1329204

Jayne, JoAnn Bitsilly

PINYON TREE GROWTH AND SOIL NUTRIENTS RELATIONSHIPS ON AREAS OF DIFFERENT SITE QUALITIES

The University of Arizona M.S. 1986

University
Microfilms
International 300 N. Zeeb Road, Ann Arbor, MI 48106

Pinyon Tree Growth and Soil Nutrients Relationships on Areas of Different Site Qualities

by

JoAnn Bitsilly Jayne

A Thesis Submitted to the Faculty of the

SCHOOL OF RENEWABLE NATURAL RESOURCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN WATERSHED MANAGEMENT

In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 8 6

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his or her judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: ____________________

APPROVAL BY THESIS COMMITTEE

This thesis has been approved on the date shown below:

Dr. Peter F. Ffolliott — 9/30/86
Thesis Director — Date
Professor of Watershed Management

Dr. Leonard Debano — 9/30/86
Soil Scientist, U.S.D.A. Forest Ser. — Date

Dr. Jack L. Stroehlein — 9/30/86
Professor of Soil and Water Science — Date

ACKNOWLEDGEMENTS

I want to express my sincere appreciation to Dr. Peter F. Ffolliott for his valuable advice and assistance throughout the period of the study and during preparation of this thesis. The completion of this study would not have been possible without the generous help, advice, and support of many other individuals. In particular, I would like to express my deepest gratitude to Dr. Leonard Debano of the U.S. Forest Service since it was he who helped me in nearly every stage of the project. I want to thank Dr. Jack L. Stroehlein and Dr. Donald F. Post, Professor of Soil and Water Science, for providing their knowledge and constructive criticism of the thesis. Gizachew Abegaz, graduate student from Ethiopia, gave unmeasurable advice, knowledge, and encouragement and I thank him generously.

My parents, Guy and Dorothy Bitsilly, provided the foundation that made all this work possible and I thank them and all members of my family who gave their confidence, support, and encouragement. Finally, I wish to express my gratitude to Niecy Tsosie for her endless love and support throughout my study.

TABLE OF CONTENTS

TABLE OF CONTENTS--Continued

LIST OF TABLES

LIST OF ILLUSTRATIONS

ABSTRACT

Concentrations of ammonium and nitrate nitrogen, bicarbonate extractable phosphorus, and pH in the upper 10 cm of soil in pinyon-juniper woodlands were not significantly different among site quality classes (I, II, and III). These findings were attributed to slope, climate, and limestone parent material, which were constant factors among the sites. Organic carbon was significantly different between site classes I and III because more organic matter was under trees of site class I.

Periodic annual tree growth (that is, volume divided by age) was significantly different between site classes I and II and between site classes I and III. Higher rates of growth for trees in site class I accounted for these findings. Bicarbonate extractable phosphorus and organic carbon were correlated to periodic annual tree growth.

This information can be used in developing future comprehensive studies of the effects of soil fertility on site productivity in the pinyon-juniper woodlands.

INTRODUCTION

The effect of soil and physiographic site parameters on tree growth has been under investigation for a relatively short period of time in the pinyon-juniper woodlands. One soil-site investigation has shown that tree growth rates are related to total soil depth, effective soil depth, and depth of topsoil (Curlin, 1968). Site productivity also can be related to soil nutrients, texture, available moisture, permeability, and drainage. Site quality indices have been predicted using several other variables besides tree growth, including: potential basal area growth, stem analysis, and canopy cover (Barth, 1980; Meeuwig, 1979; Meeuwig and Budy, 1979).

The litter accumulating under the canopies of trees can modify the chemical and physical properties of the underlying soils. A couple of investigations have been concerned with the effect of pinyon trees on soil chemical properties (Barth, 1980; Bunderson et al, 1985). However, none of the past studies in pinyon-juniper woodlands have been concerned with the effect of soil chemical properties on tree growth rates nor the relationship between soil chemical properties and site quality indices.

The objective of this study was to determine the effect of some available soil nutrients on tree growth and the relationship of these nutrients to site quality indices in pinyon-juniper stands of Arizona that occupied soils derived from limestone parent material. A better understanding of these relationships would provide a better data base for managing pinyon-juniper woodlands in the Southwest.

LITERATURE REVIEW

The recent interest in pinyon-juniper stands in the Southwest as a source of wood has intensified the need for understanding the site factors affecting tree growth. For example, it was estimated that about one-third of Arizona's total energy is consumed by residential and commercial buildings, with woody biomass expected to provide up to 7 percent for these requirements (Patterson, 1980). These figures indicate that the woodland tree species to will provide wood products and the bulk of fuelwood supplies in the Southwest thereby easing the demand on some commercial tree species currently used for fuelwood.

The woodland tree species in Arizona occupy 20 percent of the land area and consist of pinyon (*Pinus edulis*), Utah juniper (*Juniperus osteosperma*), alligator juniper (*Juniperus deppeana*), and Gambel oak (*Quercus gambelii*). These species have achieved sufficient size and form so they can also be utilized for other wood products such as particleboard, paper, and charcoal.

The pinyon-juniper woodlands in Arizona are found between elevations of 1,364 m and 1,970 m (Clary et al, 1974) where they occupy between 4.8 to 5.6 million hectares (Arnold et al, 1964; Spencer, 1966). The annual precipitation in these areas range from 30 to 46 cm (Paulsen, 1975).

Much less information is available on the quantity and distribution of soil nutrients in the pinyon-juniper woodlands as compared to other coniferous forests. Most of the available information for pinyon-juniper woodlands comes from Nevada, Utah, and California (Bunderson et al, 1985; Charley and West, 1975; Meeuwig, 1979). The past studies on pinyon-juniper woodlands in Arizona have been, for the most part, dealt with the effects of pinyon and juniper tree removal (Clary et al, 1974), wood product potential (Barger and Ffolliott, 1978), herbage production (Jameson and Dodd, 1969), and hydrologic responses to treatments (Baker, 1981). However, data on the effects of soil nutrients and pH on site quality and growth of pinyon trees are non-existant.

The following review of literature is primarily concerned with site quality and requirements for growth of trees in temperate zone coniferous forests, such as the pinyon-juniper woodlands. Data for ammonium, nitrate, organic carbon, phosphorus, and pH are from areas with a wide variety of vegetation and environmental factors.

Site Quality

Previous work on site quality indices indicate that tree growth can vary both between site and between tree species on a particular site (Frothingham, 1918; Vincent, 1961; Stage, 1963). These differences undoubtly reflect climatic, edaphic, and inherent genetic differences.

Site refers to an area in terms of its environment, particularly as this determines the type and quality of vegetation that the area can support (Avery and Burkhart, 1983; Stone, 1983). There are direct and indirect measurements of site quality. Direct measurements are often difficult and costly, making it necessary to use indirect estimates. Indirect estimates of site quality are made from measurements of volume, soil features, vegetation, and of site index. Site index is defined as the height over age relationship of dominant and co-dominant trees in a well-stocked, even-aged forest stand at a specified age. The measure of height in relation to age has been found to be practical, consistent, and useful; this is attributed to the sensitivity of height growth to site quality, volume production, and height growth is generally not affected by forest density levels or tree species composition.

The height over age relationship has been used to predict site quality in North America since 1917 (Vincent, 1961). Use of site indices has been accomplished with the knowledge that site quality indicators are constantly changing. Thus, great care must accompany their implementation and use. Frothingham (1918) presented early advantages of using height growth as a guide to site quality. These advantages of height growth guides are: (1) simple, easily obtained in the field, (2) independent of the determination of physical sites producing definite permanent forms of forest, and (3) the sites determined by height growth are species site. Site indices are useful with short-lived intolerant and with long-lived tolerant species growing in the same stand. Disadvantages of height growth as a measure of site quality are sensitivity of height growth to the history of the life of a stand, changes in density, and that a given species can exhibit the same height growth on widely different sites. Mere determination of height growth tells little about the factors which produce it, nor what the same site would produce if other species were grown, nor whether even the same species would grow equally in height on the same site a second time under the same or a different kind of treatment.

Site index at certain ages is not a true index for certain combinations of species and sites. Early height growth of a tree is not always indicative of the height it will attain at maturity (Vincent, 1961).

Young trees may grow rapidly and slow down as they reach maturity because of the variability in the soil horizons. Conversely, young trees may grow slowly when young but much more rapidly as they age. Also, growth might be slow on a coarse, dry soil, but increase if roots reach a richer, moister layer with depth. This type of index has not easily been adaptable to pinyon and juniper stands, because pinyon and juniper trees are rarely even-aged and the relationship between height growth rates and site quality often are obscured by variations in growth form and selective utilization. For instance, pinyon-juniper stands develop quite slowly, time required to approach maximum stand basal area is several times as great as that required by most commercial tree species (Meeuwig and Cooper, 1981).

Smith and Schular (1985) developed a pinyon site index curve in response to lack of a height over age relationship curve for pinyon trees. This curve reflects the growth characteristics of the pinyon tree.

Use of the height over age relationship as a site index for the pinyon-juniper woodlands has been used primarily for the preparation of volume, growth, and yield tables (Howell, 1941; Smith and Schuler, 1985). However, site evaluations of the pinyon-juniper woodlands using physiographical based parameters as vegetation similarities, topographic placement, and edaphic characteristics have increased (Blackburn and Tueller, 1970).

Potential basal area growth, stem analysis, and canopy cover have been used to classify site quality indices for pinyon and juniper trees. It is assumed that basal area growth remains essentially constant after stands become fully stocked (Meeuwig, 1979; Meeuwig and Budy, 1979). Fully stocked is defined as the "average best" of a given stand density to meet management objectives (Avery and Burkhart, 1983). Basal diameter growth rates have been found to largely depend on genetic characteristics of the tree (Meeuwig, 1979; Meeuwig and Budy, 1979; Miller et al, 1981). With stem analysis in single-leaf pinyon (Pinus monophylla) and Utah juniper stands in Neveda and eastern California, tree age was not correlated to either diameter nor height growth rates (Meeuwig, 1979). Site quality was considered here as functions of diameter growth and tree height.

A correlation between crown diameter and biomass has been expressed in pinyon-juniper because of the growth characteristics of both tree species. Both pinyon and juniper lack natural pruning and retain branches and foliage almost to the ground surface. Trees with similar crown and stem diameters can vary in biomass because of differences in crown size, form, and density of foliage.

Literature on other coniferous trees have correlated site index with soils (Zahner, 1957), stand density (Alexander, 1966) and tree age (Alexander, 1967).

Requirements for Tree Growth

Like other tree species, pinyon trees are dependent on water, light, air, and nutrients for growth. Soils can supply most of these elements. That the level of plant production can be no greater than that allowed by the most limiting of the essential plant growth factors is a guiding principle most often used to justify research on soil properties for a given tree species (Brady, 1984). It is necessary, then, to ascertain the most or the least optimum combinations of elements that may represent the conditions for pinyon. As an example, inadequate amounts of phosphorus, potassium, and nitrogen have been suggested to be growth-limiting factors in pinyon-juniper soils (Bunderson et al, 1985).

Influence of Parent Material

Parent material is one of the factors that determine soil and vegetation properties of an ecosystem (Jenny, 1941; Hendricks, 1985). The influence of limestone parent material on the fertility of soils is variable. This is due to the inherent nature of limestone, where limestone contains differences in kind and amount of impurities (Jenny, 1941). However, soils derived from limestone are generally fertile.

Welch (1973) found that tree ecosystems on limestone parent material had the highest quantity of nitrogen and carbon in the litter when compared to basalt, rhyolite, and andesite parent material. In contrast, there was early recognition of the differences in soil properties due to parent material. Bradshaw and Reveal (1943) found that soils on limestone hills were especially of a low site quality. There soils were shallow, rocky, and very gravelly. These findings are crucial in understanding the nature and complexity of micro-processes between vegetation, soil, and parent material.

Pinyon-juniper woodlands on the Colorado Plateau in northern Arizona occur on a great variety of soils, with most of the trends in the distribution of soil taxa being related to latitude, longitude, slope, aspect, landform, and geological substrate (West, 1978; Larson, 1980). General characteristics have normally been identified with the pinyon-juniper woodlands. They are shallow, rocky, low in fertility, and sparse litter cover (Baker, 1981; Daniel et al, 1966; Pieper, 1977). In contrast, Phillips (1909) found the best stands of pinyon on coarse gravel, gravelly loam, coarse sand, and often on rocky areas.

Soil horizon development varies with climate, vegetation, topography, time and parent material. Most soils of Arizona are classified as Mollisols and Aridisols although other soil orders such as Alfisols and Inceptisols are found (Hendricks, 1985).

Mollisols are thick, dark colored, and have more than 50 percent base saturation. A percentage base saturation approaching 100 results in alkalinity or neutrality of the soil (Bohn et al, 1985). Alfisols are mineral soils with either an argillic or natric subsurface horizon. This indicates silicate clay accumulation and content of sodium in the soils. Inceptisols are known to have horizons which were formed quickly and result mostly from the alteration of the parent material, with few diagnostic features (Brady, 1984).

Vegetation and Climate

Vegetation had been thought be have a minor effect on the development of soils in the pinyon-juniper woodlands because of sparse vegetation, often rapid erosion, and length of time required for soils to develop in semi-arid environments (West, 1978). However, Bohn et al (1979) and

Birkeland (1984) reported that vegetation and soils differ considerably in their response to climate. Because vegetation is an important variable producing differences in soil properties, and because of the dependence of vegetation and soil to climate, it is difficult to clearly define all the relationships associated with soil nutrients and site productivity.

Productivity of soils usually is related to the ability of roots to proliferate through the soil, degree of soil aeration, and ability of soil to supply water and nutrients. Aeration, the exchange of oxygen and carbon dioxide between the atmosphere and the soil and plant roots, is reduced by high soil water contents. This reduction in aeration reduces the aerobic respiration of both higher plants and the soil microorganisms. These reductions in respiration rates influence the rates at which nutrients become available and the rates at which they are used by higher plants (Cochran, 1984).

Furthermore, the chemical and physical properties of the soil commonly vary with tree species (Birkeland, 1984), often making it more difficult to use soil-site quality indicators from species to species, and even from site to site.

An increase in pH often is noted due to slower biotic activites during winter and spring. Differences in pH in soils, apart by inches, can be caused by variation from local microbial action and the uneven distribution of organic residues in soil (Brady, 1984).

Soil Nutrients

It has been documented that no more than 1 to 2 percent of the total quantity of nutrients in the soil is available to the plant (Birkeland, 1984).

Research on the effects of individual plants or the modifications of soil chemistry indicates that vertical and horizontal gradients in soil chemical concentrations reflect orderly patterns of accumulations (Charley and West, 1975; Barth and Klemmedson, 1978; Zinke, 1962).

Ammonium and Nitrate

Soluble inorganic ammonium and nitrate compounds are one of three major forms of nitrogen in mineral soils (Brady, 1984). The other two forms are organic nitrogen associated with humus and ammonium nitrogen fixed by clay minerals. Nitrogen in the form of ammonium and nitrate constitutes only about 1 to 2 percent of the total nitrogen present (Brady, 1984; Stevenson, 1986); this has been deemed favorable since inorganic nitrogen is subject to loss from soils by leaching and volatilization. The sources and transfer processes of organic and inorganic nitrogen is illustrated by Figure 1.

Nitrogen content of the soil increases with elevation (Stevenson, 1986); this is correlated with an approach toward cool, moist climates. Temperature and precipitation determine the kind and amount of vegetation, which in turn influence the amount of organic matter produced.

Nitrogen, phosphorus, and sulfur are released when organic tissue decomposes in the soil; making the availability of these nutrients dependent on organic matter buildup on the soil. Organic matter is the main source of nitrogen.

A high percentage of nitrogen may be (in part) a result of the rapid release of available nitrogen from decomposing litter and roots (Welch, 1973). According to Fuller and Ray (1965), Arizona soils are low in organic matter and, therefore, in reserve nitrogen.

The nature of ammonium is complex. First, ammonium ions can be fixed by certain clay minerals and to some degree by organic matter and are not subject to rapid oxidation in this form (Stevenson, 1986; Brady, 1984). Organisms such as mycorrhizal fungi are capable of using

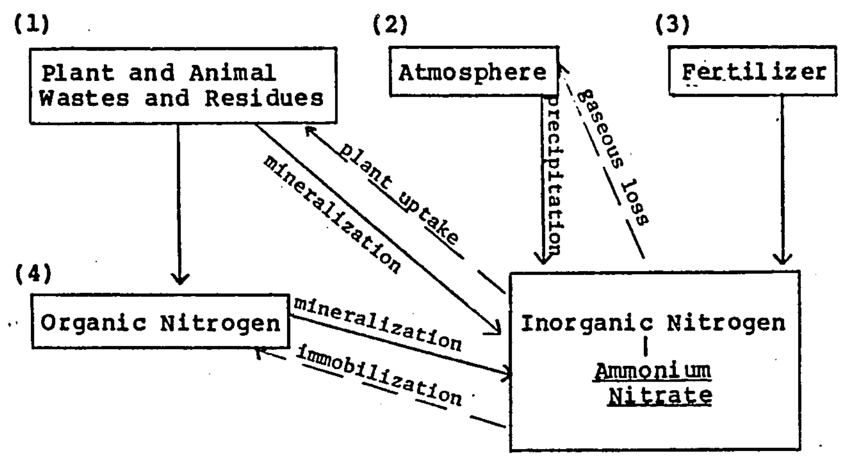

FIGURE 1.- Soil nitrogen sources and transfer processes (Brady, 1985)

this compound as well as higher plants and animals (Bohn et al, 1979). Finally, ammonium is oxidized by autotrophic bacteria and converted to nitrate nitrogen (Brady, 1984). Ammonium and nitrate in the soil is the result of lengthy biochemical interactions and transfers. These processes are important for discussion because trees absorb most of their nitrogen in ammonium and nitrate forms (Brady, 1984).

Concentrations of ammonium and nitrate in the soil indicate nitrogen availability to higher plants (Bohn et al, 1979). It is known that under ideal soil, moisture, and temperature conditions, ammonium is oxidized rapidly to nitrate (Brady, 1984).

Nitrification is defined as the process of oxidation of ammonium to nitrate by microorganisms. Soil conditions such as aeration, temperature, moisture, the carbon-nitrogen ratio (Brady, 1984), and presence of adequate ammonium ion influence nitrification. Nitrate can be incorporated by microorganisms, lost in drainage, volatilized in a gasious state (Brady, 1984), or be incorporated into higher plants such as trees.

Coile (1938) demonstrated that nitrate can be formed in surface soil, where a higher carbon-nitrogen ratio and exchangeable calcium level exist. He stated that significant differences in H-ion concentrations and amounts of calcium in various soils greatly affect the growth of nitrate-forming bacteria. Also, higher carbon/nitrogen ratios favor the growth of nitrate-forming bacteria (Coile, 1938).

Organic Carbon

Forest stands influence the fertility level of surface soil through their effects on the type of decomposition of organic debris. In general, plant and litter cover exert important influences on soil bulk density, compaction, and in promoting infiltration and, therefore, on nutrient uptake by the plant.

The amount of organic matter in soils varies due to variations in climate, vegetation, soil physical properties, and management practices. Organic matter influences soil color, water holding capacity, soil structure, cation exchange capacity, and finally, the supply and availability of nutrients.

Soil reflect the composition of its litter (Zinke, 1962). For example, decomposition of pinyon litter does not have an acidifying effect on soil beneath its canopy according to Barth (1980). The accumulation of soluble salts under the trees were sufficient to offset acidifying influences normally expected from decomposing coniferous litter. Patterns as such may be related to ion uptake and redistribution in litter fall (Charley and West, 1975).

It has been found that tree species with litter accumulations high in bases favor more complete decomposition and incorporation of organic matter into the surface of the mineral soil (Coile, 1937). Investigations with numerous forest trees also have characterized spatial patterns of soil nutrient distributions under tree canopies, with highest concentrations near the bole (Garcia-Moya and McKell, 1970; Zinke, 1962; Barth and Klemmedson, 1978). Other authors have documented the role of fungal development in the soil organic fraction which regulate decomposition and nitrogen mobilization available to plants (Brady, 1984; Parker et al, 1984).

Phosphorus

Phosphorus is required for the essential metabolic synthesis processes needed for plant growth. Plant roots absorb the inorganic and organic fraction of available phosphorous and translocate them to the biomass (Figure 2). Then, the phosphorus in the biomass is returned to the soil either in organic matter or by human and animal wastes. Phosphorus, although abundant, is minimally available in

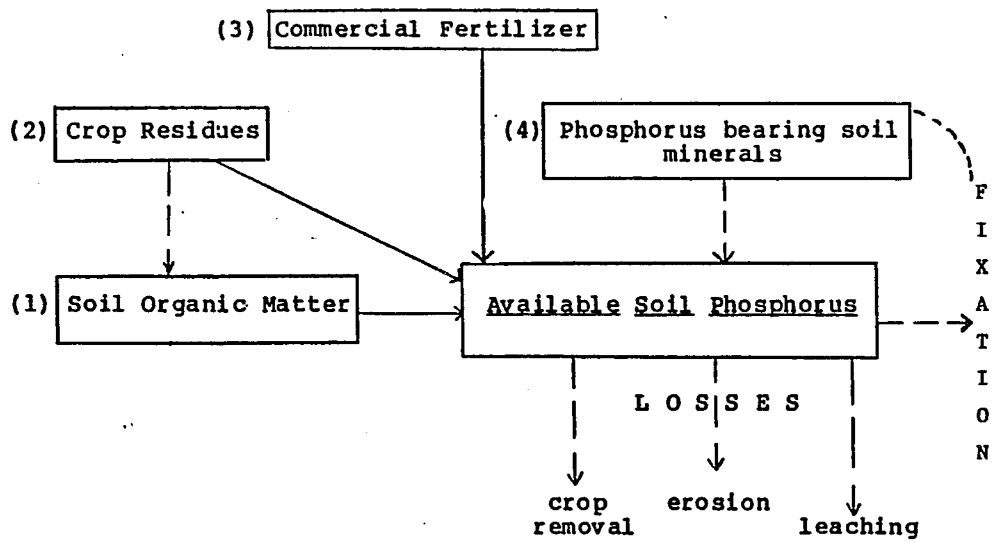

FIGURE 2.- Available phosphorus sources (Brady, 1985).

many soils. The quantity of water-soluble phosphorus in calcareous soils is low. The rate at which phosphorus becomes soluble is slow (Fuller and Ray, 1965). It has has been estimated that only 0.01 percent of phosphorus is present in the available form (Brady, 1984).

The availability of phosphorus is dependent on pH. It is known that high soil pH decreases the availability of phosphorus (Bohn et al, 1979). This relationship occurs because of the precipitation of insoluble calcium phosphate compounds (Bohn et al, 1974; Stevenson, 1986). Conversely, low availability of phosphorus in acid conditions is a result of the precipitation of insoluble iron and aluminum phosphates. Other factors which affect the availability of phosphorus are: (a) soluble iron, aluminum, and manganese, (b) presence of iron-, aluminum-, and manganese-containing minerals, (c) available calcium and calcium minerals, (d) amount and decomposition of organic matter, and (e) activities of microorganisms (Stevenson, 1986).

Several factors influence the amount and distribution of phosphorus in soils. Weathering of the soil material with subsequent leaching can be a primary reason for differences between soil depths. Vertical distribution of phosphorus is known to be altered by organic matter accumulation and by a downward movement of phosphorus-bearing materials in suspension (Godfrey and Riecken, 1954). It had been thought that soil organic phosphorus was rather inert and contributed little to the phosphorus-supplying power of the soil. Thompson and Black (1949) found that both nitrogen and organic phosphorus were more resistant to mineralization as the degree of soil organic matter decomposition advanced. The resistance of organic phosphorus to mineralization increased more rapidly than that of nitrogen with advancing decomposition. Soils have been shown to vary as to phosphorus content and in the vertical distribution of the phosphorus (Godfrey and Riecken, 1954). Vertical concentration gradients with soil surface maxima have been found to be greater for phosphorus, nitrogen and calcium than that for pH and salinity (Charley and West, 1975). In addition, horizonal changes in soil chemical concentrations, although quantitatively less pronounced, can reflect lateral accumulations with the presence of roots (Charley and West, 1975). Phosphorus concentrations beneath pinyon suggest that octacalcium phosphate can be present (Barth, 1980).

Soil Reaction (pH)

The pinyon-juniper woodlands of the Southwest are found on alkaline soils (Howell, 1941; Johnson, 1962). The alkalinity of soils derived from limestone has not been attributed to the excessive alkaline characteristics of limestone but rather to low precipitation. Low precipitation causes an accumulation of soluble salts near the surface.

If the pH of a mineral soil is raised much above 7, the phosphate nutrition of higher plants is disturbed. Phosphorus fixation is at a minimum at pH of 6 to 7 and availability to higher plants is at a maximum (Stevenson, 1986).

DESCRIPTION OF STUDY

This study was designed to evaluate the relationships of extractable ammonium and nitrate nitrogen, organic carbon, bicarbonate extractable phosphorus, and soil reaction (pH) with site quality indices and pinyon tree growth.

Location and Topography

Geology maps and field inspections were used to select pinyon woodland study areas having soils derived from limestone parent material. The study area was located on the Prescott National Forest, near Chino Valley, Arizona This area provided a range of plant cover and land use conditions, concentrated in a relatively small area where preliminary observation of slope and drainage patterns indicated uniform landform (Figure 3). The study area had mean elevation of 1,637 m, northeast and southwest exposures, and slopes averaging 33 percent.

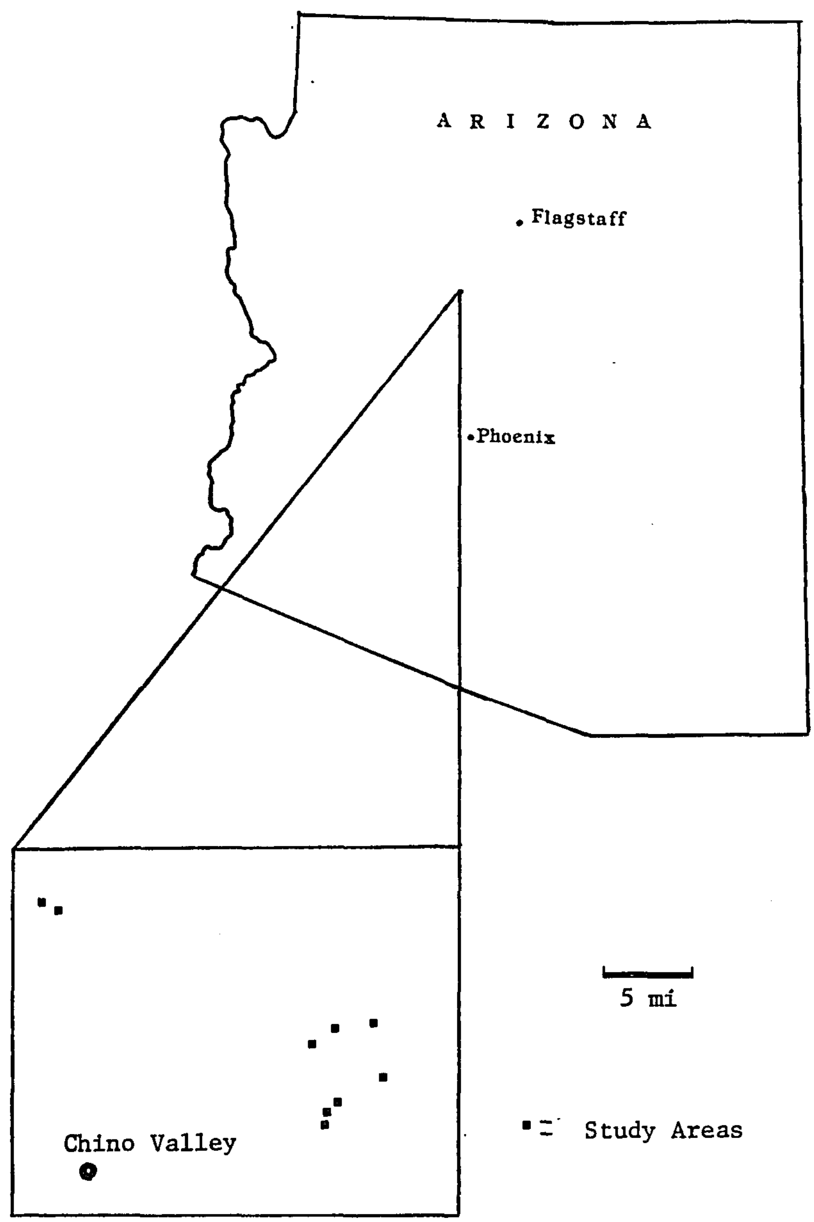

FIGURE 3.- Map of study area.

Climate

Mean annual precipitation at the Chino Valley weather station from 1964 to 1985 was 33 cm, ranging from 25 to 56 cm. Winter temperatures reach 4 degrees C, while summer temperatures frequently exceed 22 degrees C. About 66 percent of the precipitation falls during the period of July to December, with July, August, and September the most consistently wet period. Approximately 1 percent of the winter precipitation falls as snow (NOAA, 1964-1985).

Field sampling was conducted during the period of March 26 to April 9, 1986. Seasonal variation of nutrients measured was minimized by this relatively short sampling period.

Vegetation

Vegetation of the study area was composed of pinyon and Utah juniper, with little herbaceous understory. Turbinella oak (*Quercus turbinella*) occurred throughout the area studied.

Soils

Soils were formed in residuum on limestone and sandstone ridges (Hendricks, 1985). Inceptisols, Alfisols, and Mollisols dominanted the soils of the study area. A total of 28 trees were located on Inceptisols with 4 trees each on Alfisols and Mollisols (Appendix 1).

Tree Selection

The study was first conceived as being conducted on nine study sites. These nine study sites were to represent three replications of sites having three site class indices (namely, site classes I, II, and III). The site indices were based on curves developed for pinyon-juniper woodlands by Smith and Schular (1985) (Figure 4). According to this classification, pinyon trees having a site index in excess of 30 were classified as being Site Class I, those having a site index of 20 to 30 as Site Class II, and those having a site index less than 20 as Site Class III. Some of the sites used by Smith and Schular for developing the site class indices were located on the Prescott National Forest. The physical appearance of these sites, with respect to tree height and site characteristics, were used for selecting three replicate study sites for each of the three site classes indices. After these study sites had been located (Figure 3), 4 pinyon trees were selected and tagged on each of the nine study sites for further measurements and sampling. On each tree, diameter at breast height, total height, and two tree canopy measurements were taken.

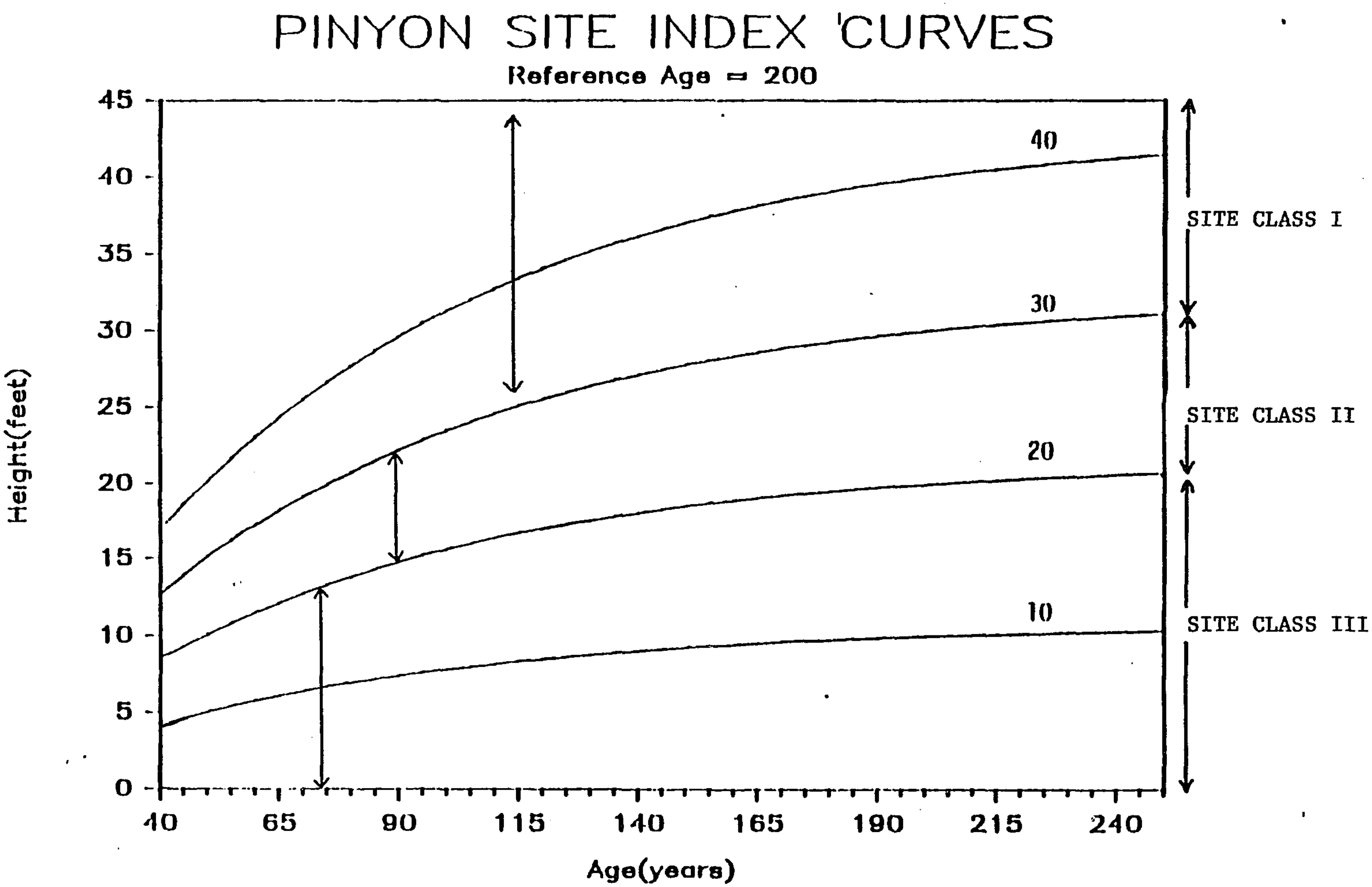

FIGURE 4.- Pinyon site index curves (Smith and Schular, 1985).

An increment boring taken at breast height was made for each tree for determining age. These tree height and age measurements were then compared to the curves developed by Smith and Schular to determine whether the initial classification of the sites was correct.

It was found that, although the site generally appeared to belong to a particular site class, the individual trees in any one study area varied among site classes. Therefore, rather than classifying the trees into nine site classes as was initially planned it was decided to reclassify the 36 individual trees into site classes based on tree height and age characteristics measured on each tree. This resulted in a modified sampling design where the 36 trees fell into 8 in Site Class I, 18 in Site Class II, and 10 in Site Class III. The average height, diameter breast height, canopy, and age are presented in Table 1 along with the slopes in Table 2.

Soil Sampling

Under each of the 36 trees sampled a composite[1] sample of the upper 10 cm of mineral soil were collected by removing four soil cores equally spaced around the mid-

---

1. Compositing samples are justified. An initial analysis found no significant differences between four samples around the tree bole.

TABLE 1.- Tree Characteristics by Site Class.

PINYON

	Site Class I	Site Class II	Site Class III
	8 Trees	18 Trees	10 Trees
	Mean Values + Standard Deviation		
Height (m)	8.15 + 1.84	4.69 + 1.70	3.78 + 0.94
dbh (cm)	23.00 + 2.00	19.00 + 3.00	19.00 + 3.00
canopy (m)	5.63 + 1.66	4.45 + 1.82	4.07 + 1.26
age (yr)	100 + 43	86 + 46	94 + 38

TABLE 2.- Slope Characteristic.

	Site Class I	Site Class II	Site Class III
	Mean Values + Standard Deviation		
slope (percent)	31.13 + 13.99	35.33 + 16.65	34.00 + 11.18

Mean slope for site classes = 33 percent.

canopy area. The 10 to 20 cm layer was sampled in the same manner. The soil samples were passed through a less than 2 mm sieve to remove gravel and cobbles. In the field, a sample of the less than 2mm fraction was placed in a plastic bottle containing 100 ml of 2M KCl which was later filtered in the laboratory. A second fraction of the soil sample was placed in a soil moisture can so that the subsequent laboratory analyses could be converted to an oven-dry basis.

Sample Preparation for Chemical Analysis

Extractable Ammonium and Nitrate Nitrogen

The soil samples stored in potassium chloride were filtered and the extractant stored in a plastic bottle and placed in a refrigerator until analyzed for ammonium and nitrate nitrogen.

Organic Carbon

About 5 grams of air dried-soil were passed through a 100-mesh sieve in preparation for organic carbon determinations. One-half-gram of this soil was set aside for chemical analysis.

Bicarbonate Extractable Phosphorus

Five grams of air-dried soil were added to 100 mls of sodium bicarbonate solution, placed on a shaker for thirty minutes, filtered, and stored in a cool place until analyzed for phosphorus.

Chemical Analysis

All soil samples were analyzed for extractable ammonium and nitrate nitrogen, organic carbon, bicarbonate extractable phosphorus, and pH.

The concentrations of KCl-extractable ammonium and nitrate nitrogen was determined by steam distillation (Bremner and Keeney, 1965, 1966). Chemical standards were prepared and analyzed to determine the percentage recovery of ammonium and nitrate during these analyses. The average recovery factor was 95 percent.

Organic carbon was determined by the Walkley-Black method (Walkley and Black, 1934; Walkley, 1947). Organic carbon in the soil was used as an index of the organic matter fraction because it is difficult to measure directly. Chemical and soil standards were analyzed using a 77 percent recovery factor for carbon.

Phosphorus was determined by the sodium bicarbonate extractable phosphorus method described by Watanabe and Olsen (1965). Standard curves plotting percent transmittance against phosphorus concentrations were developed from a method described by Olsen and Sommers (1982).

Soil reaction (pH) was measured on 1:1 soil water ratio electrometrically as described by McLean (1982).

Calculation of Period Annual Tree Growth

A graphical representation of the relationships between volume and age was established for each tree for each site class (Figure 5). Volume data to develop these relationships were obtained from pinyon volume tables developed by Clendenen (1979) and increment borings taken for each tree.

The periodic annual growth for each tree was calculated using the equation: $PAG = V_2 - V_1/n$, where PAG = periodic annual growth; V_2 = volume at end of growth period; V_1 = volume at start of growth period, and n = number of years in growth period (Avery, 1975). Volumes for the start and end of a 10 year period were determined from the graphical representation. Calculations for periodic annual growth are in Appendix 2.

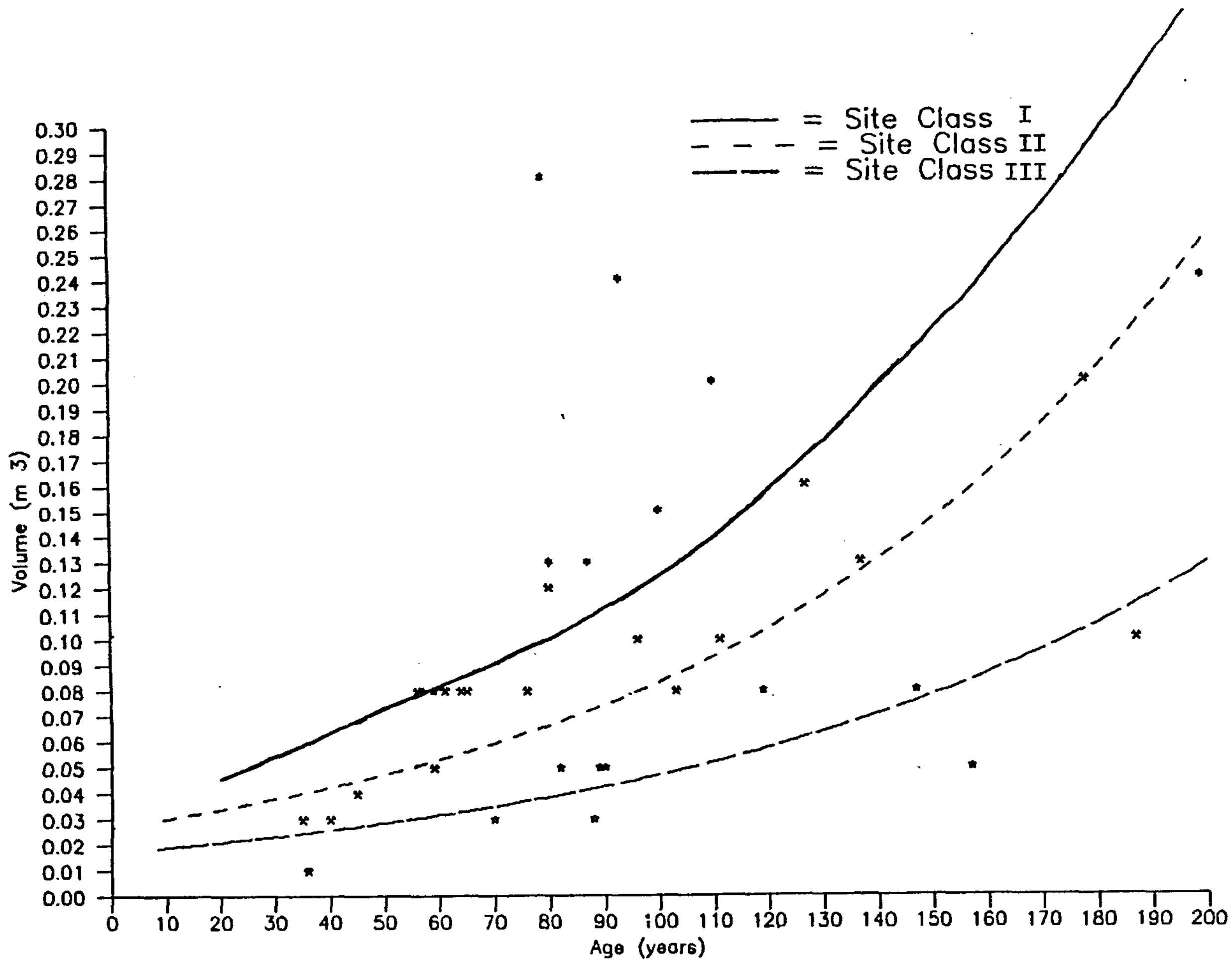

FIGURE 5.- Relationships between volume and age of pinyon trees in different site classes.

Statistical Analysis

The null hypotheses were that there were no significant differences in KCl-extractable ammonium and nitrate nitrogen, bicarbonate extractable phosphorus, organic carbon, soil reaction (pH) of the soils, and periodic annual tree growth among site classes I, II, and III. The soil nutrient parameters and pH values of the 0 to 10 and 10 to 20 cm depths were averaged because an initial analysis showed there were no significant differences in these parameters between the two soil depths.

The null hypotheses were tested using analysis of variance based on a completely randomized design. When significant differences were indicated, the significant differences were isolated by Keul's multiple range test. A summary of the analysis of variance tests is presented in Appendix 3.

Simple linear correlation analyses were used to test the relationships between soil nutrients and periodic annual tree growth. Source data for all site classes were pooled. These analyses were made to distinguish which soil parameter was more closely correlated to periodic annual tree growth.

An alpha level of 0.05 was used for all statistical tests.

RESULTS AND DISCUSSION

The results of this study are presented in two parts. The first section deals with the differences in KCl-extractable ammonium and nitrate nitrogen, bicarbonate extractable phosphorus, organic carbon, soil reaction (pH), and periodic annual tree growth that were present among areas having site class indices of I, II, and III. The second section is concerned with establishing the relationships between these soil parameters and periodic annual tree growth.

Site Class Differentiation

Extractable Ammonium and Nitrate Nitrogen

The concentrations of ammonium and nitrate nitrogen were not significantly different among the three site classes (Table 3 and 4, respectively). The mean ammonium content for all soils in site classes I, II, and III was 9.50 parts per million (ppm). The mean nitrate content for all soils in site classes I, II, and III was 2.81 ppm.

Table 3.- Ammonium nitrogen concentrations (ppm) of soils on different site classes.

Extractable Ammonium Nitrogen
Significance level = .05

Error Mean Square = 26.93
Degrees of Freedom = 33

Rank	Site Class	Mean	n	Sta. Dev.	Non-significant Range
1	II	8.22	18	4.79	a
2	III	9.83	10	3.96	a
3	I	11.98	8	7.14	a
	Average	9.50			

Means with the same letter are not significantly different.

TABLE 4.- Nitrate nitrogen concentrations (ppm) of soils on different site classes.

Extractable Nitrate Nitrogen
Significance level = .05

Error Mean Square = 11.68
Degrees of Freedom = 33

Rank	Site Class	Mean	n	Sta. Dev.	Non-significant ranges
1	II	2.02	18	1.56	a
2	I	3.09	8	1.92	a
3	III	4.00	10	5.95	a
	Average	2.81			

Means with the same letter are not significantly different.

The similarity of ammonium and nitrate in soils of trees among all site classes may be attributed to the constant factors of climate and slope. It has been found that in areas of uniform moisture conditions and comparable vegetation, similar carbon-nitrogen ratios will exist in the soils (Stevenson, 1986). Such was the case with the site classes for this study.

A second reason is that the differences among the three site classes is small and the variation within a site class is relatively high; therefore even though there was a general increase in ammonium nitrogen when going from the lower site indices to the higher site classes the differences were not statistically significant.

Organic Carbon

Percentages of organic carbon were significantly different between site class I and site class III (Table 5). Mean percentage of organic carbon for site classes I and II was 7.07 percent, as compared to 6.38 percent for site classes II and III.

For site class I plots, the ground surface under the tree canopies were observed to be covered by a thick layer of organic matter. Site class II plots had "moderate" amounts of organic matter buildup while site class III plots had small organic matter on the surface.

TABLE 5.- Soil organic carbon (percent) on areas having different site classes.

Organic Carbon
Significance level = .05

Error Mean Square = 3.06
Degrees of Freedom = 33

Rank	Site Class	Mean	n	Sta. Dev.	Non-significant ranges
1	III	5.65	10	0.65	a
2	II	6.79	18	1.56	ab
3	I	7.71	8	2.82	b

Means with the same letter are not significantly different.

The differences in amount of organic carbon between site classes I and III can be attributed to more organic matter buildup under canopies of trees in site class I as compared to site class III. In addition, trees in site class I were taller and, in general, had more canopy cover than trees in site class III; this indicates the potential of more organic matter buildup for site class I trees. The organic carbon content of the soils under trees on intermediate sites (Site Class II) were not significantly different than those on Site Classes I or III, indicating that this is a gradual gradation between the better and poorer site classes.

Bicarbonate Extractable Phosphorus

There were no significant differences in bicarbonate extractable phosphorus between site classes I, II, and III (Table 6). The mean value was 18.33 ppm for soils in all site classes.

There is a general trend that the concentrations of bicarbonate extractable phosphorus generally increase from the poor to good sites. However, this was not statistically significant because of the high variation within a particular site class.

TABLE 6.- Phosphorus concentrations (ppm) of soils on different site classes.

Bicarbonate Extractable Phosphorus
Significance level = .05

Error Mean Square = 32.72
Degrees of Freedom = 33

Rank	Site Class	Mean	n	Sta. Dev.	Non-significant ranges
1	III	16.98	10	4.62	a
2	II	17.50	18	5.24	a
3	I	21.90	8	7.76	a
	Average	18.33			

Means with the same letter are not significantly different.

Soil Reaction (pH)

Soils in all site classes were moderately alkaline, with a mean pH value of 8.04 (Table 7); this was not surprising, because all the soils of the study area had calcareous parent material. In Site Class I, the pH is lower because there is more organic matter in these soils that tends to lower the pH. Moreover, due to the limited annual rainfall of the area, leaching of the exchangeable bases is not appreciable. High pH values of soils can indicate that the availability of phosphorus to higher plants as trees is low. This is attributed to the precipitation of insoluble calcium phosphate compounds in the soil. The availability of phosphorus in alkaline soils is determined by the solubility of these calcium compounds.

Periodic Annual Tree Growth

Periodic annual tree growth was significantly different between site classes I and II and between site classes I and III (Table 8). This finding was attributed to higher rates of growth for trees in site class I as compared to trees in site classes II and III.

TABLE 7. - Soil reaction (pH) values on areas having different site classes.

pH
Significance level = .05

Error Mean Square = 3.71
Degrees of Freedom = 33

Rank	Site Class	Mean	n	Sta. Dev.	Non-significance ranges
1	I	8.00	8	0.20	a
2	II	8.03	18	0.16	a
3	III	8.15	10	0.23	a
	Average	8.04			

Means with the same letter are not significantly different.

TABLE 8.- Periodic annual tree growth (m3/yr) on areas having different site classes.

Periodic annual tree growth
Significance level = .05

Error Mean Square = .000003
Degrees of freedom = 33

Rank	Site Class	Mean	n	Sta. Dev.	Non-significant ranges
1	III	.0006	10	.0004	a
2	II	.0010	18	.0007	a
3	I	.0035	8	.004	b

Means with the same letter are not significantly different.

Correlations between Soil Nutrients and Periodic Annual Tree Growth

The simple linear correlations between soil nutrients and periodic annual tree growth were significant for bicarbonate extractable phosphorus ($r = 0.36$) and organic carbon ($r = 0.68$). This indicated that as phosphorus and organic carbon increased there was an increase in periodic annual tree growth. These findings have shown that inspite of high pH values, which can lower phosphorus availability, phosphorus was correlated with an increase in tree growth.

The other soil nutrients were not correlated to periodic annual growth; which can indicate that soil nutrient parameters not mesured in this study may have offset the significance of ammonium and nitrate nitrogen and pH to periodic annual growth.

CONCLUSIONS

This study investigated tree growth and soil nutrients relationships of pinyon trees growing on areas of different site quality indices. From the research results and computations, the following conclusions were drawn:

Ammonium and nitrate nitrogen, bicarbonate extractable phosphorus, and pH were not significantly different among site classes. However, these nutrients and pH increased as site class increased. The reason that these were not statistically different was because the differences among the site classes were small and the variation within a site class was relatively large.

The amount of organic carbon in the soil was found to be significantly different between site classes I and III because of more organic matter buildup under canopies of trees on site class I. The organic carbon content increased as site class increased.

Periodic annual tree growth was significantly different between site classes I and II and between site classes I and III. Higher rates of growth for trees in site class I accounted for these results. There was no significant differences between site classes II and III.

Bicarbonate extractable phosphorus and organic carbon were correlated to periodic annual tree growth. This indicated that as phosphorus and organic carbon increased an increase in periodic annual tree growth resulted.

The cation exchange capacity of the soil and the physical properties (soil depth and texture) were additional responsible factors which were anticipated to have significant effects on site quality. The former gives the measure of the potential of the soil to supply nutrients to the tree, whereas the latter indicate the availability of water, nutrients, and root development of the tree.

Nutrient budgets for total nitrogen, calcium, sulfur, potassium, and magnesium be developed for above ground biomass of the trees, litter, and soil. This information can be useful in designing future comprehensive studies in assessing the effects of soil fertility on site productivity for pinyon trees in the pinyon-juniper woodlands in Arizona.

APPENDIX 1

SOIL TAXONOMY OF STUDY SITES[3]

Order	Subgroup Family	No of Trees in Site Classes		
		I	II	III
Alfisol	Udic Haplustalfs	2	2	0
Inceptisol	Lithic Ustochrepts, loamy-skeletal, mixed, mesic	4	12	8
Mollisol	Lithic Haplustoll	2	1	1
Inceptisol	Lithic Ustocrepts	0	3	1
	Total	8	18	10

3. Data from U.S.D.A. Forest Service (1982).

APPENDIX 2

PERIODIC ANNUAL TREE GROWTH

tree	dbh (cm)	height (m)	volume (m3/yr)
1	26.37	8.91	.001
2	23.62	9.33	.004
3	20.69	7.09	.001
4	24.11	11.25	.0009
5	21.41	8.55	.0012
6	23.13	7.91	.0015
7	22.12	5.03	.0009
8	18.75	7.15	.009
9	23.94	7.27	.0025
10	21.41	7.15	.0012
11	18.75	6.66	.0009
12	18.85	6.42	.0027
13	20.32	6.12	.001
14	20.69	4.24	.0006
15	17.79	5.62	.001
16	17.57	4.09	.0006
17	22.56	6.15	.0013
18	24.23	4.85	.0011
19	17.92	4.55	.0003
20	20.98	4.91	.0007
21	19.15	3.52	.0005
22	16.59	4.79	.0006
23	15.88	3.76	.0005
24	14.10	2.54	.0006
25	14.10	3.09	.0005
26	11.60	2.52	.0007
27	21.05	4.85	.0003
28	17.49	3.76	.0006
29	12.86	2.86	.0008
30	22.46	4.91	.0006
31	22.29	3.39	.0005
32	17.04	3.03	.0006
33	20.16	2.36	.0015
34	17.92	2.79	.0004
35	22.29	4.00	.0001
36	13.66	1.92	.0003

APPENDIX 3

Analysis of Variance Data
(Unequal sample sizes)

Extractable Ammonium Nitrogen

Source of Variation	df	SS	MS	F	P
Among site class	2	79.89	39.94	1.48	.24
Error	33	888.65	26.93		
Total	35	968.54			

Extractable Nitrate Nitrogen

Source of Variation	df	SS	MS	F	P
Among site class	2	26.00	13.00	1.11	.34
Error	33	385.53	11.68		
Total	35	411.53			

Organic Carbon

Source of Variation	df	SS	MS	F	P
Among site class	2	19.49	9.75	3.18	.054
Error	33	101.00	3.06		
Total	35	120.49			

APPENDIX 3--Continued

Analysis of Variance Data
(Unequal sample sizes)

Bicarbonate Extractable Phosphorus

Source of Variation	df	SS	MS	F	P
Among site class	2	132.41	66.21	2.02	.15
Error	33	1079.75	32.72		
Total	35	1212.16			

pH

Source of Variation	df	SS	MS	F	P
Among site class	2	.12	.06	1.65	.21
Error	33	1.23	.04		
Total	35	1.35			

Periodic annual growth

Source of Variation	df	SS	MS	F	P
Among site class	2	.00004	.00002	7.5	.0002
Error	33	.00010	.000003		
TOTAL	35	.00014			

LITERATURE CITED

Alexander, R.R. 1966. Site indexes for lodgepole pine, with corrections for stand density: Instructions for field use. U.S. For. Ser. Res. Pap. RM-24, 7 pp.

Alexander, R.R. 1967. Site indexes for Engelmann spruce in the central Rocky Mountains. U.S. For. Ser. Res. Pap. RM-32, 7 pp.

Arnold, J.F., D. A. Jameson, and E.H. Reid. 1964. Pinyon-juniper type of Arizona. Effects of grazing, fire, and tree control. U.S. D. A. Agric. Prod. Res. Pap. 84, 24 pp.

Avery, T. E. 1975. Natural resources measurements. 2nd edition. McGraw-Hill Book Company, New York, 339 pp.

Avery, T.E. and H.E. Burkhart. 1983. Forest measurements. Third Edition. McGraw-Hill Book Co., Inc., New York, 331 pp.

Baker, M.B. 1981. Hydrologic regimes of three vegetation types across the Mogollon Rim. In: Hydrology and water resources in Arizona and the Southwest. Proc. of May 1-2, 1981 Arizona Section, Amer. Water Res. Assoc. and Hydrology, Arizona and Neveda Academy of Science, pp. 5-12.

Barger, R.L. and P.F. Ffolliott. 1972. Physical characteristics and utilization of major woodland tree species in Arizona. U.S.D. A. For. Ser. Res. Pap. RM-83, 80 pp.

Barth, R.C. 1980. Influence of pinyon pine trees on soil chemical and physical properties. Soil Sci. Soc. Am. J. 44: 112-114.

Barth, R.C. and J.O. Klemmedson. 1978. Shrub-induced spatial patterns of dry matter, nitrogen, and organic carbon. Soil Sci. Soc. Am. J. 42: 804-809.

Birkeland, P.W. 1984. Soils and geomorphology. Oxford University Press, New York, 372 pp.

Blackburn, W.H. and P.T. Tueller. 1970. Pinyon and juniper invasion in black sagebrush communities in east-central Neveda. Ecol. 51: 841-848.

Bohn, H., B. McNeal, and G.A. O'Connor. 1979. Soil chemistry. John Wiley and Sons, Inc., New York, New York, 329 pp.

Bradshaw, K.E. and J. E. Reveal. 1943. Tree classifications of _Pinus monophylla_ and _Juniperus utahensis_. J. For. 41: 100-104.

Brady, N.C. 1984. The nature and properties of soils. MacMillan Publishing Co., New York, 750 pp.

Bremner, J.M. and D.R. Keeney. 1965. Steam distillation methods for determination of ammonium, nitrate, and nitrite. Anal. Chim. Acta 32: 485-495.

Bremner, J.M. and D.R. Keeney. 1966. Determination and isotope-ratio analysis of different forms of nitrogen in soils: 3. Exchangeable ammonium, nitrate, and nitrite by extraction-distillation methods. Soil Sci. Soc. Am. Proc. 30: 577-582.

Bunderson, E.D., D.J. Weber, I.N. Davis. 1985. Soil mineral composition and nutrient uptake in Juniperus osteosperma in 17 Utah sites. Soil Sci. 139: 139-148.

Charley, J.L. and N.E. West. 1975. Plant induced soil chemical patterns in some shrub-dominated semi-desert ecosystems in Utah. J. Ecol. 63: 945-963.

Clary, W.P., M.B. Baker, Jr., P.F. O'Connell, T.N. Johnson, Jr., and R.E. Campbell. 1974. Effects of pinyon-juniper removal on natural resource products and uses in Arizona. U.S.D.A. For. Ser. Res. Pap. RM-128, 28 pp.

Clendenen, G.W. 1979. Gross cubic-volume equations and tables, outside bark, for pinyon and juniper trees in northern New Mexico. U.S.D.A. For. Ser. Res. Pap. INT-228, 21 pp.

Cochran, P.H. 1984. Soils and productivity of lodgepole pine. In: Lodgepole pine. The species and its management symposium proceedings. May 8-10, 1984. Spokane, Washington, pp. 89-93.

Coile, T.S. 1937. Composition of the leaf litter of forest trees. Soil Sci. 43: 349-355.

Coile, T.S. 1938. Forest soil fertility: Influence of stand composition in nitrogen transformation in the surface soil. Soil Sci. Soc. Am. Proc. 3: 225-229.

Curlin, J.W. 1968. Nutrient cycling as a factor in site productivity and forest fertilization. In: Youngberg, C.T. and C. B. Davey (eds.). Proc. 3rd North Amer. Forest Soils, pp. 313-325.

Daniel, T.W., R.J. Rivers, H.E. Isaacson, E.J. Eberhard, and A.D. LeBaron. 1966. Management alternatives for pinyon-juniper woodlands: A. Ecology of the pinyon-juniper type of the Colorado Plateau and the Basin and Range Province. Bureau of Land Management, Utah Agric. Exp. Station, Logan, Utah, 242 pp.

Frothingham, E. H. 1918. Height growth as a key to site. J. For. 16: 754-760.

Fuller, W.H. and H.E. Ray. 1965. Basic concepts of nitrogen, phosphorus, and potassium in calcareous soils. University of Arizona, Agric. Exp. Stat. and Coop. Ext. Ser. Bull. A-42, 30 pp.

Garcia-Moya, E. and C. M. McKell. 1970. Contribution of shrubs to the nitrogen economy of a desert-wash plant community. Ecology 51: 81-88.

Godfrey, C.L. and F.F. Riecken. 1954. Distribution of phosphorus in some genetically related loess-derived soils. Soil Sci. Soc. Amer. Proc. 18: 80-84.

Hendricks, D.M. 1985. Arizona soils. University of Arizona, Tucson, Arizona, 244 pp.

Howell, J., Jr. 1941. Pinyon and juniper woodlands of the Southwest. J. For. 39: 542-545.

Jameson, D.A. and J.D. Dodd. 1969. Herbage production differs with soil in pinyon-juniper type of Arizona. U.S.D.A. For. Ser. Res. Note RM-131, 4 pp.

Jenny, H. 1941. Factors of soil formation. McGraw-Hill Book Co., Inc., New York, 281 pp.

Johnson, T.N. 1962. One-seed juniper invasion of northern Arizona grasslands. Ecol. Monog. 32: 187-207.

Larson, F.R. 1980. Pinyon-juniper. In: F.H. Eyre (ed.). Forest cover types of the United States and Canada. Society of Amer. Foresters, Washington, D.C. pp. 116-117.

Meeuwig, R.O. 1979. Growth characteristics of pinyon-juniper stands in the western Great Basin. U.S.D.A. Forest Ser. Res. Pap. INT-238, 22 pp.

Meeuwig, R.O. and J.D. Budy. 1979. Pinyon growth characteristics in the Sweetwater mountains. U.S.D.A. Forest Ser. Res. Pap. INT-227, 26 pp.

Meeuwig, R.O. and S.V. Cooper. 1981. Stand estimates of biomass and growth in pinyon-juniper woodlands in Neveda. U.S.D.A. Res. Note INT-311, 3 pp.

McLean, E.O. 1982. Soil pH and lime requirement. In: Methods of Soil Analysis, Part 2. Chemical and microbiological properties. (2nd edition), pp. 199-209.

Miller, E.L., R.O. Meeuwig, and I.D. Budy. 1981. Biomass of singleleaf pinyon and Utah juniper in Neveda and eastern California. U.S.D.A. Res. Pap. INT-273, 18 pp.

National Oceanic and Atmospheric Administration. 1964-1985. Climatological Data. Annual Summary. Arizona. Vol. 68-89, Number 13. National Climatic Data Center, Asheville, North Carolina, 306 pp.

Olsen, S.R. and L.E. Sommers. 1982. Phosphorus. In: Methods of Soil Analysis, Part 2. Chemical and microbiological properties. (2nd edition), pp. 403-430.

Parker, L.W., P.F. Santos, J. Phillips, and W.G. Whitford. 1984. Carbon and nitrogen dynamics during the decomposition of litter and roots of a Chihuahuan desert annual, Lepidium lasiocarpum. Ecol. Mo

Patterson, J.G. 1980. Potential energy equivalents of vegetation types in Arizona. M.S. Thesis. University of Arizona, Tucson, Arizona, 136 pp.

Paulsen, H.A., Jr. 1975. Range management in the central and southern Rocky Mountains. A summary of the status of our knowledge by range ecosystems. U.S. D.A. For. Ser.Res. Pap. RM-154, 34 pp.

Phillips, F.J. 1909. A study of pinyon pine. Bot. Gaz. 48: 216-223.

Pieper, R.D. 1977. The southwestern pinyon-juniper ecosystem. In: Ecology, uses and managment of pinyon-juniper woodlands. U.S.D.A. Forest Ser. Gen. Tech. Rep. RM-39, pp. 3-10.

Smith, F.W. and T. Schuler. 1985. Site quality and growth of pinyon-juniper woodlands in the Southwest. Rocky Mountain Forest and Range Experiment Station. Final report. Project No. 28-K3-303. Fort Collins, Colorado, 21 pp..

Spencer, J.S. 1966. Arizona's forests. U.S.D.A. For. Ser. Bull. INT-6, 56 pp.

Stage, A.R. 1963. A mathematic approach to polymorphic site index curves for grand fir. Forest Sci. 9: 167-180.

Stevenson, F.J. 1986. Cycles of soil. Carbon, nitrogen, phosphorus, sulfur, micronutrients. John Wiley and Sons, New York, 380 pp.

Stone, E.L. 1983. Site quality and site treatment. In: Forest soils and treatment impacts. Proc. Sixth North Amer. Forest Soils Conf., University of Tennessee, Knoxville (June, 1983), pp. 41-52.

Thompson, L.M. and C.A. Black. 1950. The mineralization of organic phosphorus, nitrogen, and carbon in Clarion and Webster soils. Soil Sci. Soc. Am. Proc. 14: 147-151.

United States Department of Agriculture. Forest Service. 1982. Soil survey of the Prescott National Forest, Prescott, Arizona. Unpublished report, 15 pp.

Vincent, A.B. 1961. Is height/age a reliable index of site? Forest Chron. 37: 144-149.

Walkley, A.. 1947. A critical examination of a rapid method for determining organic carbon in soils: Effect of variations in digestion conditions and of inorganic soil constituents. Soil Sci. 63: 251-263.

Walkley, A., and I.A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37: 29-38.

Watanabe, F. S. and S. R. Olsen. 1965. Test of an ascorbic acid method for determining phosphorus in water and NaHCO3 extracts from soil. Soil Sci. Soc. Am. Proc. 29: 677-678.

Welch, T.G. 1973. Distribution of nitrogen and carbon in ponderosa pine ecosystems as a function of parent material. PhD. Dissertation. University of Arizona, Tucson, Arizona, 120 pp.

West, N.E. 1978. Soils associated with pinyon-juniper woodlands of the Great Basin. In: C.T. Youngberg (ed.) Proc. 5th North Amer. Forestry and Soils Conference, pp. 68-88.

Zahner, R. 1957. Mapping soils for pine site quality in south Arkansas and north Lousiana. South. For. Exp. Stat. Report, pp. 430-433.

Zinke, P.J. 1962. The patterns of influence of individual forest trees on soil properties. Ecology 43: 130-133.