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Research Note No. 26 January 12, 1989

Soil and Environmental Factors as Predictors of Cubic Volume Growth in California Mixed Conifer Stands

by

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ABSTRACT

This report describes the development of models to predict the cubic foot productivity of second-growth mixed conifer forest stands in Northern California. These models are developed using only soil chemical and physical site factors or forest stand factors and also using all information combined. Thus, a forest manager can obtain estimates of productivity for bare soil conditions based on soil chemistry, or she can obtain efficient estimates of productivity based upon stand factors alone. In both cases predictions are improved when both stand and soil chemistry factors are used for prediction.

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[1] The authors are Associate Professor, Professor, and Graduate Assistant at the University of California, Berkeley. Thanks to Drs. Jim Bertenshaw for laboratory analysis and Alan Stangenberger for laboratory analysis and programming assistance in adapting the US Forest Service's water balance program --Regime4. The Soil Conservation Service deserves recognition for collecting the soil samples at each cluster location. Thanks also to Gary Nakamura for taking a lead role in designing the soil sampling techniques and to Dr. Robert Powers for consultation and advice regarding soil nitrogen mineralization analysis.

INTRODUCTION

Research in the area of soil-site productivity has usually focused on predicting site index as a function of soil physical and chemical properties and topography (cf e.g. Alban, 1974, Payandeh, 1986, Schmidt and Carmean, 1987, and Wall and Loewenstein, 1969). This technique is valuable when it is difficult or impossible to find adequate site index trees (Schmidt and Carmean, 1987 and Munn and Vimmerstedt, 1980).

Many soil-site studies have been conducted in the United States. Results of these studies vary with different species, regions, soils, topography and climatic conditions (Schmidt and Carmean, 1987). While there have been many studies, few have been conducted in the important mixed conifer forest type of California. Zinke (1960) found that the site index of Ponderosa pine (*Pinus ponderosa* Laws.) is related to the total nitrogen content of the soil. The relation of site index to soil depth was developed from data obtained by the soil-site evaluations of the California Cooperative Soil-Vegetation Survey (Zinke, 1958).

Soil - site studies have been conducted in the mixed conifer forests of the Northern Rocky Mountains, notably in Idaho and Montana. Wall and Loewenstein (1969) studied the relationship between grand fir site index and soil and topographic factors. They found that topography, depth, texture and color of soil was related to site index. Working in lodgepole pine stands in western Montana, Holmes and Tackle (1962) found that most of the variation (86%) in the height growth of dominant trees was explained by the stand characteristics of trees per acre, crown-height ratio, average diameter of the dominant trees, and the reciprocal of the average age of dominant trees. When soil variables were added to the equation (such as the percentage silt plus clay in the B horizons weighted by the effective depth of the B horizon, available moisture, organic matter, nitrogen, exchangeable phosphorus and potassium in the B horizon) there were only minor improvements to the height predictions over using stand characteristics alone.

Brown and Loewenstein (1978) studied Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and grand fir (*Abies grandis* (Dougl.) Lindl.) in mixed conifer stands in Northern Idaho. They found that soil and topographic variables explained 70% of the variation in height of site trees. Soil physical properties explained 36 percent of the variation in site indices; soil chemical values explained 23 percent of the variation, and topographic features accounted for 11 percent. Important soil variables included extractable calcium, exchange acidity, cation exchange capacity, organic matter, total nitrogen, and soil to rock ratio of the buried soils.

Generally speaking, most researchers studying even-aged relatively pure single-species stands have found poor correlation between site index and soil factors and lesser vegetation (Broadfoot, 1969, McQuilkin, 1976, Payandeh, 1986, and Monserud et al, 1986). The generally low correlations may be attributable to the improper identification and measurement of the true causes of site productivity such as nutrient availability during the growing season, soil aeration and physical conditions such as root growing space (Broadfoot, 1969).

Alternatively, site index may not be the best measure of site productivity (Carmean, 1975 and Monserud et al, 1984). Analyzing the causal environment (Lee and Sypolt, 1974) is an alternative means of estimating site quality. Kozlowski (1982), for example, has shown that water availability has a strong effect on forest productivity. Measures of available water, derived from an annual water balance equation, have been shown to exhibit correlation with productivity (Giles et al, 1985). Since plant growth is controlled by the processes of transpiration and photosynthesis, McLeod and Running (1987) used a process model to calculate leaf area index, available water index and estimates of seasonal photosynthesis for even aged ponderosa pine stands in Western Montana. They found that for these ideal stands, several measures of productivity ranked stands equivalently. These indices included site index, leaf area index, and an available water index.

In the complex second-growth mixed conifer stands sampled for this study, the traditional definition of a site index is not entirely satisfactory, since most trees have experienced suppression at some point in their development. Thus, in this paper we focus on cubic foot volume growth as an alternative measure of site productivity. The use of cubic foot volume growth is not typically used since repeated measurement of the trees or stem analysis at each study location is required. Hence, most researchers opt for the simpler method of relating site index to soil factors and topography. In this paper we also investigate several measures of available moisture relative to site productivity.

In our next research note we will analyze the ability of soil chemical and physical factors along with stand and site variables to predict site index. The two productivity measures will be compared.

METHODS

Data for this study were provided by the Northern California California Forest Yield Cooperative's growth and yield project and the soil-site project. Thirty-nine cluster locations (see Figure 1) were established to obtain tree and soil measurements within four geographical regions (see Figure 2).

The tree measurements were taken on thirty-nine clusters. Thirty-one of these clusters contained three one-fifth acre (0.08 ha) plots each and eight clusters contained two one-tenth acre (0.04 ha) plots each. The plots were located at the vertices of an equilateral triangle with side lengths equal to 198 feet (three chains). The eight clusters containing two one-tenth acre plots, however, had plots which were located 198 feet apart.

Every plot was stem mapped and DBH, total height, and crown length were recorded for trees greater than 6 inches (15.2 cm) in diameter at breast height (DBH). On each plot, approximately one dozen trees were felled. Four to six dominants (two to three for each of the two most prevalent species in the overstory) were chosen randomly for felling from the plot as site index trees. Up to seven additional trees were felled for stem analysis on each plot and were randomly selected, but proportional to their representation in the following diameter classes: 6-10.99"; 11-12.99"; 13-14.99"; 15-16.99"; 17-18.99"; 19-20.99"; and >20.99" which correspond to 15.2-27.9 cm; 27.9-33.0 cm; 33.0-38.1 cm; 38.1-43.2 cm; 43.2-48.2 cm; 48.3-53.3 cm; and >53.3 cm. No more than four trees were selected from any one of these diameter classes. This method ensured that trees would be selected from all size classes, but in approximate proportion to their occurrence on the plot.

Each tree selected for stem analysis was felled and discs (1-2 in (2.5-5.1 cm) thick) were taken at stump height (1.5 ft (0.46 cm)), breast height, and subsequent log lengths (16.5 ft (5.03 m) or 20.5 feet (6.25 m)). Each disk was tagged and photographed. Laboratory analysis to determine age and annual radial growth from the photos followed a procedure given by Biging and Wensel (1984) in which a digitizer was used to record the Cartesian coordinates of annual ring boundaries from the pith to the outer edge of a disc.

Five-year cubic foot volume productivity was calculated on each of the stem analysis trees. Because not all trees on a plot (or cluster) were felled for stem analysis, the non-felled trees' five-year cubic foot volume growth was estimated using the California Conifer Timber Output Simulator (Wensel, Meerschaert, and Biging, 1987). First, the growth model was calibrated to each cluster to ensure that the growth predictions would be accurate. The calibration factor used was the ratio of the observed growth for the stem analysis trees to the predicted growth for those trees. This adjustment ensures that the total predicted volume growth for these trees will equal the total observed growth. This calibrated model was then used to estimate the five-year cubic foot volume growth of all the non-felled trees on each plot using the cluster ratio adjustment.

Total growth on each plot was then the sum of the growth of the felled trees and the non-felled trees expanded to a per acre basis. By averaging the per acre growth based on either two or three plots per cluster, a cluster average was calculated. The cluster average for cubic volume growth is used in subsequent analysis with soil chemical values, physical site factors, and stand factors.

The soil sampling consisted of one representative soil profile to be described and sampled by the Soil Conservation Service (Soil conservation Service, 1975) and five satellite soil samples to be collected from the cluster area to evaluate soil variability. The profile description included soil depth, color, texture, structure, coarse fragments, pH, degree of horizonation, roots and pores, and general site factors of slope, aspect, elevation, and climatic regime. Soil samples included one two quart sample per horizon with 3 samples from the surface 12 inches and 2 samples from the 12 to 48 inch depth. Additionally, bulk density samples were collected for each horizon. The satellite samples included 5 additional samples from the cluster area taken to evaluate site variability. Each satellite sample consisted of five subsamples from the 7 to 9 inch depth.

Horizon sample were analyzed for the for the soil properties listed in Table 1: organic carbon, nitrogen, phosphorous, cation exchange capacity, percent base saturation, manganese, mineralizable nitrogen, available soil moisture, and soil depth. All analyses, except for mineralizable nitrogen, were completed according to the procedures described by Black et al. (1965): carbon by combustion; nitrogen using the Kjeldahl method; cation exchange capacity by pH 7.0 ammonium acetate extraction and then measurement with a Perkin-Elmer Model 303 atomic absorption spectrophotometer; percent base saturation by dividing the sum of the Ca, Mg, K, and Na equivalents with the cation exchange capacity and then multiplying by 100; available phosphorus by water soluble extraction; and available soil moisture by calculating the soil moisture retention difference between -15 and -1/3 atmospheres of pressure. Mineralizable nitrogen was determined by measuring Kjeldahl nitrogen after a sample of the soil had been incubated for two weeks (Powers, 1980).

The horizon values were then summed to a depth of one meter or the bottom of the soil profile (whichever came first) and their units converted to values per square meter of soil; thus one can think of this as a measure of a given property per cubic meter of soil for soils that are a meter or more deep and something less than a cubic meter for shallower soils. This measure attempts to be proportionate to the amount of an element in a soil with which a tree normally comes in contact.

The water balance variables -- potential evapotranspiration, runoff, and transpiration during the growing season -- were calculated using Regime4, a water balance program by Warrington and Weatherred (1983), which is based on the water balance model of Thornthwaite and Mather (1955). The required input variables -- latitude, slope, azimuth, available soil moisture, soil depth -- were measured for each cluster. However, rainfall and temperature data -- average values as of 1987 -- had to be extrapolated from the nearest weather stations (National Oceanic and Atmospheric Administration, 1987). Potential evapotranspiration is the amount of water that can potentially evaporate from an open pan at the site. Runoff is the amount of excess precipitation at the site that cannot be held in the soil and therefore runs off. Evapotranspiration is the amount of water used by vegetation during during the growing season.

The carbon level was ranked according to Weibull Distributions of carbon levels in mixed conifer forests determined by Zinke (1986).

The data set used for this final analysis as predictors of cubic volume growth contains the following three categories of variables: (1) measurements of soil chemical properties, (2) measurements of physical factors of the site, and (3) measurements of various stand characteristics. All of these variables are shown in Table 1. Although numerous other factors were measured, they were eliminated from the data set after preliminary screening showed that they were not useful predictors of growth.

The data set was stratified by wet and dry sites, using the sample average of approximately 8 cm as a cutoff; soils with less than 8 cm available soil moisture were grouped as dry sites, while those with 8 or more cm of available soil moisture were grouped as wet sites. This was done with the hope that different environmental factors would control tree growth on the different types of sites and that separate models would more effectively predict growth for the different data sets. Thus, analysis was then done separately on the complete data set and then on the two subsets.

All analyses were completed using SAS software (SAS Institute, 1982). Using multiple stepwise regression (the STEPWISE procedure), the data sets were analyzed in order to look for useful relationships. Initially, cubic volume growth was analyzed against environmental factors only, and using this process, the most significant and interpretable variables were kept, while the others were discarded. Thus, from this process base models were developed which predict growth from only a few environmental factors. In discussing the failure of his soil-site equation to adequately predict site index on an independent sample of plots, McQuilkin (1976) noted that there was a high degree of correlation among the independent variables which obscured the relation between any one soil factor and site index. Because of the high autocorrelation between soil factors measured in this study, we eliminated some of variables to produce a "base model" which provided good predictions, minimized the autocorrelation problems observed by McQuilkin, and are more interpretable.

Regression analysis (the REG procedure) was then used for the selected base models, stand variables only, and finally for stand variables combined with the base models for each data set. Thus the ability to predict growth from environmental variables, stand variables, and environmental and stand variables combined could be compared.

RESULTS AND DISCUSSION

Three different types of results for each data set are presented: (1) growth prediction based on a soil and physical site factors only; growth prediction based on forest stand variables only; and growth prediction based on both soil and physical site factors and forest stand factors. The means, standard deviations, minimum values, and maximum values for these factors are listed in Table 2. The first model has the advantage of allowing growth predictions when no suitable forest stands are available for measurement and only soil and physical site factors can be measured. The second model allows prediction simply from stand variables, which is efficient if a suitable stand is present. The third model, although more complicated than either of the first two models, gives the strongest predictions of growth.

Environmental Factors Only

Initially stepwise procedures were performed for the 3 data sets (all data combined, wet sites, and dry sites). These regressions (See Table 3) show which variables are correlated with the dependent variable (cubic foot growth). However, we wanted to derive a simple, more interpretable model which summarized important variables, at least some of which were common to all three data sets. These three base models finally selected are presented in Tables 4-6. They differ, yet contain a common set of variables, and across all models the signs of the coefficients are consistent. The predictive value of the base model for the complete data set is strongest with an adjusted R^2 value of 0.46, which compares with a R^2 value (unadjusted) of 0.53 for the "full" model selected by the STEPWISE procedure which contains 8 variables.

Some of the coefficients, at first glance, may seem counter-intuitive and therefore need explanation. It is important to keep in mind that the clusters do not represent all possible site qualities, but, instead, range from moderate to good. Thus, these environmental factors are less likely to show as strong a relationship to growth as they would if sites of extremely different qualities were being compared.

Cation exchange capacity is positively related to growth as expected. It represents the amount of cations -- such as potassium, calcium, and magnesium -- that can be held by the soil in a form available to plants. Base saturation -- the percent of the cation exchange capacity occupied by potassium, magnesium, calcium, and sodium -- however is negatively related to growth. This can be explained by considering cation uptake by the stands; fast growing stands take up more cations than slow growing stands. Thus, in stands with high cubic volume growth, much of the cation content has been taken up and stored in the trees. While cation exchange capacity is a relatively constant measure of the ability of the soil to supply cations, base saturation fluctuates with growth of trees, fast-growing stands taking up more than slow-growing stands.

Mineralizable nitrogen is also negatively related to tree growth. Powers (1980) found that mineralizable nitrogen at low levels shows a positive linear relationship with mean annual increment. However at levels higher than 12 ppm, the relationship is difficult to define, probably remaining positive to about 20 ppm and then leveling off. Our data -- with a mean of 49.36 ppm and a standard deviation of 29.87 ppm (See Table 2) -- do not span such a wide range of site conditions and, therefore, probably reflect the portion of the curve after it has leveled off. Also it should be noted that our soil samples were stored before measurement of mineralizable nitrogen, which could have contributed to the wide variation in our results.

Elevation is positively related to growth, possibly because the lower elevation sites tend to be drier. If the clusters had been located at higher elevations, this relationship could have been reversed, with growth decreasing as average temperatures decrease with increasing elevation.

Slope is positively related to growth, perhaps because as slope increases, so does the volume of soil available to each stand of a given area. Since trees grow vertically, regardless of what the slope is, they have access to an increasing volume of soil as slope increases. In extreme cases, the positive relationship might not hold true, because factors such as soil depth decrease with increasing slope. However, it should again be stressed that these clusters do not represent the entire range of site conditions for mixed conifer forests, but, rather, represent moderate to good conditions.

We had expected that measures of available soil moisture (potential evapotranspiration, runoff, and transpiration) to be important predictors of site productivity. One reason for their lack of inclusion may be due to the limitations in the input data required for determining water balance with Regime4. Rainfall and temperature data were extrapolated from the nearest weather stations and in mountainous terrain the distance between stations is significant. The extrapolation process may have obscured the underlying relations between available moisture and productivity. Development of a modeling system for extrapolating weather variation in mountainous terrain as per Running et al (1987) may be required to improve the predictive capability of this variable.

Stand Factors

Tables 7 through 9 show model fitting results for cubic volume growth of stand factors only. Regardless of the data set (all data, wet sites or dry sites) four stand variables were important. The adjusted R^2 values were 0.60, 0.48, and 0.66, respectively for these data sets. In general, the stand variable models were superior predictors over the models based on environmental factors.

All Factors Combined

Tables 10 through 12 show the model fitting results when stand factors, soil factors, and physical site factors are combined. The highest R^2 values are obtained when all variables are included. For the complete data set the adjusted R^2 value is 0.73, an increase of 0.13 over the model including only stand variables; for the dry site data set the adjusted R^2 value is 0.74, an increase of 0.08 over the stand-variables-only model. And for the data set including only wet sites the adjusted R^2 is 0.74, an increase of 0.26 over for the stand-variables-only model. Thus, soil and physical site factors can improve the predictive strength of a stand-variables-only model and visa versa.

Literature Cited

Alban, David H. 1974. Red pine site index in Minnesota as related to soil and foliar nutrients. For. Sci. 20(3): 261-269.

Biging, Greg S. 1984. A photographic technique for use with stem analysis. For. Sci. 30(3): 715-729.

Black, C. A. ed. 1965. Methods of soil Analysis. American Society Monograph no. 9.

Broadfoot, W. M. 1969. Problems in relating soil to site index for southern hardwoods. For. Sci. 15:354-364.

Brown, H. E., and H. Loewenstein. 1978. Predicting site productivity of mixed conifer stands in northern Idaho from soil and topographic variables. Soil Sci Soc Am J 42: 967-971.

Carmean, W. H. 1975. Forest site quality evaluation in the United States. Adv. Agron. 27: 207-269.

Giles, D. G., T. A. Black, and D. L. Spittleman. 1985. Determination of growing season soil water deficits on a forested slope using water budget analysis. Can. J. For. Res. 15:107-114.

Holmes, J. R., and D. Tackle. 1962. Height growth of lodgepole pine in Montana related to soil and stand factors. Montana State Univ School of Forest. Bull 21.

Kozlowski, T. T. 1982. Water supplies and Tree Growth. Part I. Water deficits. For. Abstr. 43(2):57-95.

Lee, R. and C. R. Sypolt. 1974. Toward a biophysical evaluation of forest site quality. For. Sci. 20(2): 145-154.

McLeod, Scott D., and Steven W. Running. 1987. Comparing site quality indices and productivity in ponderosa pine stands of western Montana. Can. J. For. Res. 18: 346-352.

McQuilkin, Robert A. 1976. The necessity of independent testing of soil-site equations. Soil Sci. Soc. Am. J. 40:783-785.

Monserud, Robert A. 1984. Problems with site index: An opinionated review. *In* Forest land classification: experiences, problems, perspectives. *Edited* by J. G. Bockheim. Dept. of Soil Science, University of Wisconsin, Madison. pp 167-180.

Monserud, R.A., Moody, U., and Breuer, D. 1986. Soil-site relationships for inland douglas-fir. USDA For. Serv., Intermount. Res. Stn., For. Sci. Lab., Moscow, Submitted for publ. in Forest Science. 42 ms p.

Munn, Larry C., and John P. Vimmerstedt. 1979. Predicting height growth of yellow-poplar from soils and topography in Southeastern Ohio. Soil Sci. Soc. Am. J. 44:384-387.

National Oceanic and Atmospheric Administration. 1987. Climatological data for California. Vol. 91. no. 1-12.

Payandeh, Bijan. 1986. Predictability of site index from soil factors and lesser vegetation in northern Ontario forest types. Great Lakes For. Res. Cntr. Can. For. Serv. Info. Rep. O-X-373. 12 pgs.

Powers, R. F. 1980. Mineralizable soil nitrogen as an index of nitrogen availability to forest trees. Soil Science Soc. Amer. Journal. 44(6):1314-1320.

Running, Steven W., Ramakrishna R. Nemani, and Roger D. Hungerford. 1987. Extrapolation of synoptic meteorological data in mountainous terrain and its use for simulating forest evapotranspiration and photosynthesis.

SAS Institute. 1982. SAS user's guide: statistics. SAS Institute, Cary, North Carolina. 584 p.

Schmidt, Margaret G., and Willard H. Carmean. 1987. Jack pine site quality in relation to soil and topography in north central Ontario. Can. J. For. Res. 18: 297-305.

Schmoldt, Daniel L., Martin, George L., and James G. Bockheim. 1985. Yield based measures of northern hardwood site quality and their correlation with soil-site factors. For. Sci. 31(1): 209-219.J

Soil Conservation Service. 1972. rev. soil survey laboratory methods and procedures for collecting soil samples. US Dep. Agric. Soil survey Investigation Report No 1. Washington, DC.

Thornthwaite, C. W. and J. R. Mather. 1955. The Water Balance. Publications in Climatology, Drexel Institute of Technology Laboratory of Climatology. Vol VIII. No. 1, 104 p.

Wall, H. G., Jr. and H. Loewenstein. 1969. The relationship of certain soil and topographic properties to site quality of grand fir in northern Idaho. Univ of Idaho, Forest Wildl and Range Exp Stn, Moscow, Note 14, 4 p.

Warrington, G. E. and J. W. Weatherred. 1983. Regime4: a deterministic soil water balance model. WSDG Report . WSDG-AD-00008. Fort Collins, Colorado.

Wensel, Lee C., Meerschaert, Walter J., and Greg S. Biging. Tree height and diameter growth models for Northern California. Hilgardia. 55(8): 1-20.

Zinke, Paul J. 1958. Site quality for Douglas-fir and Ponderosa pine in Northwestern California as related to Climate, Topography, and Soil. Proc. 1958 Meeting, Soc. of American Foresters, pp 167-171.

Zinke, Paul J. 1960. Forest site quality as related to soil nitrogen content. 7th Intern. Congress of Soil Science, Madison, Wisc. Vol III pgs 411-418.

Zinke, P. J. 1986. Problems related to site specific chemical assessment of soil. Proc. Div. 1, Intl. Union of Forest Res. Organizations. 18th World Congress, Lublyana, Yugoslavia. Vol. 1. pp. 405-414.

Table 1. Variables used in final analysis as predictors of cubic volume growth.

Variable	Description
Soil Chemical Factors	
botc	organic carbon (kg/m^2)
botn	Kjeldahl nitrogen (g/m^2)
botp	water soluble phosphorus (g/m^2)
botmn	extractable manganese (meq/m^2)
botcec	cation exchange capacity (eq/m^2)
minn	mineralizable nitrogen (ppm)
basesat	percent base saturation (eq/m^2)
rnkc	ranked organic carbon (percent)
Physical Site Factors	
botasm	available soil moisture (inches)
elev	elevation (feet)
slope	slope (percent)
depth	soil depth (inches)
pet	potential evapotranspiration (inches)
runoff	calculated runoff (inches)
trans	calculated transpiration from April through October (inches)
X1	forest region 1
X2	forest region 2
X3	forest region 3
X4	forest region 4
Stand Factors	
ba	basal area (ft^2)
site	average site index (ft)
ringsm	average age of dominants and codominants (years)
tpa	trees (> 6 in.) per acre