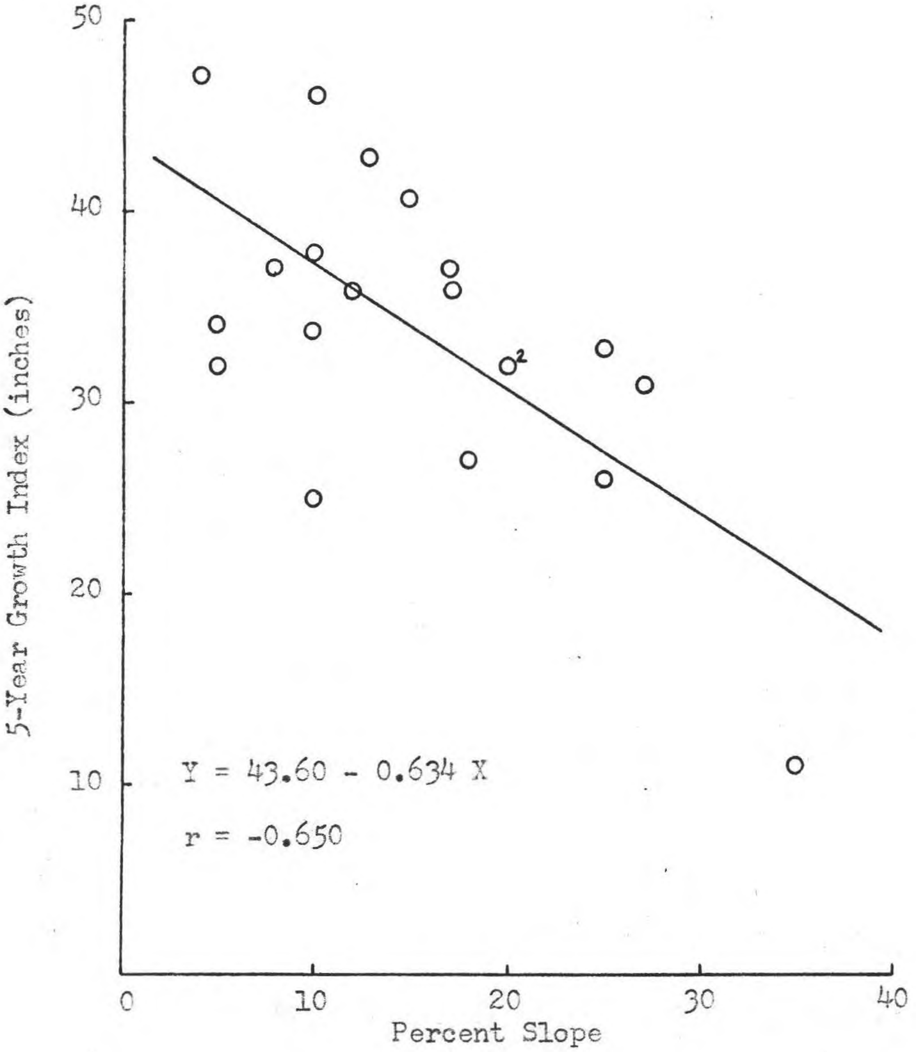
A negative correlation between percent slope and the production of both crops studied, indicates that perhaps the increased runoff associated with steeper slopes is reflected in reduced growth.

A general increase in production with increasing elevation appears to be the result of the associated increase in precipitation and decrease in both temperature and frost-free season. For ponderosa pine, the increase in growth with elevation appears to level off at upper elevations. This does not seem to be the case for the herbaceous vegetation since the plot of herbaceous production against elevation indicates a uniform slope.

Correlations between herbaceous production and nutrient variables indicate that nutrient competition among grasses and forbs may be a major influence on production of these species in the study area. A significant correlation between the amount of organic matter and the cation exchange capacity index indicates that the organic matter is the principal source of exchangeable nutrients. Soils were generally low in silt and clay, and low r-values between expressions of these variables and exchange capacity further indicate the importance of organic matter to soil fertility. Relatively shallow rooting would appear to be advantageous to vegetation from the nutrient standpoint since organic matter content is higher in upper soil horizons.

Further study of these relationships and perhaps others on additional sites is recommended to improve the accuracy of the prediction equations and obtain more information, which may or may not strengthen interpretations made from results obtained in this research effort.

APPENDIX



IGURE 9. Regression of 5-year growth index against percent slope.

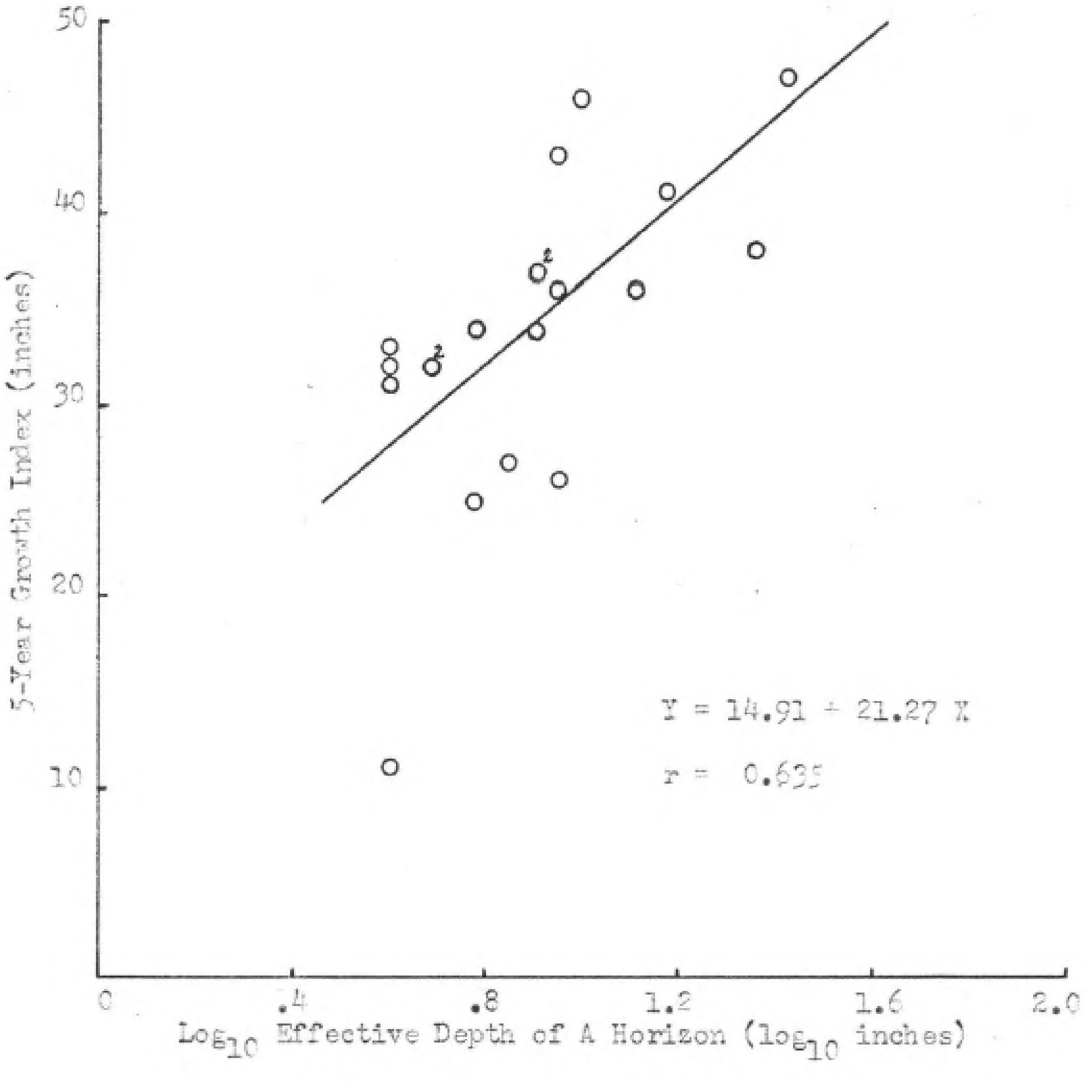


FIGURE **10.** Regression of 5-year growth index against log$_{10}$ effective depth of the A horizon.

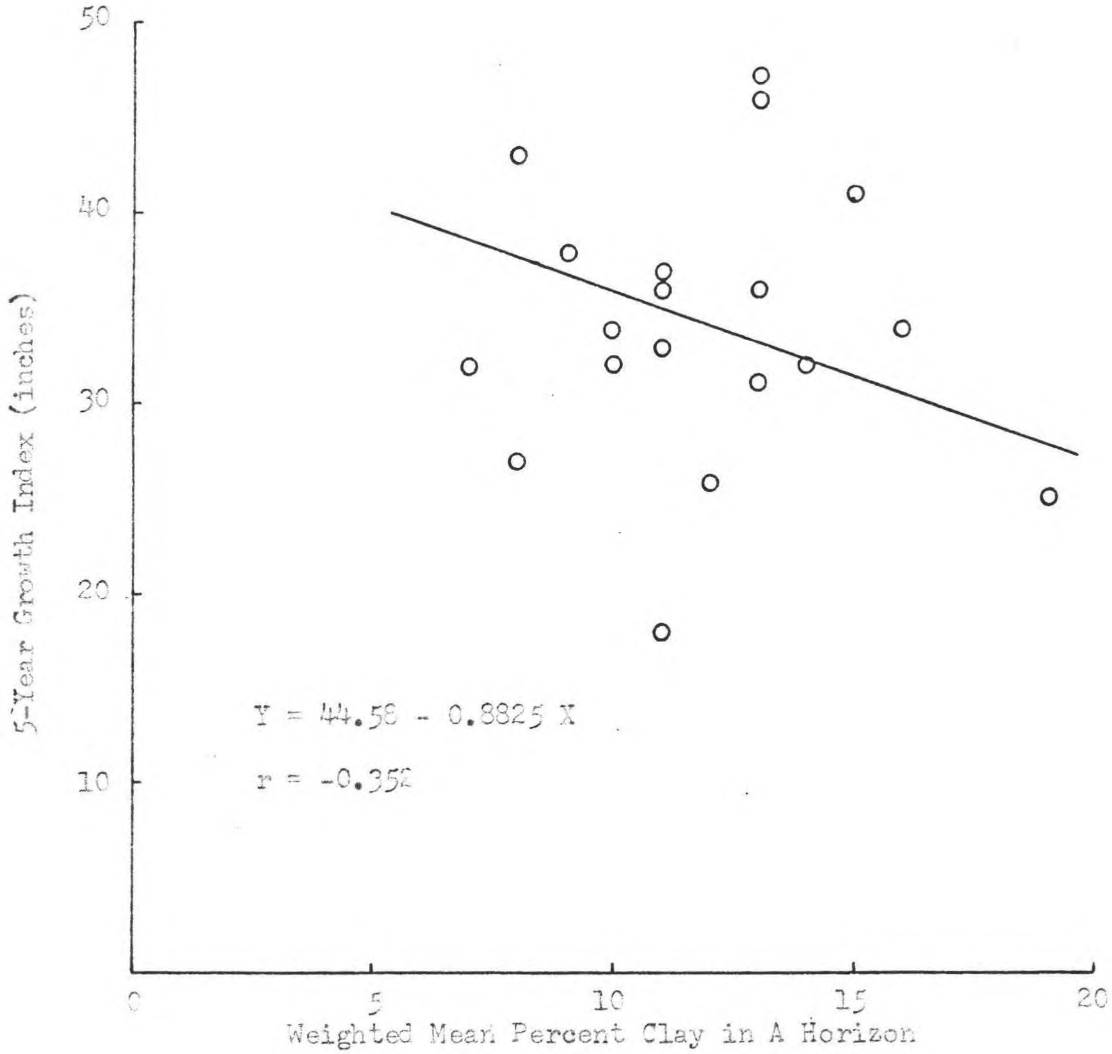


FIGURE **11**. Regression of 5-year growth index against the weighted mean percent clay in the A horizon.

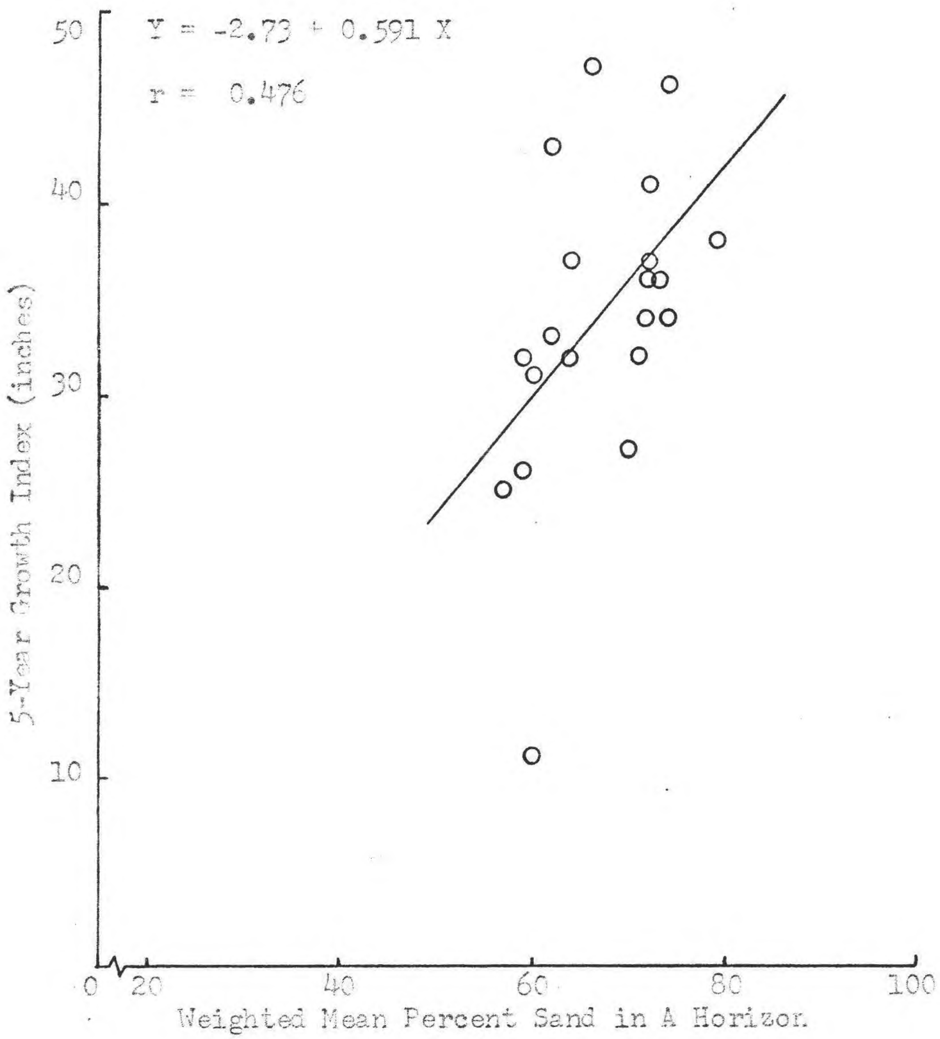


FIGURE 12. Regression of 5-year growth index against the weighted mean percent sand in the A horizon.

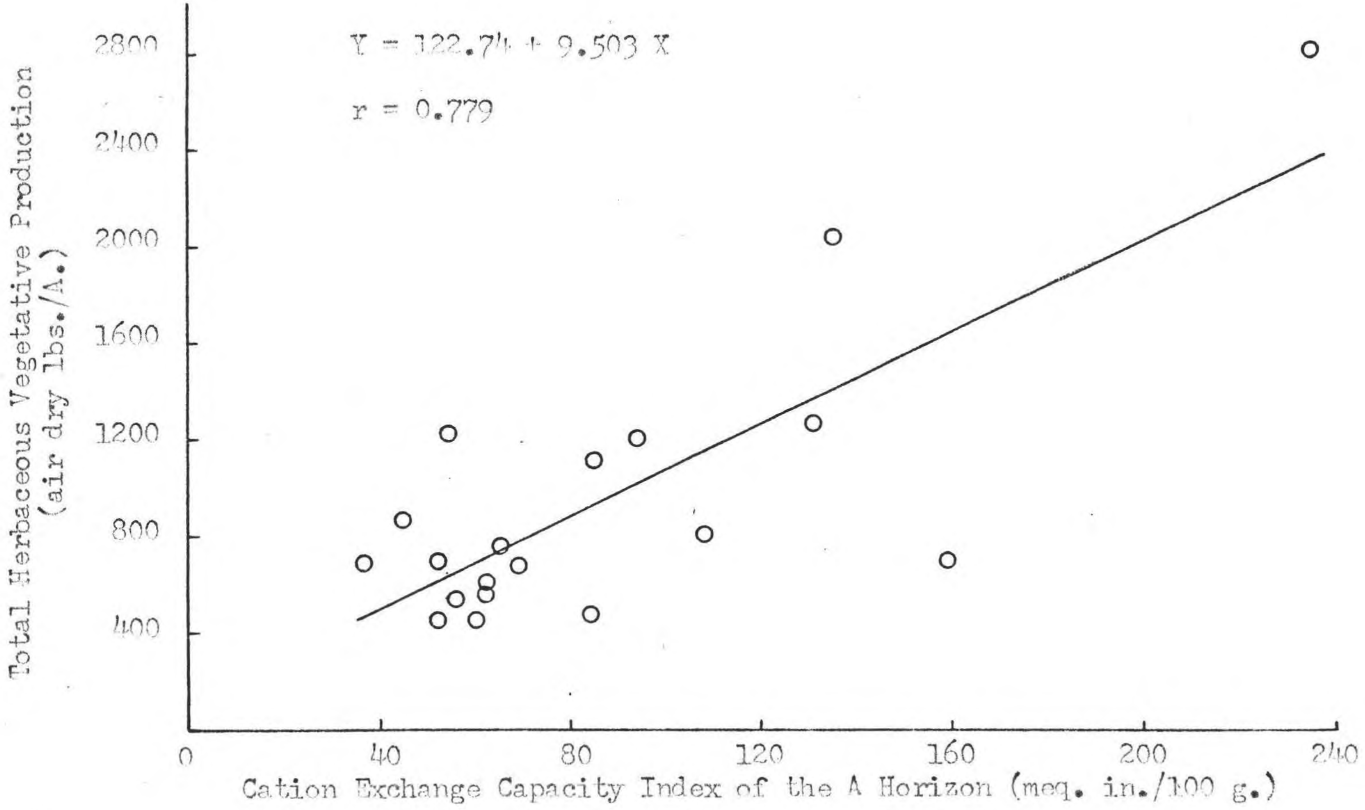


FIGURE 13. Regression of total herbaceous vegetative production against cation exchange capacity index of the A horizon.

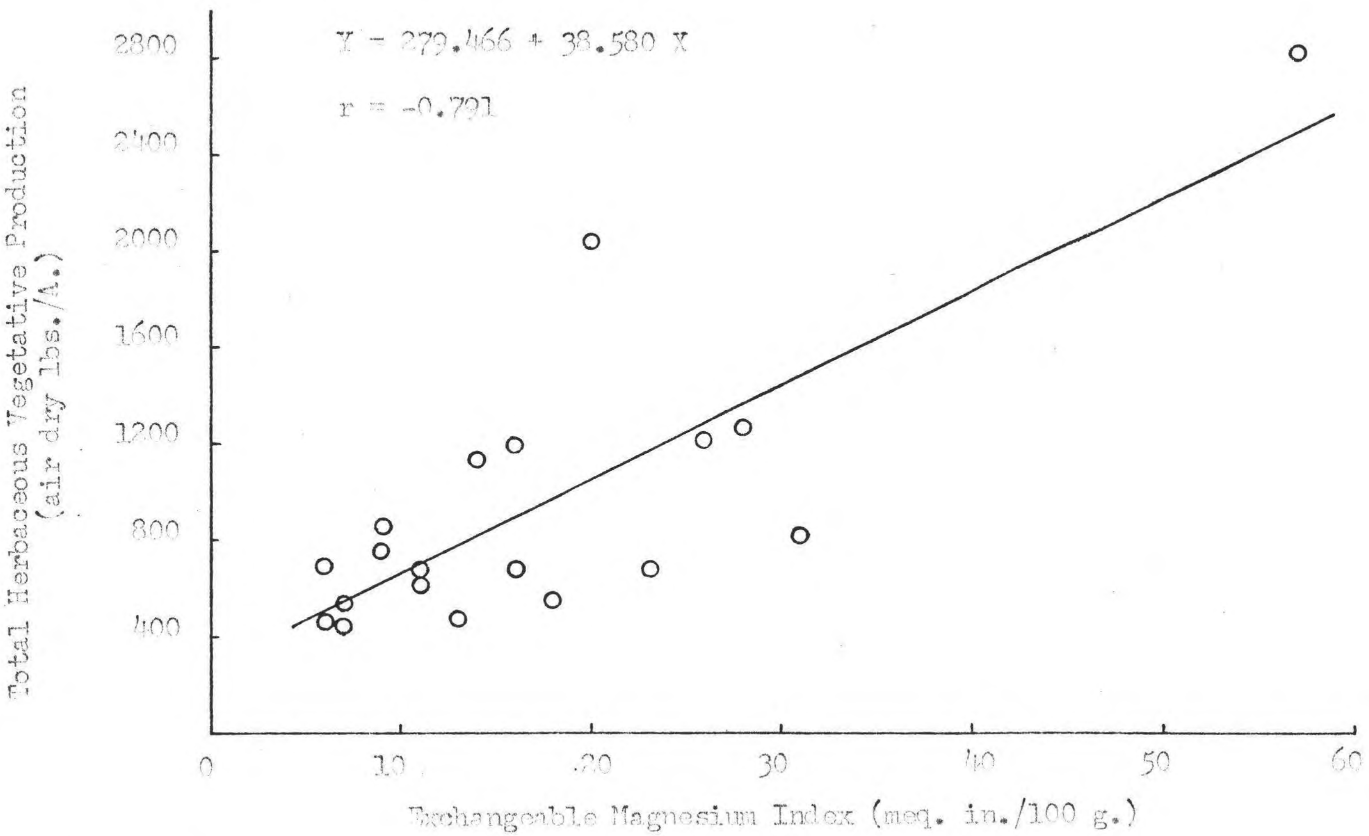


FIGURE 14. Regression of total herbaceous vegetative production against exchangeable magnesium index.

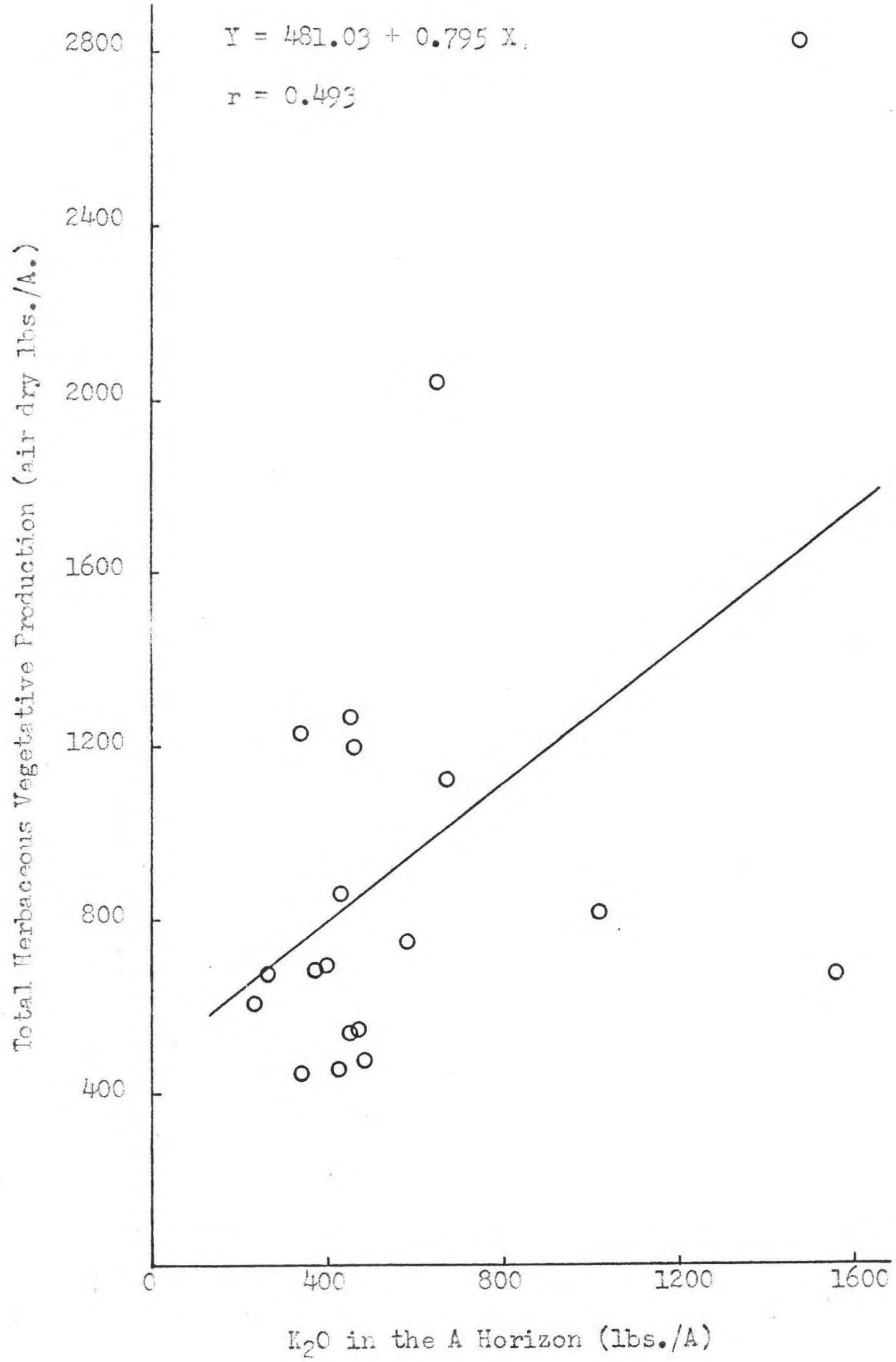


FIGURE 15. Regression of total herbaceous vegetative production against K$_2$O in the A horizon.

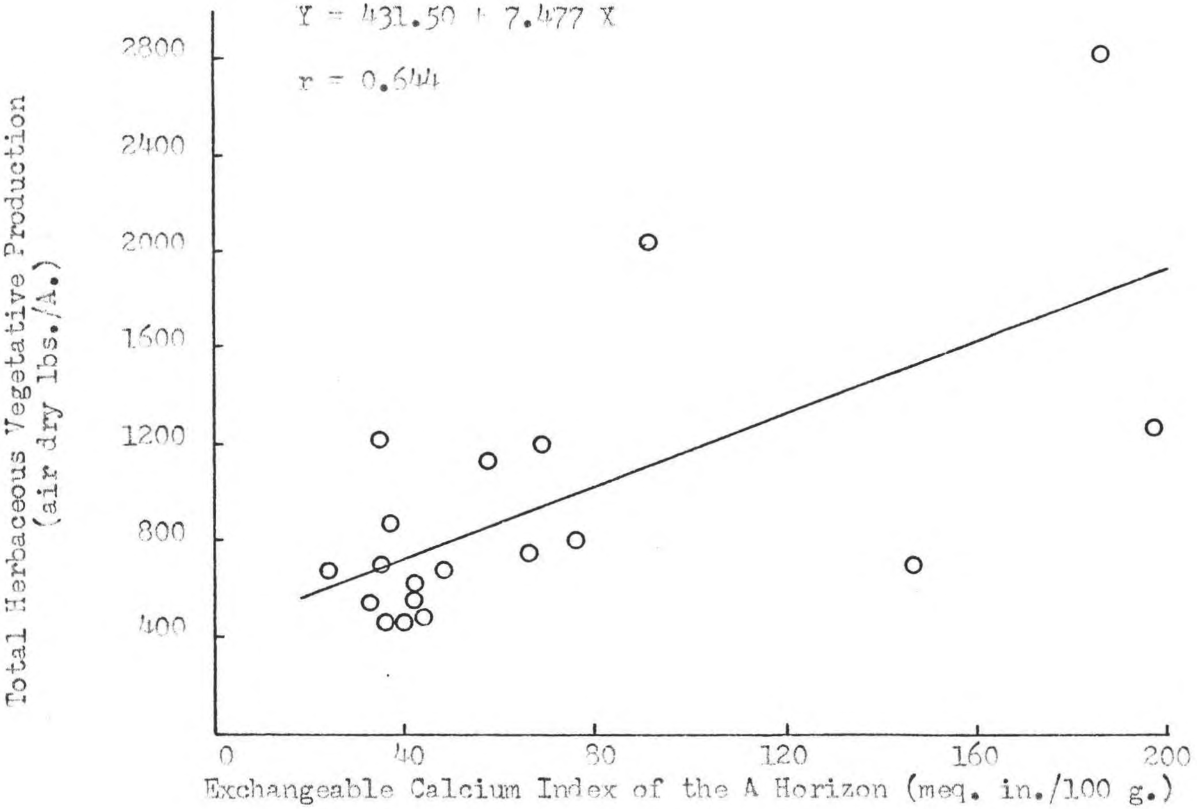


FIGURE **16.** Regression of total herbaceous vegetative production against exchangeable calcium index of the A horizon.

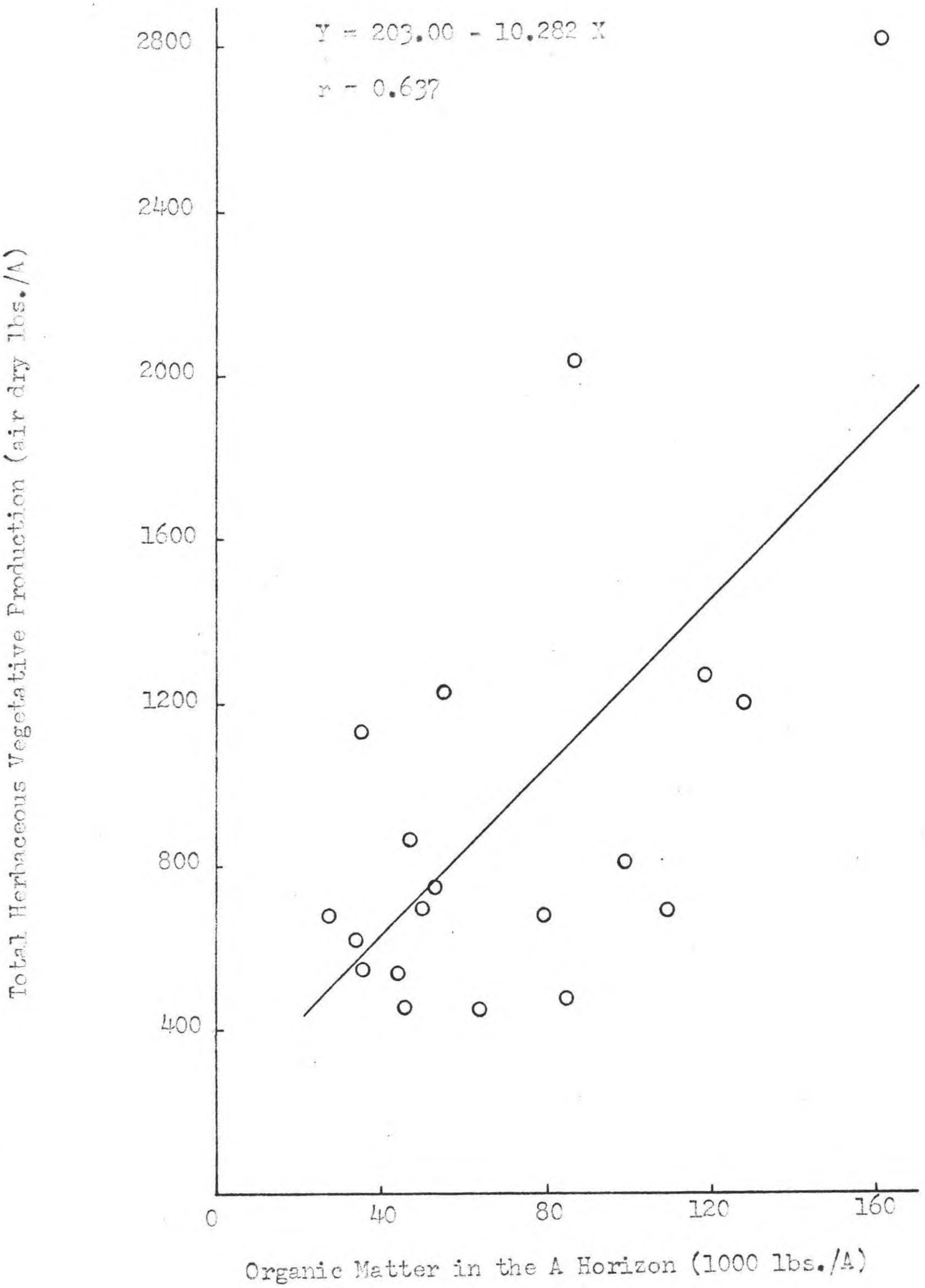
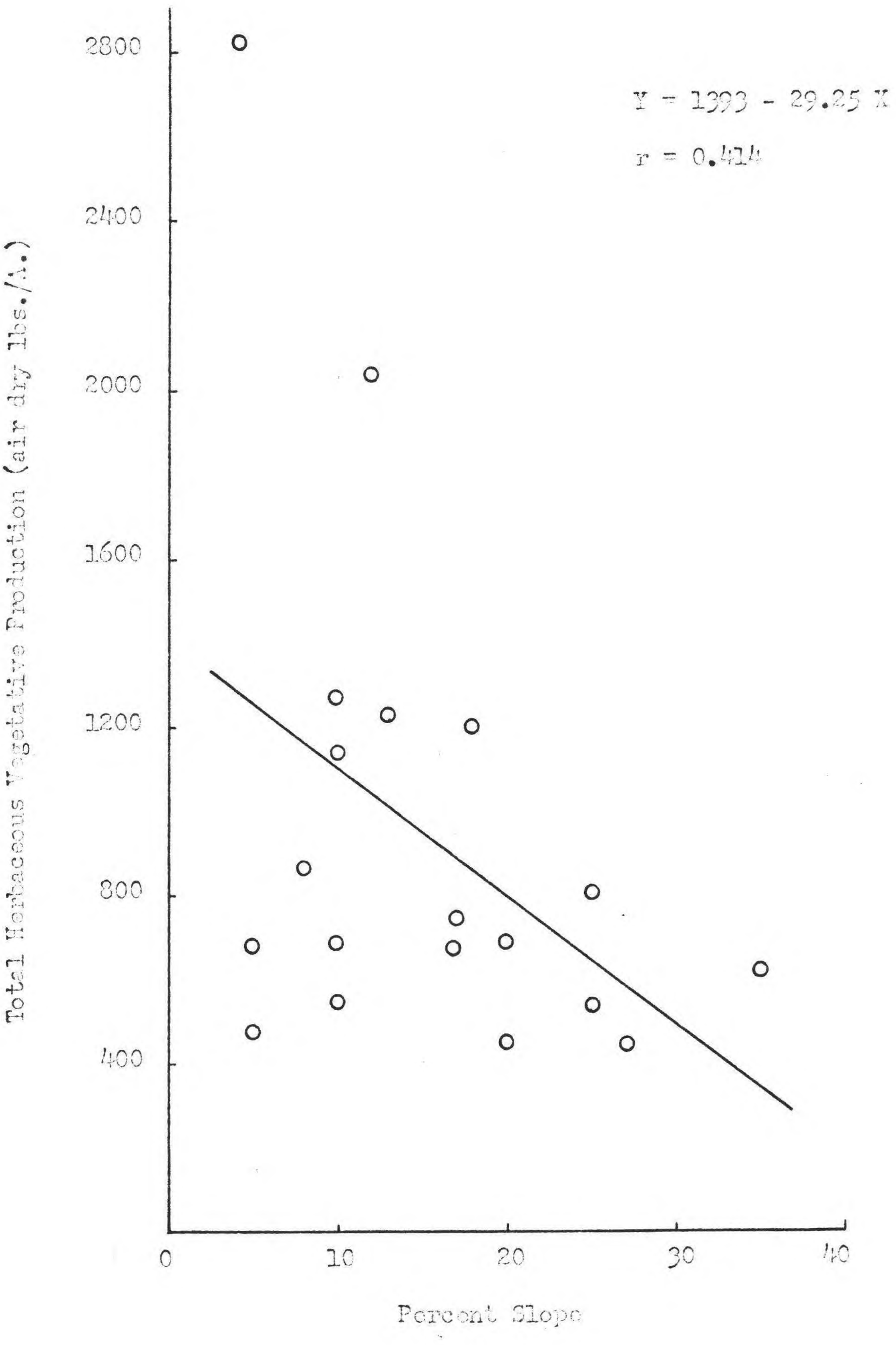


FIGURE 17. Regression of total herbaceous vegetative production against organic matter in the A horizon.



'IGURE 18. Regression of total herbaceous vegetation production against percent slope.

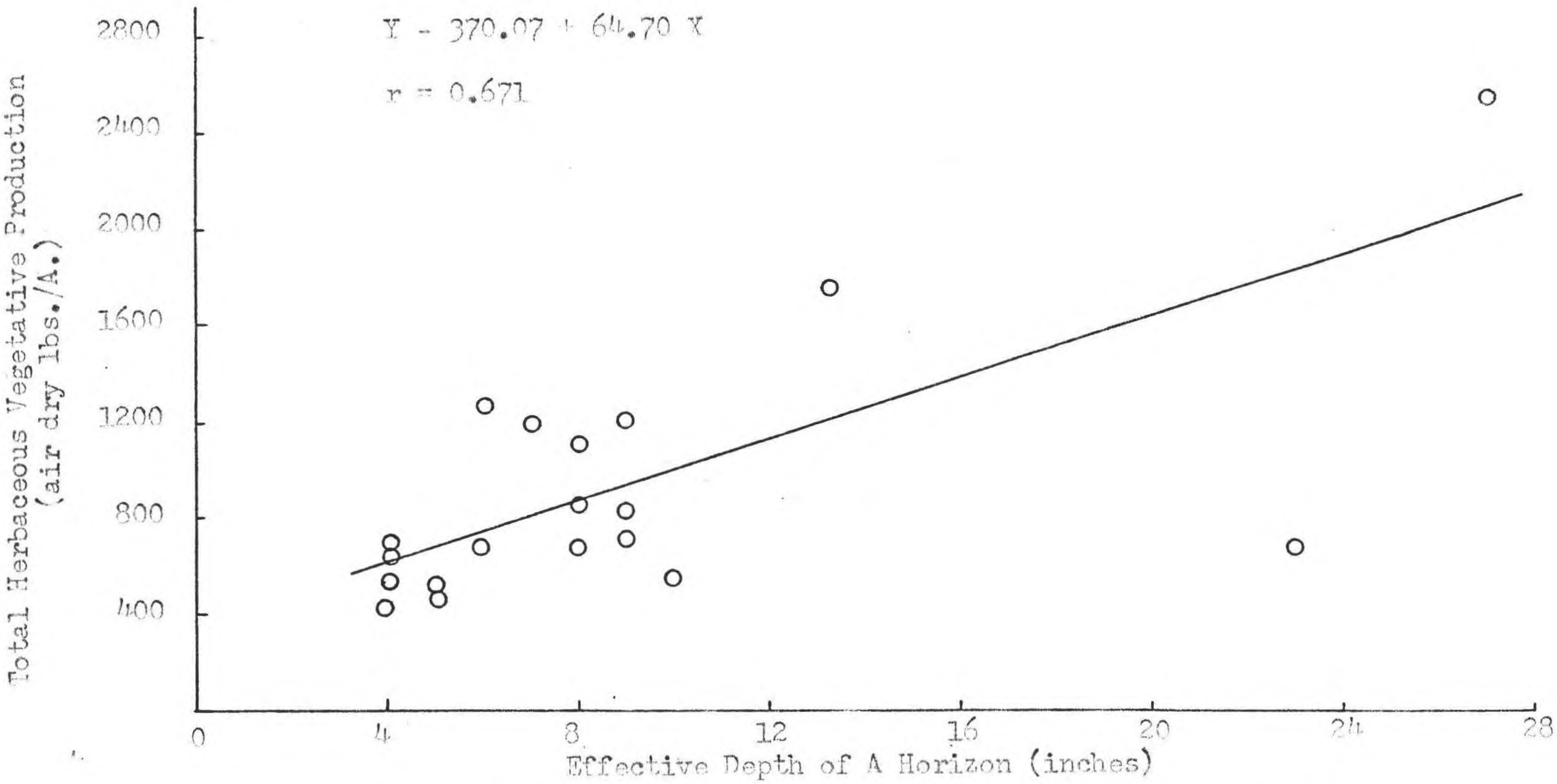


FIGURE 19. Regression of total herbaceous vegetation production against the effective depth of the A horizon.

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Abstract of Thesis

SITE-VEGETATION RELATIONSHIPS IN THE MONTANE ZONE OF NORTHERN COLORADO

A means of determining the suitability of sites in the montane zone of northern Colorado for production of ponderosa pine and the native herbaceous vegetation from soil and landscape characteristics has not previously been developed. The objectives of this study are to identify the site factors important in determining the productivity of an area for both of these crops, and to develop a growth prediction equation, utilizing these factors, for each of the crops.

Twenty sites, which spanned a continuous range of productivity, were located in portions of the Cache La Poudre River watershed in Larimer County, Colorado. Each site was investigated to determine the physical soil and landscape characteristics. Chemical soil characteristics were determined from analyses of soil samples obtained in the field. Production measurements of both crops were made at each site, also.

Correlation coefficients (r) were computed between measured site factors and productivity. Some of the significantly correlated factors were used as independent variables to develop a multiple linear regression equation for each crop. The following expressions resulted, with independent variables listed in decreasing order of importance to prediction of Y:

for the ponderosa pine equation

Y (5-year growth index) = :

+79.13 (regression constant)
-.7346 X_1 (percent slope)
+13.63 X_2 ($\log_{10}$ effective depth of the A horizon)
-.8505 X_3 (weighted mean percent clay in the A)
-.0038 X_4 (elevation)
-.0129 X_5 (weighted mean percent sand in the A)

for herbaceous vegetation equation

Y (mean annual herbaceous production) = :
-1279 (regression constant)
+17.56 X_1 (cation exchange capacity index of the A horizon)
+15.56 X_2 (exchangeable magnesium index of the A horizon)
-.9786 X_3 (K_2O in the A)
-3.629 X_4 (exch. Ca index of the A)
-6.180 X_5 (organic matter in the A)
+.1916 X_6 (elevation)
+10.49 X_7 (percent slope)
+18.36 X_8 (effective depth of the A).

The multiple coefficient of determination (R^2) for the ponderosa pine prediction equation was 0.66 and the R^2-value for the herbaceous vegetation prediction equation was 0.84. The coefficient of variation of Y was 23.7 percent for the ponderosa pine equation and 63.3 percent for the herbaceous production equation.

Correlation coefficients indicated that ponderosa pine height growth was positively correlated with the log effective depth of the A horizon, elevation, and weighted mean percent sand in the A. Negative correlations existed between height growth and the percent slope and weighted mean percent clay of the A horizon.

Herbaceous production was positively correlated with all independent variables shown in the growth prediction equation except percent slope.

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