Order Number 8912613

Soil nutrients in glaciated Michigan landscapes: Distribution of nutrients and relationships with stand productivity

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Soil Nutrients in Glaciated Michigan Landscapes: Distribution of Nutrients and Relationships With Stand Productivity.

BY

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A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Forestry

1988

ABSTRACT

SOIL NUTRIENTS IN GLACIATED MICHIGAN LANDSCAPES: DISTRIBUTION OF NUTRIENTS AND RELATIONSHIPS WITH STAND PRODUCTIVITY

by

Dennis Michael Merkel

Historically the evaluation of soils for forest land management has not included soil features or properties beneath the surface 15-150 cm. On sandy, glacially derived soils, subsolum soil features have been found to influence site quality. The sandy soils of the Manistee National Forest are known to have subsolum textural strata with finer textures than the soil immediately above the strata. The purpose of this research was to examine the chemical properties of these soils and determine whether the presence and fertility of subsolum textural strata were associated with site quality of the stands above them. A stratified random sample of twenty nine stands was selected and soils were sampled to a depth of 450 centimeters. Total Kjeldahl nitrogen, phosphorus, and 1

N boiling nitric acid extractable potassium, magnesium and calcium were determined. Nutrient concentrations (mg kg^{-1}) were converted into nutrient contents (kg ha^{-1}) as a measure of site fertility. Differences in site fertility were determined with a one way analysis of variance (AOV). The AOV results were confirmed with a non-parametric Kruskal-Wallis analysis. Associations of site fertility with mean annual volume increment (MAI) were evaluated by multiple regression analysis and by principal components analysis. The evaluation of site fertility using subsolum textural strata (bands) found that soil series phases had nutrient contents and variabilities which differed noticeably between banded and unbanded phases of the same soil series. MAI was successfully estimated using site fertility variables incorporating either surface (forest floor to 45 cm) or subsolum data (forest floor to 450 cm). Adjusted R^2 values were 0.86 for the subsolum data and 0.74 for the surface data, the standard errors of the estimate were 0.357 and 0.481 m^3 ha^{-1} yr^{-1}, respectively. Soil fertility variables from the forest floor to 200 cm were found to have significant associations with MAI. Examination of subsolum features, especially on soils with sandy surface textures, can lead to collection of information important in accurate determination of site quality and these features should not be ignored in forest land evaluations.

DEDICATION

To my wife Cindy;

and

To the lads,

Woody and Spinner

ACKNOWLEDGEMENTS

The research reported in this dissertation was funded in part by the EPA, USDA Forest Service, and Michigan Agricultural Experiment Station. Without their support these investigations would not have been completed. Special thanks are extended to Mr. David T. Cleland, Soil Scientist for the Huron-Manistee N.F., whose tireless efforts on behalf of the ECS project allowed this research to be undertaken.

I would like to recognize the work of the ECS crew who collected forest inventory, soils, and vegetative data during the summer of 1983. They were, Dr. George Host, Mr. Steve Westin, and Dr. Donald Zak.

A great deal of credit for this work is due to the many individuals (too many to list separately) who assisted in sample preparation, laboratory analysis, and data entry.

Sincere thanks also go to Drs. J.B. Hart Jr. and C.W. Ramm, whose thoughtful review comments were a welcome source of guidance during the preparation of this dissertation.

Particular appreciation is offered to Dr. Phu V. Nguyen who often put aside his own work to rescue me from predicaments in laboratory or data analysis. His assistance was always rendered with a contagious enthusiasm which I will strive to maintain.

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Chapter 1.

Introduction

My interest in forest soil fertility was renewed when the opportunity to participate in the Ecological Classification System Project on the Huron-Manistee National Forest presented itself. Upon a review of the literature it was apparent that almost all forest soil studies were concerned with characterisatics of the upper soil. Since a tree is a long-term inhabitant of a site, and its roots can exploit a considerable soil volume, it did not seem unreasonable that features beneath the surface meter (subsolum features) had the potential to influence forest growth. The paucity of information on this topic left many questions to be answered and few hints on how to proceed. My own interests directed the course of this study towards examination of soil nutrients associated with subsolum features and the determination of their impact on forest productivity.

These studies were undertaken to determine the extent that soil nutrients affect site quality and whether nutrients supplied by subsolum soil features (including strata of fine textured fluvial material) have any association with forest growth. Samples were collected to a depth of 450 cm to thoroughly examine soil volumes exploited by tree roots. Nutrients were expressed as contents (kg ha^{-1}) rather than concentrations (mg Kg^{-1}) to give a better perspective of the site nutrient resource.

This dissertation consists of three main chapters which examined different aspects of site fertility. The chapter format was chosen to facilitate their submission for publication. The chapters are presented in the chronological order of their development.

The conceptual basis for Chapter 2 was to determine whether regional site fertility studies could be used to detect changes in forest growth resulting from increases in nutrient contents due to municipal sludge additions. A concurrent sludge fertilization project provided the opportunity to examine whether regressions of growth and nutrients developed on a regional sample set would predict changes in forest long-term productivity due to fertilization by municipal sewage sludge additions.

It was assumed that there was an association between nutrients and forest growth and that nutrient changes in the period since sludge application (2 years) would be confined to the forest floor and surface soils. Similar sampling and chemical analysis between the two studies allowed utilization of forest floor and surface soil nitrogen and phosphorus contents. These were used to develop an empirical model relating site fertility and growth. Regressions of mean annual volume increment and nitrogen and phosphorus contents in the forest floor and surface soils were used to predict changes in forest growth.

Chapter 2 was presented at the Forest Land Applications Symposium held at the University of Washington in Seattle on June 25-28, 1985. It was co-authored by Drs. J.B. Hart Jr., P.V. Nguyen, and C.W. Ramm and was published as Chapter 27 in the proceedings of the symposium by the University of Washington Press. It is reproduced here with their permission.

Chapter 3 is a quantitative examination of the distribution and variability of total nitrogen, total phosphorus, organic carbon, and acid extractable cations (potassium, magnesium and calcium) contents. These were accumulated by 50 cm increments to a depth of 450 cm. Chapter 3 also investigates the influence of subsolum textural strata on soil nutrient contents.

Soils are not uniform throughout their depth, especially soils of glacial and alluvial origin. Horizontal strata can exist which have distinctly finer textures than the surrounding soil matrix. The abrupt textural changes in such soils can cause percolating water to accumulate at the interface. It is not unreasonable to assume that nutrients being carried by the percolating water will also accumulate. Finer textured strata have increased water holding and cation exchange capacity, and should provide a greater nutrient and water resource for the stand growing above. The presence of textural strata on soils in the Huron-Manistee National Forest and a scarcity of information on deep soil nutrient distributions (on soils with and without subsolum textural strata) led to the investigation reported in Chapter 3.

Use of the soil series (a taxonomic unit based on upper soil features) has been criticized as a mapping unit for forest applications. The sampling depth employed in this study allows an examination of whether inclusion of a phase relating to the presence or absence of textural strata in the soil series taxonomic unit results in more homogenous mapping units with respect to nutrient contents. In addition, differences between banded and unbanded phases of a soil series will be tested for significance.

Chapter 4 examines associations of site fertility with growth of upland oak and northern hardwood stands by multiple regression methods, and principal components analysis. Conflicting reports of the utility of soil nutrients as predictors of forest growth and yield motivated this study. It was hypothesized that the inclusion of subsolum nutrient data would lead to stronger relationships with stand growth and yield than examination of the surface soils alone. Stand growth was measured by mean annual volume increment (MAI). The associations of soil nutrient contents accumulated by forest floor and the surface 45 cm of the soil were compared to those obtained with the 50 cm accumulations.

The research presented collectively in the following chapters is unique in several aspects. First, the soil sampling depth of 450 cm is much deeper than is routinely reported in the literature. This allowed a more comprehensive evaluation of site fertility for the entire volume of tree root exploitation and examination of subsolum nutrient distribution and variability.

Second, these studies utilized a boiling nitric acid extraction to obtain a better representation of the site K, Mg, and Ca nutrient resources. Nutrient analysis of forest soils has traditionally been performed using agronomic procedures. Forest cover occupies a site for time spans much longer than agronomic crops and potentially interacts with a more diverse soil biota. These factors can lead to release and utilization of nutrients which are not extracted by the mild agronomic extractants.

Third, this study used quantitative nutrient and organic carbon data of soils to evaluate whether the incorporation of landscape features as a phase of the soil series resulted in a more homogeneous mapping unit than the soil series alone.

Finally, multivariate analyses of stand growth and yield and site nutrient variables were performed to determine which soil nutrients and what depths had significant associations with site productivity.

Chapter 2.

Municipal Sludge Fertilization on Oak Forests In Michigan: Estimations of Long-Term Growth Responses.

INTRODUCTION

Forest growth in regions of similar climate, soils, and stand histories are dependent on an adequate and balanced supply of nutrients. Nutrient contents (kg ha^{-1}) to a given depth represent a site's resource based not only on nutrient concentrations, but also soil or horizon depths and bulk density. Forest ecosystems are understood to actively cycle nutrients between biotic and abiotic components. Available nutrients are taken up from the forest floor and soil by forest vegetation and utilized for growth. If a nutrient is limiting growth, then increases in forest floor and surface soils should relate to increases in overall stand growth.

Correlations of forest growth with site nutrient contents have received little attention in the literature, but have yielded significant associations when applied. Site index of mature ponderosa pine trees in California showed a positive correlation with N content in the top 1.22 m (4 ft) of soil (Zinke 1960), and total height of 30 year old red pine trees in New York had a significant correlation with extractable potassium (K) contents in the top 152 cm (5 ft) of soil (White and Leaf 1964).

Trees growing on sandy outwash sands in northern lower Michigan rely on mineralization of soil organic matter for N requirements. In soils of similar origin and texture in northern New York it was found that organic amendments increase soil nutrient reserves, site productivity, and therefore site quality (Heiberg and Leaf 1961). The addition of organic matter in the form of municipal sewage sludge to sandy soils has been shown to significantly increase N and P levels in the forest floor of red and white pine stands in northern lower Michigan (Brockway 1983) and can be expected to increase water holding capacity of surface soil horizons.

Few sludge studies have been concerned with long term growth changes in mature forest stands. Intuitively it is expected that sludge additions will result in increased forest growth as do fertilizer applications. However, studies of basal area and radial DBH growth from detailed stem analysis at 2 years (Koterba <u>et</u> <u>al</u>. 1979) and 14 months (Brockway 1983) after sludge applications found no significant increases in growth of mixed northern hardwoods or red pine, respectively. An inherent difficulty is the poor resolution obtained when measuring forest growth differences over a short time frame. Growth lag periods, from time of fertilization until tree response, such as the two to five year period reported for fertilized red pine in northern New York (Leaf <u>et</u> <u>al</u>. 1970) may further obscure short-term examinations.

Growth effects from sludge applications have been measured for time periods as short as two years, while effects of sludge application on forested systems may take longer to completely assess. One method of evaluation is with establishment of long-term sludge fertilization study sites. Such monitoring efforts have only been recently installed at the University of Washington in 1974, and at Michigan State University in 1981. Results from long-term measurements will not be available for some time. Until these studies reach fruition other methods of assessing long-term growth effects are needed.

OBJECTIVES

To determine if a correlation exists between site nutrient resources and stand growth. If a relationship exists, then to identify nutrient components with the strongest associations with stand growth.

To use site nutrient resources to estimate changes in forest stand growth with sludge application.

MATERIALS AND METHODS

The forest stand was chosen as the unit for measurement of nutrient contents and stand growth. Mean annual volume increment (MAI) was used as a measure of long-term growth and may be thought of as average growth over the age of a stand which integrates site factors and climate. In this study MAI's of stands averaging 72 years old were used. Stand growth is a complex response to many soil and environmental factors. No single site characteristic or measurement of growth can completely quantify site quality. We are using MAI as a growth measurement realizing the inherent limitations in its use arising from variations in stand age and species composition.

Because of small nutrient fluctuations in soil at depths below 15 cm (6 in) in sludged stands on similar soils in northern Michigan (Brockway 1983), and on this study area (Hart et al. 1984), only forest floor and surface soil contents were used. The Kjeldahl total contents for N and P are reported here. Acid extractable Ca, K, and Mg should also be related to MAI and are being evaluated. No heavy metals were examined due to the extremely low metal loadings with sludge application (Nguyen et al. 1985).

Estimation of long-term growth changes encompassing a range of nutrient resources was accomplished by sampling a total of 29 stands within the region. The stands were located across an upland productivity gradient ranging from low productivity scrub oak to high productivity sugar maple stands. Regression equations were developed using data from the 29 stands for the nutrient contents of soil and forest floor components exhibiting linear associations with stand growth.

Nutrient contents for sludge and control plots on the sludge study area two years after treatment were inserted into the equation to predict changes in growth from sludge applications. The oak ecosystem in the sludge study has stand growth and composition which falls within the range sampled in the regional study; therefore, implications for changes in stand growth should be applicable.

Sludge Study Area:

Located in Montmorency county, Michigan, the sludge study was conducted on a 70 year old oak stand composed of red oak (*Quercus rubra* L.), white oak (*Quercus alba* L.), and red maple (*Acer rubrum* L.) with scattered pines (*Pinus* spp. L.) and aspen (*Populus* spp. L.). The experimental design, sludge loading rates, and further details of the site and methodology are presented elsewhere (Hart *et al*. 1984, Nguyen *et al*. 1985). The soils at this site belonged to the Graycalm series, a mixed, frigid Alfic Udipsamment; with small inclusions of the Rubicon soil series, a mixed, frigid Entic Haplorthod (Soil Conservation Service 1979, 1976). Both series are distinguished by being deep, excessively drained soils formed in sand on glacial drift materials (Soil Conservation Service 1979). On the oak site the Graycalm series consisted of a weakly developed sandy glacial drift overlying a calcareous, indurated till, with textural bands of varying thickness occurring at fluctuating depths; features not unlike other soils in the immediate vicinity (Farrand 1982).

Regional Study Areas:

The 29 stands were located in the Manistee National Forest, 80-90 miles southwest of the sludge study plots. Figure 2.1 shows the general locations of the two study areas. Soils on the two areas are similar, predominantly sandy surface soils overlying glacial drift, with analogous soil series occurring in both areas. Stands were sampled to give equal representation across a range of productivities and stand compositions. Specific stands were randomly selected from a list of stands provided by the Huron-Manistee National Forest. Stands occupied by pioneer species, or showing signs of disturbance in the past 40 years were excluded from sampling. The minimum basal area of stands sampled was 18.36 m^2 ha^{-1} (80 ft^2 ac^{-1}).

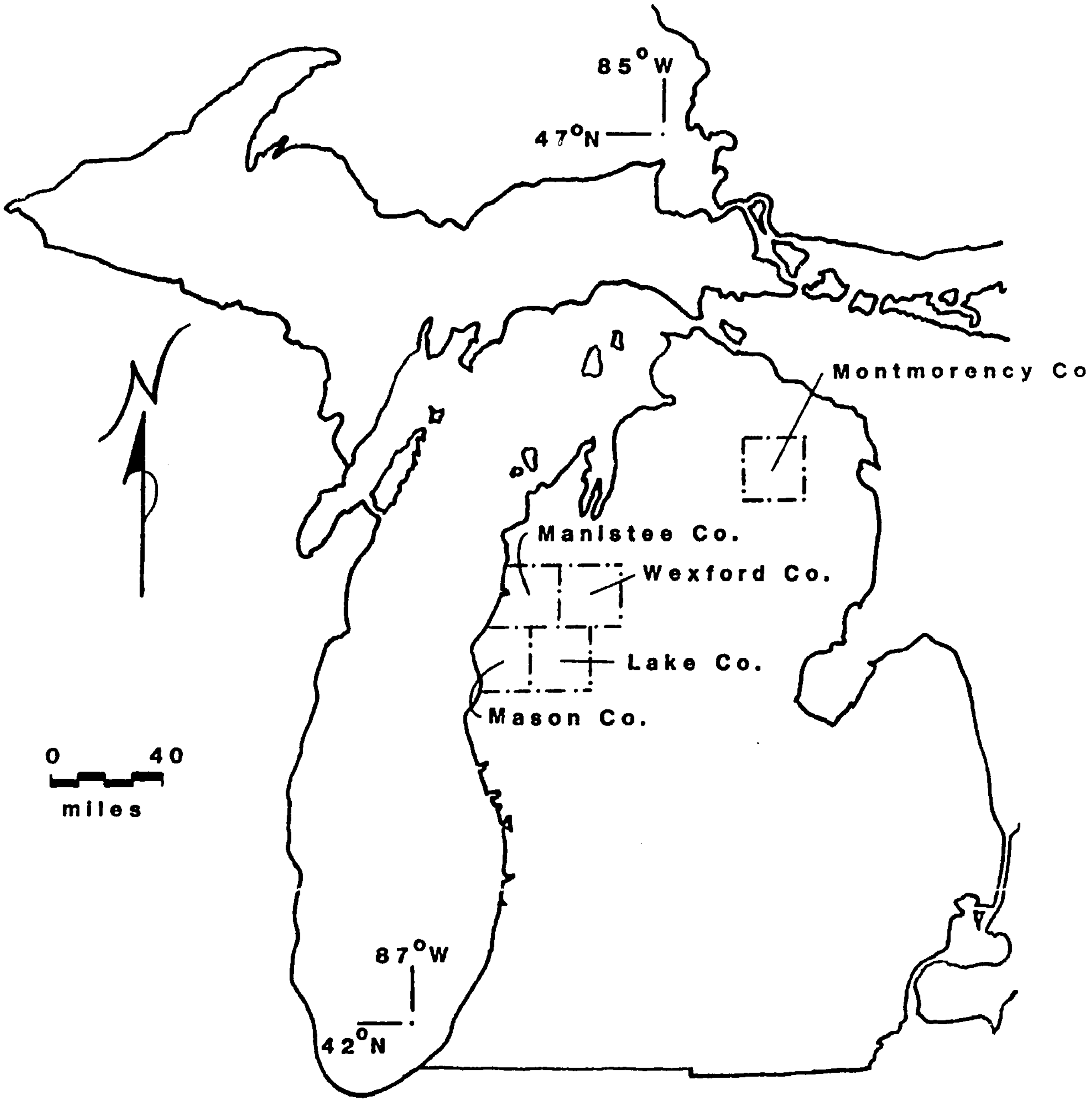

Figure 2.1. Location of sample stands.

Other stand selection criteria included:

1) the overstory must be at least 55 years old,
2) the stand must be normally stocked, i.e. the canopy should be closed as far as site conditions will permit,
3) stocking must be uniform throughout the stand with no extensive open areas,
4) the topography must be representative of upland conditions,
5) the soils must be well drained, and
6) no more than 30% of dominant overstory in multiple stems.

Sample Collection on the Sludge Study Area:

Site nutrient resources on the oak sludge study area were calculated from forest floor and soil samples collected in 1983, two years after application. Thirty points each on sludge and control treatments were sampled.

Sample Collection on Regional Stands:

Samples were collected for the regional nutrient resource study in the summer of 1983. A soil pit 150 cm in depth was located near the center of a homogeneous one hectare portion of the stand. The soils were then characterized and classified to the series level. Three additional sample points were randomly located and soil, forest floor and understory samples were collected. Forest floor samples were collected from 6 sampling points (three at the pit and one at each of the three additional points) with a 30 x 30 cm metal frame and systematically separated into litter or fermentation and humus fractions. Litter (Oi) samples included recognizable and nearly entire leaf material not affected by decompositional processes, and woody material. Fermentation and humus layer (Oe and Oa) samples consisted of finely divided decomposed organic materials extending to the upper boundary of the mineral soil. Soil samples collected directly beneath the forest floor samples were divided into surface (S1, A and E horizons), and subsurface (S2, upper B horizon to a depth of 45 cm) layers. Twenty eight bulk density samples were collected with a hammer-type core sampler and were used to convert nutrient concentration data from the laboratory to a content by depth basis.

Forest growth was measured at each sampling point using a 10 basal area factor prism. All trees at each prism point were measured for DBH, total height and merchantable height to a 10.2 cm top. Trees were sampled across the range of DBH values to determine total age at DBH. Stand growth was calculated by averaging measurements of the four subplots.

Chemical Analysis:

Forest floor samples were oven dried at 70^0C, weighed, ground, and subsampled prior to analysis. Soil samples were air dried, sieved, and subsampled prior to analysis.

Total Kjeldahl N and TKP were determined by a micro-Kjeldahl digestion procedure and analyzed on a Technicon[1] Auto Analyzer II system (Technicon 1977). The data were used with forest floor weights and areas, and soil depths and bulk densities to calculate TKN and TKP contents.

All chemical analyses were performed in the MSU Forestry Department laboratory using 10% sample replication to insure precision and bulk sample analysis with each sample set to insure accuracy. The quality assurance procedures confirmed with a probability of .95 the determination of mean TKN and TKP concentrations with a 10% confidence interval.

Statistical Analysis:

Scatterplots between MAI and stand nutrient contents of the eight forest floor and soil components revealed several nonlinear relationships. More linear scatterplots were obtained with log (base 10) transformations of the variables.

A multiple regression equation was formulated using a stepwise procedure available in the MICROSTAT statistical package (Ecosoft 1984).

[1] Use of a trade name does not constitute an endorsement by either Michigan State University or the EPA.

The equation was of the form:

$$Y = B_0 + B_1X_1 + B_2X_2 \ldots + B_nX_n$$

where:

Y = growth (MAI, $m^3ha^{-1}yr^{-1}$),

n = number of variables in equation

B_n = regression coefficients, and

X_n = nutrient contents in the particular soil horizon ($kg\ ha^{-1}$).

The normal matrix solution for the vector of regression coefficients (B) is: $(X'X)^{-1}\ X'Y$

(Draper and Smith 1981).

Confidence intervals for the predictions on sludge and control plots on the sludge study were calculated using:

$$Y +/- t(v, 1-1/2\quad)*s \quad 1/g + X_0'CX_0$$

Where:

Y = Predicted value

v = Sample size of regional study minus the number of parameters in the regression equation including B_0, (29-4)

s = Standard error of estimate

g = number of observations in X_0

X_0 = a (nx1) Data Matrix, and

C = the (nxn) Inverse of the Variance-Covariance matrix $(X'X)^{-1}$

(Draper and Smith 1981).

RESULTS AND DISCUSSION

The regression equation developed from the 29 regional stands was:

$$\text{MAI } (m^3\ ha^{-1}\ yr^{-1}) = 1.1883$$
$$+ (-5.5847 * \text{LOG TKN CONTENT IN S1})$$
$$+ (5.7873 * \text{LOG TKP CONTENT IN S1})$$
$$+ (2.6515 * \text{LOG TKN CONTENT IN O2})$$

The standard error of the estimate was 0.5241 $m^3\ ha^{-1}\ yr^{-1}$. Contributions of individual variables to the equation can be evaluated through their partial correlation coefficients (calculated with the effects of all other predictor variables removed). The partial correlation coefficients were 0.357 for TKN in the A and E horizons, 0.437 for TKP in the A and E horizons, and 0.519 for TKN in the fermentation and humus layers. The three partial correlation coefficients had similar magnitudes indicating that they made comparable contributions to the estimation of stand growth. Total Kjeldahl N in the fermentation and humus layers was the strongest contributor to long term growth, while TKN in the litter layer had the weakest association. If the Oe and Oa horizons are thought of as nutrient repositories for sludge applied nutrients, then mineralization should result in greater nutrient availability in these horizons and greater growth. The N concentrations are total determinations, and do not reflect the availability or immobilization of sludge N applied to the forest floor.

The residuals were examined and no deviations from normality were noted. Nearly 70% of the variability in MAI was explained (adjusted R^2 of .691). The results of the regression analysis confirm that a site's nutrient resources have correlations with stand growth as measured by MAI.

Table 2.1 presents mean TKN and TKP contents for forest floor and soil components on sludge and control plots. Increases from control existed with sludge treatment for all

Table 2.1. Means of TKN and TKP contents for forest floor and soil components two years after treatment on the sludge fertilization study.

NUTRIENT COMPONENT	TREATMENT	
	CONTROL n=30	SLUDGE n=30
	Kg ha^{-1}	
Nitrogen in S1	833.8	895.9
Phosphorus in S1	110.2	149.3
Nitrogen in O2	391.6	584.1

variables in the regression equation for MAI. Insertion of control and sludge treatment means into the regression equation yielded the results presented in Table 2.2. The predicted growth on the sludged plots of 4.62 m^3 ha^{-1} yr^{-1} is greater than that predicted for the control plots (3.57 m^3 ha^{-1} yr^{-1}) by 29%. This suggests that sludge application has resulted in nutrient changes in soils and forest floor that may have long-term growth effects on this site, assuming that the two year changes will persist or can be maintained by retreatment. A significant 44% increase in three year basal area growth, and a significant 63% increase in three year diameter growth were found using conventional fertilizer trial techniques (Nguyen et al. 1985).

Table 2.2. Predicted mean annual increments over two years for sludge and control treatments.

TREATMENTS	PREDICTED MAI	10% CONFIDENCE INTERVAL
	$m^3ha^{-1}yr^{-1}$	
Control	3.57 a(*)	+/- .3403
Sludge	4.62 b	+/- .4998

(*)Predictions followed by the same letter are not significantly different at an alpha =.10 level.

The difference between treatments exceeded the confidence intervals for the sludge and control predictions and was statistically significant. The growth predicted for the sludge treatment was 8.5% higher than the maximum growth from the regional study (4.62 vs. 4.26 m^3 ha^{-1} yr^{-1}). This is an extrapolation of the data and results should be cautiously interpreted.

It should be pointed out that although the predicted sludge growth was beyond the range of the 29 regional stands, it was not greater than measured growth in the region. Stands in the region which had MAI measured in the summer of 1983 had growth rates of up to 5.11 m^3 ha^{-1} yr^{-1}. The small magnitude of the over-range, high statistical significance, and results of short-term observations tend to reinforce the interpretations reached here. Namely, that there was a significant difference between sludge and control treatments equivalent to 1.05 m^3 ha^{-1} yr^{-1}.

The use of MAI-nutrient resource relationships to assess potential changes in long term growth from sludge is a new approach. Development of this approach and regression model are still being refined and verification of the technique must be performed.

The MAI-nutrient resource relationship was also used to calculate changes in potential long-term growth with hypothetical retreatments of the oak site. This requires three major assumptions. First, the difference between sludge and control nutrient contents of components (Table 2.1) were assumed to represent two year retention of sludge added nutrients on the oak site. Second, subsequent reapplications were assumed to have loading rates and retention rates equivalent to the initial loading and two year retention. Third, N and P contents from previous sludge additions have different retention rates than nutrients and organic matter from newly applied sludge.

Figure 2.2 presents MAI predictions for initial application and three retreatments over eight years using three different retention rates of sludge more than two years old. Curve `A' assumes a retention rate of 100% for sludge nutrients after the second year. The MAI predicted in the eighth year using this assumption was 70% greater than the highest MAI observed in the 29 regional stands and represents an extrapolation which must be interpreted with caution. The 100% retention rate would result in maximum nutrient accumulations with no further degradation of applied organic matter and nutrient release. This may not be a reasonable assumption for a forest system. Curve `B' presents growth when sludge nutrients were assumed to have nutrient retention rates equivalent to those of the first two years after application. The MAI in curve `B' in the eighth year was 23% above the maximum sampled MAI. However, retention rates for the first two years after application may be unreasonably low for `older' (and probably more resistant) organic nutrient

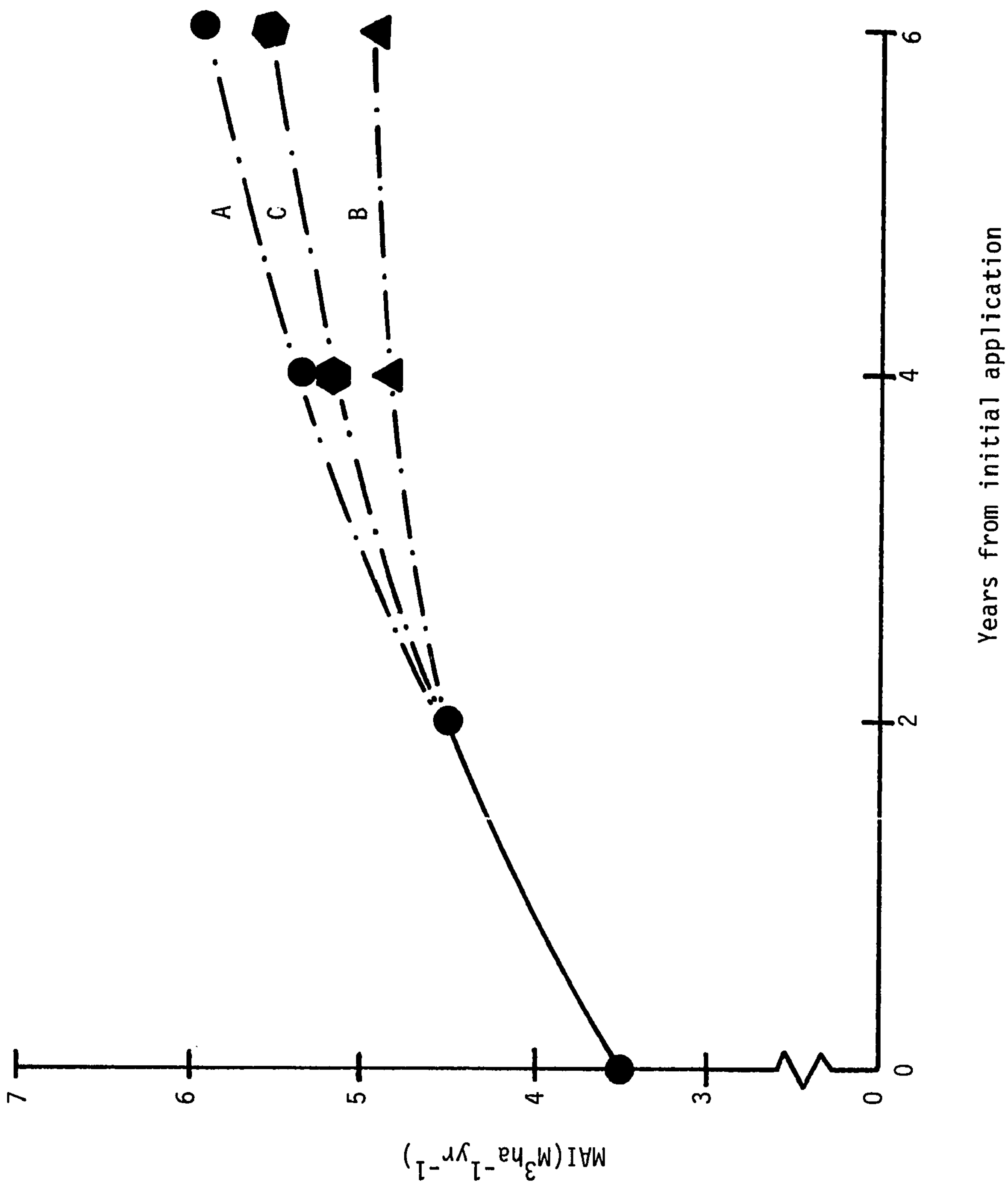

Figure 2.2. Hypothetical MAI curve. Changes over time with three different nutrient retention rates for sludge nutrients > 2 yrs old; a. 100%, b. initial retention rate, and c. 75%.

pools. For this study area, Hart et al. (1984) report that significant increases in nutrients and organic matter were found in the forest floor following sludge application. With this in mind use of a 75% retention rate, which falls between the two extremes, seems a reasonable stand response as represented by curve `C'.

From the first application onward the MAI's exceed the range of MAI's in the 29 stand regional sample from which the regression was developed and, therefore, constitute extrapolations which may limit interpretations. From the point of view of regional stand growth, curve `B' is the only one which does not exceed MAI's measured in the field (5.11 m^3 ha^{-1} yr^{-1}), although it does exceed the maximum growth rate of the regional study stands (4.26 m^3 ha^{-1} yr^{-1}). The figure should be interpreted on the basis of the general form of the curve from a biological basis rather than to strictly accept the accuracy of the MAI predictions. The shape of the curve is similar to many growth curves with nutrient additions and the model appears to be sensible from a biological point of view.

If no retreatments are made to the stand, one would predict nutrient contents might decrease over time until they attain levels close to control levels. Stand growth should also decrease over time until it reaches a rate similar to the control. The length of this response period is not known.

In summary, site nutrient resources explained almost 65%

of the variation in stand growth for 29 regional stands, and use of the nutrient resource approach with sludge and control plots predicted significant increases in growth with sludge application.

ACKNOWLEDGEMENTS

Although the information in this document has been funded in part by the United States Environmental Protection Agency under assistance agreement No. S005551-01 to the Michigan Department of Natural Resources and Michigan State University, it has not been subjected to the Agency's publication review process and, therefore, may not necessarily reflect the views of the Agency and no official endorsement should be inferred. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Special appreciation is extended to Connie Bobrovsky, Barbara Kinnunen, Leslie Loeffler, Laurie Zwick, Michael and David Richmond, Robert Morell, and Brenda Ellens for their invaluable assistance in sample preparation, laboratory analysis, and data entry, and to Donald Zak, George Host, and Steve Westin for their efforts in sample collection.

Particular appreciation is extended to coauthors Dr. J.B. Hart Jr., Dr. P.V. Nguyen; and Dr. C.W. Ramm for their insightful review comments.

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Chapter 3.

Distribution and Variability of Nutrients and Organic Carbon Across Glaciated Michigan Landscapes.

INTRODUCTION

The most influential soil nutrient pools are often assumed to be located in the surface soil. Coile noted in his 1937 article that fine roots were concentrated in the upper 30 cm of the soil profile (Coile 1937). This has led to extensive examination of nutrients in the upper solum as indicators and predictors of site quality (Broadfoot 1969, Leaf 1956; Pawluk and Arneman 1961, Youngberg and Scholz 1959). Most plants have a potential for nutrient uptake which exceeds their requirements if the roots have sufficient contact with the soil solution, and if there is an adequate nutrient supply (Mengel and Kirkby 1982). Trees with roots which utilize nutrient enhanced subsolum strata may support greater forest growth. The branching and proliferation of red pine (*Pinus resinosa*), jack pine (*Pinus banksiana*), and big tooth aspen (*Populus grandidentata*) roots in subsolum textural strata are examples of adventitious root exploitation of deep soil features (Hannah and Zahner, 1970). Greater growth of red oak (*Quercus rubra* L.) has been found on Kalkaska soils (Sandy, mixed, frigid typic Haplorthods) in northern lower Michigan which had subsolum textural strata within the rooting range[2].

If the effects of factors known to influence site quality such as landform, climatic variability, and effective soil depth (Spurr and Barnes 1973, Broadfoot 1969) are held constant, then recognition of subsolum features may make taxonomic classifications more useful in determining site quality. This is particularly true for soils developed in sandy, glacial drift and alluvial materials which have potential occurrences of subsolum textural strata. It was hypothesized that inclusion of subsolum features as phases of soil series would reduce the variability which has made soil taxonomic classifications inadequate for separating sites by productivity differences (Grigal 1984, Esu and Grigal 1979; Shetron 1972, Spurr and Barnes 1973; Wilde and Leaf 1955, Wilde and Scholz 1934).

Significant variations in the productive capacity of a site have been associated with subsolum features (Comerford et al. 1984, Hart et al. 1969, White and Leaf 1964; White and Wood 1958, and Wilde and Leaf 1955). On a potassium (K) deficient glacial outwash soil in northern New York a two-fold difference in volume growth at age 25 was found between adjacent sites. Both sites had sandy surface horizons with one having a fine textured strata occurring at 1.8 m while the other had a similar strata of fine textured material

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[2]D.T. Cleland, Deep Bands and Forest Growth on Kalkaska Sands. Unpublished Report.

occurring at 2.7 m (White and Wood 1958). The authors attributed the site quality difference to tree roots being able to tap into the greater nutrient and available water supplying capacity of the fine textured strata on the shallower site. Later studies on these sites found that mean basal area, mean forest floor weights, and the mean K content of the forest floor were all greater on the site with the shallower textural strata (Hart et al. 1969).

The deeper roots penetrate into soils with subsolum textural strata, the more likely it is that subsolum sampling will identify nutrient reserves which influence site quality. This is particularly true when the solum consists of sandy silicious materials. Despite the recognition of potential increases in site quality due to subsolum properties there have been no regional evaluations of the distribution of nutrient contents by depth in soils underlying oak and northern hardwood forests to quantify nutrient differences which may be associated with these subsolum properties.

Site quality is a combined effect of factors which influence the growth of stands on a site. Under certain conditions it can be expressed by direct long term measurements of growth such as volume. Alternately, it may be estimated by features which are strongly associated with stand growth, in which case it is important to measure site features which most directly influence stand growth (Carmean 1975, Coile 1952). Examinations of nutrient contents (e.g.

kg ha^{-1}) have resulted in good correlations with stand growth of red pine (Pinus resinosa Ait.) (White and Leaf 1964), and ponderosa pine (Pinus ponderosa Laws.) (Zinke, 1960), indicating the association of nutrient contents with site quality.

Collection and analysis of forest soil samples are often performed to group forest sites into classes of similar site quality and response to environmental perturbations such as clearcutting or acidic precipitation. Forest site classification allows more efficient forest management by estimating the productive potential of forested lands which are not suitable for normal site quality measurements (Carmean 1979, Coile 1952).

The precision and accuracy of nutrient estimates may limit the utility of management information derived from soil-site relationships. In order to obtain precise estimates of soil characteristics, knowledge of soil variability is needed to calculate an adequate sample size. Nutrient variability of forest soils has been found to be greater than agricultural soils. Greater increases in soil variability were found when the entire zone of root proliferation was examined (Mader 1963). In addition, on forest soils of glacial and alluvial origin it has been observed that variability increases as one proceeds further into the soil profile (Hart et al. 1969, Mollitor et al. 1980). However, the variability in nutrient contents associated with depths greater than the surface 150 cm has not been thoroughly investigated in forested soils.

OBJECTIVES

The two primary objectives of this research were: 1) to examine and report distributions of nutrient and organic carbon contents and their variability to a depth of 450 cm, and 2) to determine whether the inclusion of a banding phase (indicating presence or absence of fine textured subsolum strata) in the soil series taxonomic unit provides a more precise estimation of soil fertility than the soil series alone. Both of the primary objectives are concerned with determining whether sites differentiated by physical presence of subsolum textural strata displayed elevated nutrient levels. The secondary objectives were to compare stand growth grouped by soil series and phased soil series, and to examine nutrient distributions and variability regionally, across soil series, and across phased soil series.

MATERIALS AND METHODS

Study Area:

Study plots were located in the Manistee National Forest in the northern lower peninsula of Michigan between 85^{0}30' and 86^{0}15' west longitude and 45^{0}52' and 44^{0}30' north latitude (Figure 3.1). The climate alternates between continental and semi-marine depending on the direction of individual weather patterns. The 29 year (1940-1969) mean annual precipitation was 821 mm (32 in) and the 29 year mean annual temperature was 5.8^{0}C (42.5^{0}F) (Strommen 1974). The soil series encountered on the sites, (Rubicon, Kalkaska, and Grayling) all developed in materials of Wisconsinian age (Soil Conservation Service 1976, 1981, 1982). The Grayling soil is a mixed, frigid, Typic Udipsamment; the Kalkaska soil is a Sandy, mixed, frigid Typic Haplorthod; and the Rubicon soil is a Sandy, mixed, frigid Entic Haplorthod. All soils were well to excessively drained and were formed from sandy glacial drift parent materials. The more productive soils developed in or were underlain by till plain, ground moraine, or lake plain materials with textures of sandy loam or finer.

Thirty stands stratified by low, moderate, and high productivity were sampled. Table 3.1 shows the pre-sampling

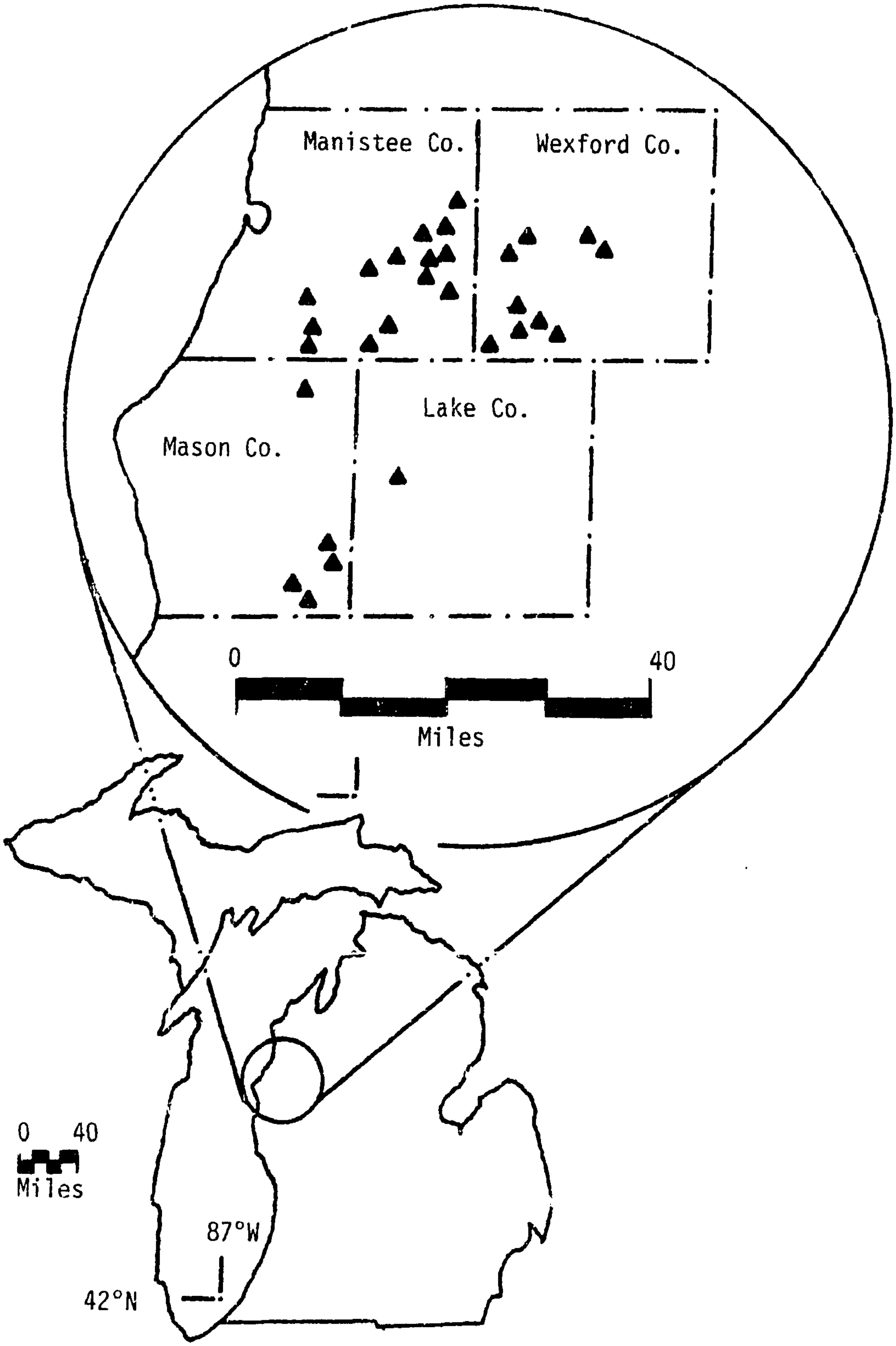


Figure 3.1. Location of sample stands.

Table 3.1. Pre and post sampling stratification for the 30 sample stands.

Pre-Sampling Stratification	n	Post-Sampling Stratifications Series	n	Series Phase	n
Low Productivity (hills and Plains)	6	Grayling (Gy)	3	Gy	3
				Rb	10
Moderate Productivity (hills and Plains)	10	Rubicon (Rb)	16	Rb(Band)	6
High Productivity (hills and Plains)	14	Kalkaska (Ka)	10	Ka	4
				Ka(Band)	6

stratification and subsequent post-sampling stratifications by soil series and soil series phase.

Stands occupied by pioneer species, or showing evidence of disturbance in the past 40 years were excluded from sampling. Stands originating from stump sprouts (determined by more than 30% of dominant overstory having multiple stems) were also excluded from sampling. The minimum basal area of stands to be sampled was 18.36 m^2ha^{-1} (80 ft^2ac^{-1}). Other selection criteria were that the stand must be at least 55 years old, the stand must be normally and uniformly stocked, (i.e. the canopy should be closed as far as site conditions will permit), and that the topography be representative of well drained upland conditions.

Sample Collection:

Forest floor samples, soil samples, and stand growth and yield data were collected during the summer of 1983 in conjunction with an ongoing ecological classification system project carried out jointly by the USDA Forest Service and Michigan State University. At each stand a homogeneous area of one hectare or more was selected for sampling. Four randomly located points per stand were measured for forest growth.

Forest floor samples were collected with a 30x30 cm metal frame at six points (three at the pit and one each at three additional points) and systematically separated into litter or fermentation and humus layers (Figure 3.2a). Litter samples (Oi horizon) included recognizable and nearly entire leaf material not affected by decompositional processes. Fermentation and humus layer samples (Oe and Oa horizons) consisted of finely divided decomposed organic materials extending to the upper boundary of the mineral soil.

A soil pit about 1.5 m in depth (which extended into the C horizon) was located near the center of the stand (Figure 3.2b). After the pits were dug the soils were classified to the series level and equal volumes of soil were collected from each horizon. Bucket auger samples, stratified by horizons, were collected beginning at the pit bottom and ending at 4.5 m (Figure 3.2c). Bulk density samples were collected to

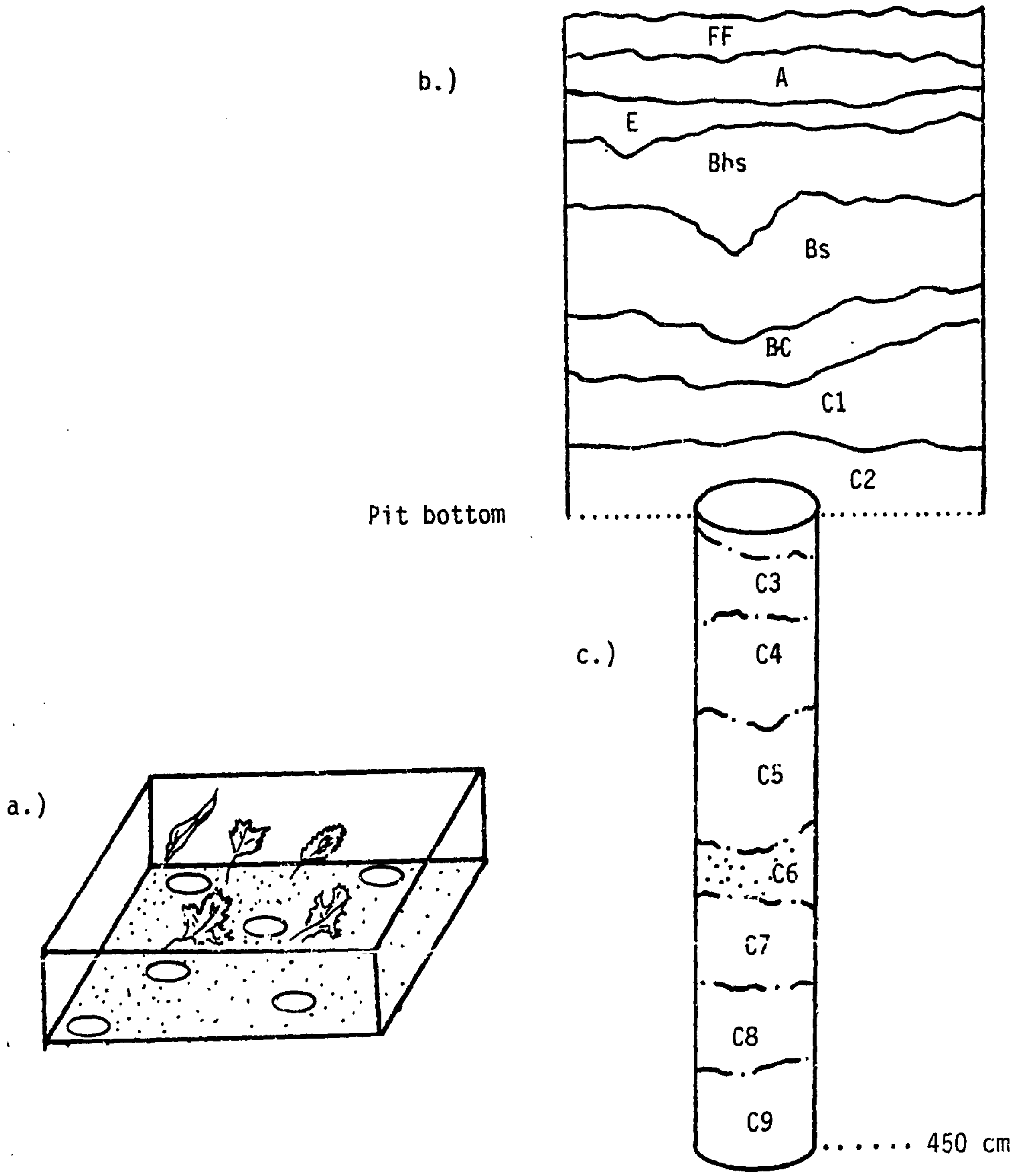


Figure 3.2. Detail of forest floor and soil sampling; a. forest floor, b. soil pit, and c. bucket auger.

allow conversion of nutrient concentrations to nutrient contents. The areal extent of subsolum textural strata was determined from observations at the pit bucket auger boring and from observations at three additional bucket auger borings at the randomly located points.

Laboratory Analysis:

Forest floor samples were oven dried at 70^{0}C, weighed, ground, and subsampled prior to analysis. Forest floor total Kjeldahl nitrogen (TKN) and total Kjeldahl phosphorus (TKP) were determined after sulfuric acid digestion (Page et al. 1982) using a Technicon[3] Auto-analyzer II procedure (Technicon, 1977). Total cations (K, Mg, and Ca) were determined by dry ashing at 500^{0}C for 4 hours with ash dissolution in 8 N HCl (Wilde et al. 1972). Nutrient concentrations were converted to nutrient contents by use of areas and weights of the forest floor samples. Statistical analyses were to be performed with the stand as the sample unit, therefore, forest floor data was averaged by stand.

Soil samples were air dried, sieved to pass a 2 mm screen, and subsampled for analysis. Both coarse (>2 mm) and fine fractions weights were recorded for each sample and used to calculate horizon contents corrected for coarse fragment

[3] Use of trade name does not constitute an endorsement by either Michigan State University or the USDA.

contents.

A 2 g soil sample was boiled for 10 minutes with 10 ml of 0.5 N nitric acid to extract potassium (K), magnesium (Mg), and calcium (Ca). This extraction has been shown to be associated with tree K uptake and growth in red pine (Leaf 1958, White and Leaf 1964), and with critical foliar Mg levels in radiata pine (Pinus radiata D. Don) (Adams 1973). Since Mg and Ca are usually extracted concurrently from soils and have many chemical properties in common (Page et al. 1982), Ca was also extracted by this method.

Acid extractions are thought to represent cations both adsorbed and mineral which replenish elements depleted by plant uptake and leaching (Page et al. 1982). Metson, (1974) concluded that the rate of Mg release from soil reserves was correlated with Mg extracted by a moderately strong acid attack and is a good guide to available Mg in continuous cropping or forest systems.

Aliquots of the boiling nitric acid extractions and of the dry ash total cation determinations had cation concentrations (K, Mg, and Ca) determined by plasma emission spectroscopy. The extracts were brought to a concentration of 1,000 ppm LiCl to stabilize the plasma and suppress interferences. TKN and TKP were determined after sulfuric acid digestion similar to the forest floor samples.

Percent organic carbon (OC) in the soils was determined by the Walkley-Black method with .5 N ferrous sulfate and

1 N potassium dichromate (Page et al. 1982). Sample size varied from 1-5 g in samples with high and low organic carbon concentrations.

Horizon concentrations were converted into nutrient contents per horizon using concentrations, soil bulk densities, and horizon depths. The contents were corrected for percent coarse soil separates. Nutrient contents were accumulated by 50 cm depths to circumvent problems with differences in horizon thickness.

All chemical analyses were performed in the MSU Forestry Department forest soils laboratories using 10% sample replication, National Bureau of Standards specimens, and bulk sample analysis to insure precision and accuracy.

Statistical Analysis:

Nutrient contents were tested for normality by a Chi-square goodness of fit test, (Steel and Torrie 1980), which rejected the null hypothesis of data normality for most nutrients. With the exception of Ca contents, log transformed data had no departures from normality. Based on these findings log transformed nutrient contents were used in the statistical analyses. A one way analysis of variance (AOV) was used to test for differences in mean nutrient contents between series and between phased series groups. Duncan's multiple comparison test with corrections for unequal sample sizes was used to identify specific group differences (Steel and Torrie 1980).

The inferences of the AOV and multiple comparisons were confirmed using a non-parametric Kruskal-Wallis one way analysis on ranked nutrient contents with mean separation by Dunn's method (Dunn 1964, Hollander and Wolfe 1973, Steel and Torrie 1980). Overall, the non-parametric methods were slightly more conservative than the parametric methods, finding fewer significant differences between groups. Results between the two tests led to similar interpretations of the data. Since the sensitivity of the parametric tests was greater, and the log transformed data satisfied the assumptions of the analysis of variance, the results of the parametric tests are reported. Coefficients of variability (CV's) were chosen to compare the relative variability of series and species groups because of their ability to compare variances between group means differing in magnitude (Steel and Torrie 1980).

RESULTS AND DISCUSSION

Characteristics of Sampled Stands:

For ease of description soils with subsolum textural strata will be referred to as 'banded', and soils without subsolum textural strata will be referred to as 'unbanded'.

Taxonomic grouping by soil series resulted in a trend of differentiation by site quality. As presented in Table 3.2, a gradient of increasing volume productivity corresponded with the gradient of increasing profile development (Grayling (Gy) < Rubicon (Rb) < Kalkaska (Ka)). However, no significant differences were found between soil series productivities by the one way AOV. The same correspondence between site quality and profile development was evident when presence or absence of subsolum textural strata was included in the series descriptions (Table 3.2). An analysis of variance performed on the soil series phased by subsolum textural strata found significant differences between group mean volumes. Duncan's

Table 3.2. Stand volume grouped by series and series phase with one way AOV results.

Series	n	Stand Volume $m^3\ ha^{-1}$	Phased Series	n	Stand Volume $m^3 ha^{-1}$
Grayling	3	147[a]	Grayling	3	147 a
Rubicon	16	189	Rubicon	10	149 a
Kalkaska	10	227	Kalkaska	6	211 b
			Banded Kalkaska	4	251 b
			Banded Rubicon	6	256 b

[a] - Column means followed by different letters are significantly different by Duncan's multiple comparison test at an alpha = 0.10 level.

mean separation procedure determined that the banded phase of the Rb series had significantly higher volumes than the unbanded phase. The Gy series had significantly lower volumes than the banded phases of the Rb and Ka series, and the unbanded phase of the Ka series. The low relative productivity of the Gy series and the unbanded Rb phase was similar to that reported by Shetron (1972). Although not significantly different, the banded phase of the Ka series had slightly greater volume productivity than the unbanded phase.

Nutrient and Organic Carbon Distributions:

Nutrient and organic carbon contents accumulated by 50 cm depths for all stands are presented in Table 3.3. The distribution pattern by depth varied with the nutrient examined. Total Kjeldahl N (presented in Figure 3.3a) and OC displayed patterns of asymptotic decline with increasing depth. Total Kjeldahl P displayed a less abrupt decline, while acid extractable K showed little deviation between depths. Acid extractable Mg (shown in Figure 3.3b) and Ca had patterns of increasing content with depth, opposite that of TKN and OC. These distribution patterns are consistent with known properties of soils and nutrients. Much of the N and P in soils is in organic form, or fixed in living or dead organic material and the distributions of TKN and TKP follow that of organic matter in the soil (Armson 1977, Kimmons

Table 3.3. Mean nutrient and organic carbon contents and coefficients of variability for all sam

	FF		0-50 cm		50-100 cm		100-150 cm		150-200 cm		200-250 cm		250-3
	$\bar{x}$ kg/ha	CV %	$\bar{x}$ kg/ha	CV %	$\bar{x}$ kg/ha	CV %	$\bar{x}$ kg/ha	CV %	$\bar{x}$ kg/ha	CV %	$\bar{x}$ kg/ha	CV %	$\bar{x}$ kg/ha
	n=29		n=30		n=30		n=30		n=29		n=29		n
Nitrogen	289	37	2688	43	698	50	294	47	226	75	262	139	224
Phosphorus	19	37	982	37	544	37	344	37	332	48	369	99	323
Potassium	18	35	537	35	473	35	587	72	599	71	687	76	815
Magnesium	27	45	629	59	983	84	1128	72	1326	94	2894	283	4910
Calcium	395	45	1069	203	5591	396	8152	332	7034	325	24397	363	31156
Organic Carbon	N.D.		43225	26	11077	51	5257	40	3910	52	3077	48	3379

N.D. - organic carbon determinations were not made on forest floor samples.

on contents and coefficients of variability for all samples.

-100 cm		100-150 cm		150-200 cm		200-250 cm		250-300 cm		300-350 cm		350-400 cm		400-450 cm	
a	CV %	$\bar{x}$ kg/ha	CV %	$\bar{x}$ kg/ha	CV %	$\bar{x}$ kg/ha	CV %	$\bar{x}$ kg/ha	CV %	$\bar{x}$ kg/ha	CV %	$\bar{x}$ kg/ha	CV %	$\bar{x}$ kg/ha	CV %
n=30		n=30		n=29		n=29		n=29		n=27		n=25		n=24	
8	50	294	47	226	75	262	139	224	89	196	78	158	80	182	97
4	37	344	37	332	48	369	99	323	81	433	111	350	55	368	54
3	35	587	72	599	71	687	76	815	123	931	110	719	65	746	68
13	84	1128	72	1326	94	2894	283	4910	223	5341	220	5912	212	7174	202
1	396	8152	332	7034	325	24397	363	31156	288	40729	240	31559	186	33672	162
7	51	5257	40	3910	52	3077	48	3379	69	3660	105	2635	56	2879	72

s were not made on forest floor samples.

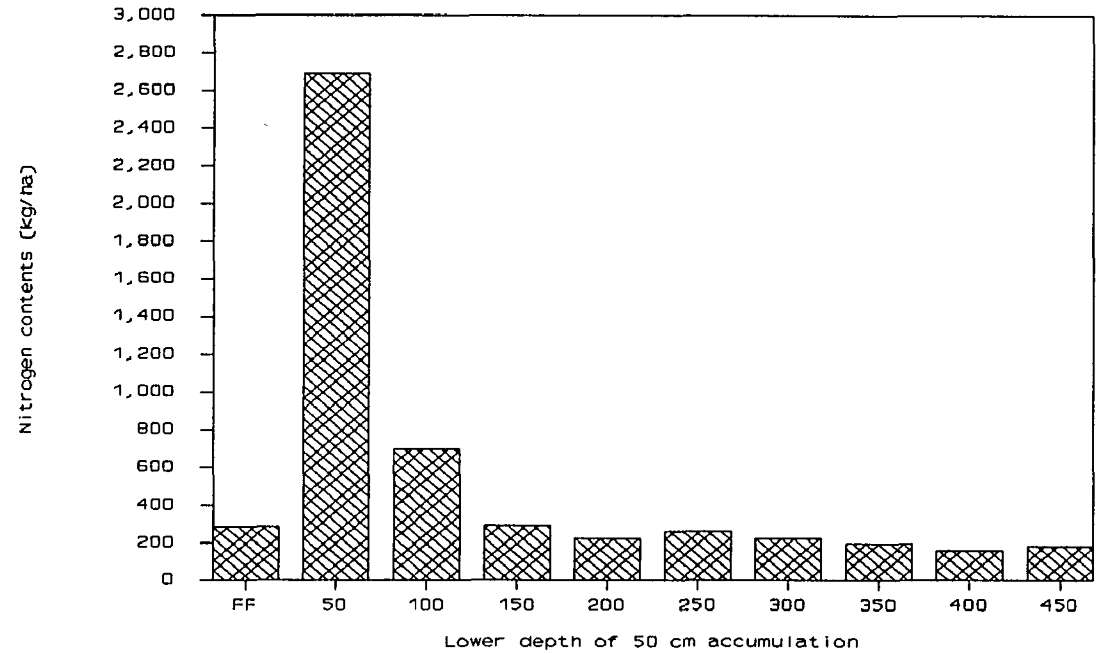


Figure 3.3a. TKN contents accumulated by 50 cm depths for all stands.

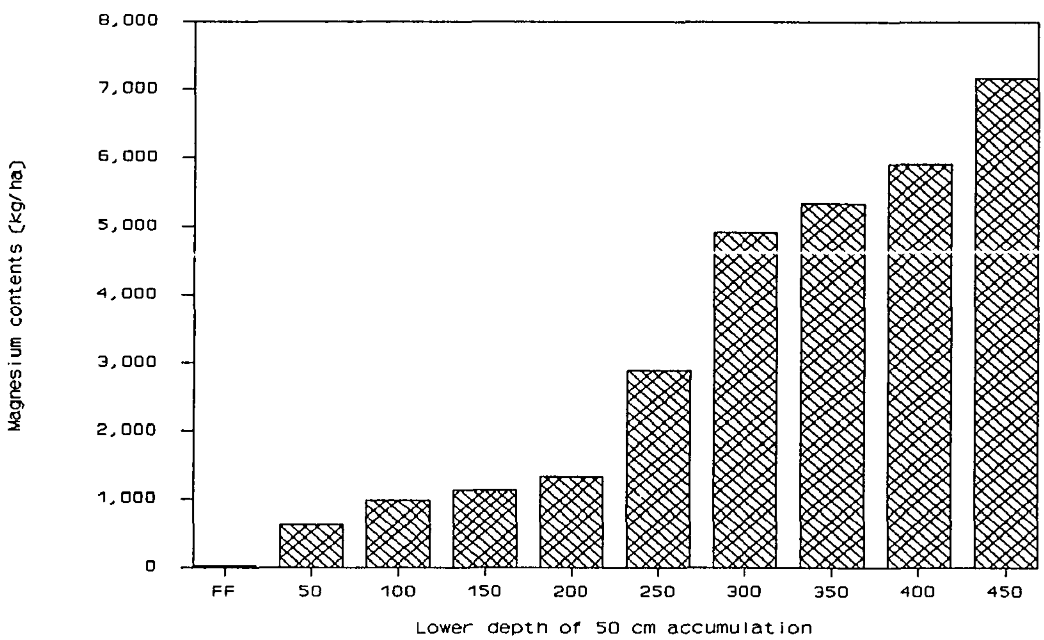


Figure 3.3b. Forest floor total and soil acid extractable Mg contents accumulated by 50 cm depths for all stands.

1986). Acid extractable K, Mg, and Ca are released from soil minerals, readily leached from surface soils, and may accumulate deeper in the soil profile. Especially when a feature such as a subsolum textural strata impedes the flow of water through the soil.

The nutrient contents in the forest floor (FF) comprised only a minor fraction of the site's nutrient resource in comparison to the soil contents. Figure 3.4 displays the relative percentages of acid extractable K contents by the various depths. As shown here the FF total K is only 0.3% of the FF - 450 cm acid extractable K content.

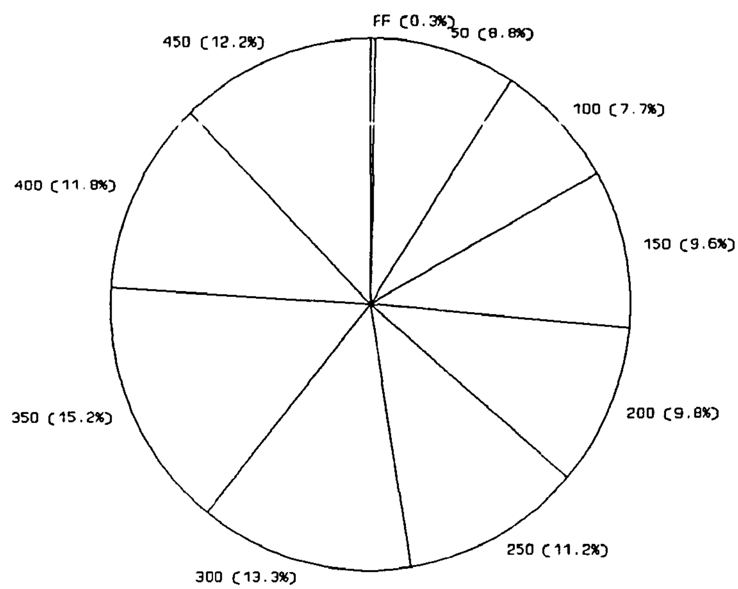


Figure 3.4. Percentages of K contents accumulated by FF and 50 cm depths to 450 cm.

Nutrient and Organic Carbon Variability:

As presented in Table 3.3 the variability of nutrient contents in the FF, the surface 150 cm, and the 350-450 cm depths of the soil were lower than at the intermediate depths. Figure 3.5 displays this pattern for TKP variability. This figure shows three discrete variability regions, the FF-200 cm depth which has the least variability; the 200-350 cm depth which has the maximum variability, and at depths of 350-450 cm the variability decreases.

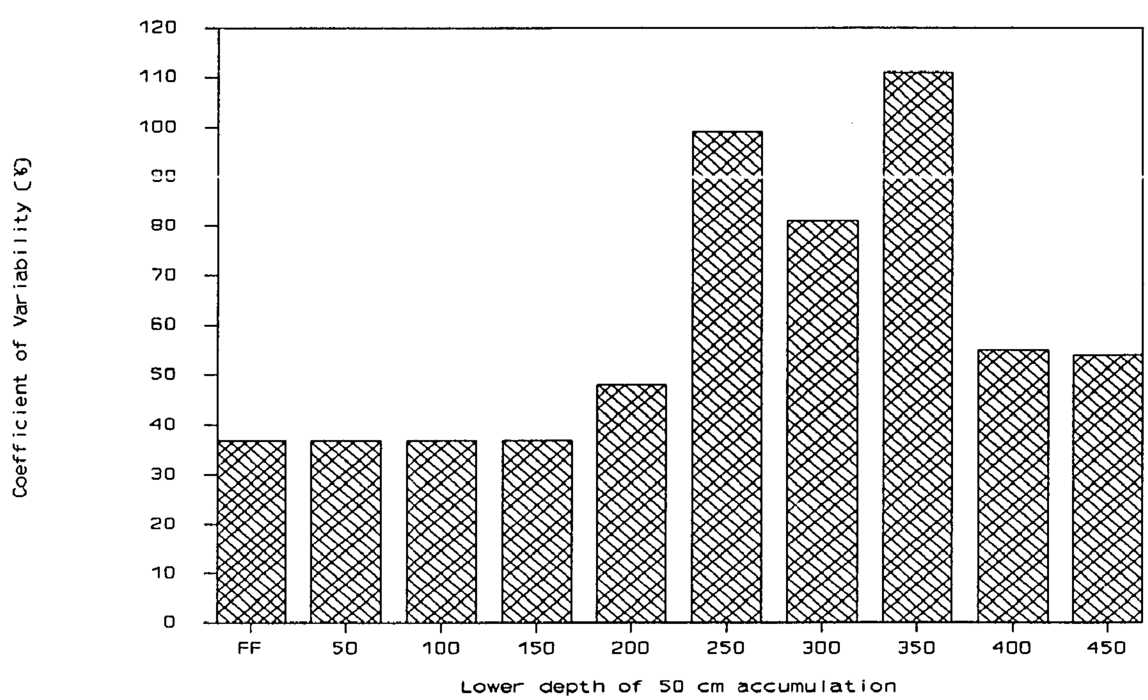


Figure 3.5. Variability of TKP contents for all stands.

An increase in variability was noted at depths greater than 150 cm for all nutrients in Table 3.3 except acid extractable Ca (Figure 3.6). Acid extractable Ca and Mg had CV's 2-3 times that of TKN, TKP, acid extractable K, and OC. This increased variation may be due to variability in limestone and/or dolomite composition of the glacial drift (Veatch 1953). As shown in Figure 3.6 acid extractable Ca had high CV's throughout the profile (e.g. 203% in the surface 50 cm) and displayed a decrease in variability at depths beneath 250 cm. From Figures 3.5 and 3.6 it is apparent that

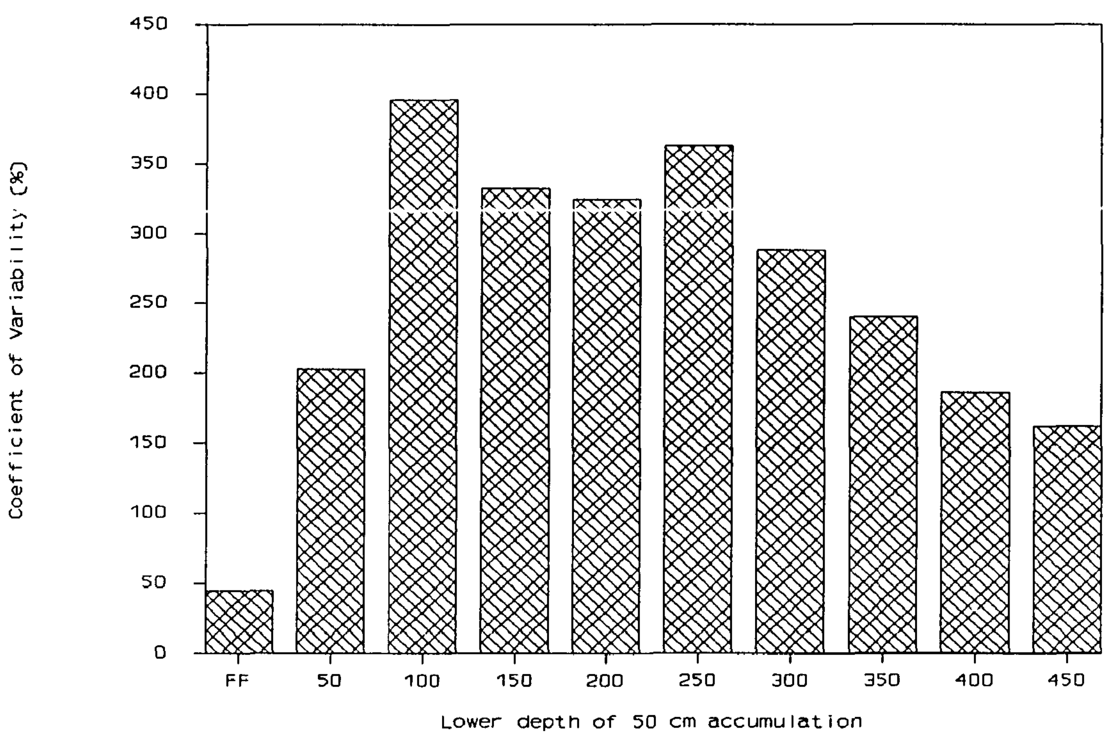


Figure 3.6. Variability of forest floor total and soil acid extractable Ca contents for all stands.

a general pattern exists of increasing variability with depth to about 350 cm, then decreasing to 450 cm.

Nutrient and Organic Carbon Distribution by Soil Series:

Nutrient contents, to the nearest kilogram per hectare, were evaluated by soil series and are presented in Table 3.4. As determined by one way AOV and Duncan's mean separation procedure, the FF nutrients displayed the greatest sensitivity to series differences despite their relatively low nutrient contents (see Figure 3.4). Forest floor TKN, TKP, and total Ca contents displayed significantly different contents between all three series groups. This was the only depth/content component which differentiated between all three series. The AOV found that the surface 150 cm showed the greatest sensitivity to series differences, with only two significant differences occurring below this depth. TKN, TKP, and K contents had the greatest sensitivity to series differences. The AOV found that all accumulations to 150 cm had significant series differences.

All nutrient contents, except for acid extractable Mg, reflected the degree of soil profile development (Kalkaska > Rubicon > Grayling) in the surface 200 cm. This pattern was well-defined for K contents presented in Figure 3.7.

Table 3.4. Mean nutrient and organic carbon contents, coefficients of variability, and results of one way AOV for soi

	FF			0-50 cm			50-100 cm			100-150 cm			150-200 cm			200-25	
	n	$\bar{x}$ kg/ha	CV %	n	$\bar{x}$ kg/ha	CV %	n	$\bar{x}$ kg/ha	CV %	n	$\bar{x}$ kg/ha	CV %	n	$\bar{x}$ kg/ha	CV %	n	$\bar{x}$ kg/
Nitrogen																	
Grayling	3	157 a	27	3	2083 a	29	3	394 a	37	3	153 a	52	3	176	21	3	21
Rubicon	16	260 b	27	16	2294 a	36	16	604 a	40	16	276 a	53	15	213	87	15	21
Kalkaska	9	374 c	31	10	3423 b	41	10	936 b	44	10	381 b	23	10	276	61	10	37
Phosphorus																	
Grayling	3	11 a	53	3	799	50	3	369 a	38	3	223 a	17	3	219	17	3	21
Rubicon	16	17 b	29	16	931	42	16	495 a	32	16	339 b	35	16	295	41	15	37
Kalkaska	9	24 c	31	10	1048	24	10	629 b	30	10	377 b	38	10	401	49	10	39
Potassium																	
Grayling	3	10 a	11	3	391	35	3	384	24	3	348 a	46	3	402	53	3	50
Rubicon	16	17 b	33	16	516	28	16	476	37	16	474 a	38	15	529	57	15	77
Kalkaska	9	20 b	29	10	597	39	10	497	35	10	806 b	79	10	759	80	10	61
Magnesium																	
Grayling	3	12 a	41	3	422	20	3	553	21	3	486	29	3	495	30	3	146
Rubicon	16	27 b	28	16	668	57	16	1104	94	16	1111	65	15	1446	101	15	152
Kalkaska	9	32 b	53	10	589	68	10	904	62	10	1364	75	10	1440	77	10	557
Calcium																	
Grayling	3	177 a	16	3	211	50	3	176	51	3	201	82	3	246	77	3	247
Rubicon	16	358 b	27	16	1317	221	16	7737	377	16	9239	325	15	5253	237	15	339
Kalkaska	9	501 c	41	10	937	92	10	4225	284	10	9483	297	10	12299	297	10	189
Organic Carbon																	
Grayling				3	36796	19	3	8922	2	3	5484	11	3	4771	11	3	355
Rubicon		N.D.		16	39690	25	16	9701	42	16	4685	51	15	3545	52	15	309
Kalkaska				10	49050	23	10	14170	55	10	6099	28	10	4520	51	10	315

Column means for nutrient or organic carbon contents followed by different letters are significantly different

N.D. - organic carbon determinatons were not made on forest floor samples.

…ients of variability, and results of one way AOV for soil series groups.

…00 cm		100-150 cm			150-200 cm			200-250 cm			250-300 cm			300-350 cm			350-400 cm		
x̄ …/ha	CV %	n	x̄ kg/ha	CV %	n	x̄ kg/ha	CV %	n	x̄ kg/ha	CV %	n	x̄ kg/ha	CV %	n	x̄ kg/ha	CV %	n	x̄ kg/ha	CV %
594 a	37	3	153 a	52	3	176	21	3	211	30	3	125	10	3	160	36	3	135	36
04 a	40	16	276 a	53	15	213	87	15	210	87	15	219	72	13	219	66	12	163	64
036 b	44	10	381 b	23	10	276	61	10	374	87	10	276	159	10	189	100	9	166	107
569 a	38	3	223 a	17	3	219	17	3	212	16	3	205	16	3	262	23	3	203	42
495 a	32	16	339 b	35	16	295	41	15	371	82	15	354	75	13	467	118	12	361	52
29 b	30	10	377 b	38	10	401	49	10	394	91	10	289	135	10	429	116	9	355	61
584	24	3	348 a	46	3	402	53	3	507	49	3	496	61	3	593	21	3	441	48
476	37	16	474 a	38	15	529	57	15	774	141	15	917	80	13	1037	120	12	740	63
497	35	10	806 b	79	10	759	80	10	614	87	10	775	72	10	923	103	9	791	69
553	21	3	486	29	3	495	30	3	1461	164	3	11594	110	3	1495	51	3	8171	159
04	94	16	1111	65	15	1446	101	15	1529	79	15	1374	76	13	2182	117	12	1713	81
004	62	10	1364	75	10	1440	77	10	5572	179	10	8612	250	10	11046	165	9	11320	169
76	51	3	201	82	3	246	77	3	2473	169	3	13535	158	3	1981	101	3	9877	162
237	377	16	9239	325	15	5253	237	15	33914	303	15	40082	354	13	48719	272	12	30257	223
225	284	10	9483	297	10	12299	297	10	18989	159	10	26021	211	10	45890	126	9	43835	137
022	2	3	5484	11	3	4771	11	3	3552	39	3	3122	46	3	3025	48	3	2391	7
701	42	16	4685	51	15	3545	52	15	3091	80	15	3779	51	13	4163	116	12	2880	66
70	55	10	6099	28	10	4520	51	10	3154	30	10	3124	43	10	3495	89	9	2543	43

…ollowed by different letters are significantly different by Duncan's multiple comparison test at an alpha = 0.10 level.

…orest floor samples.

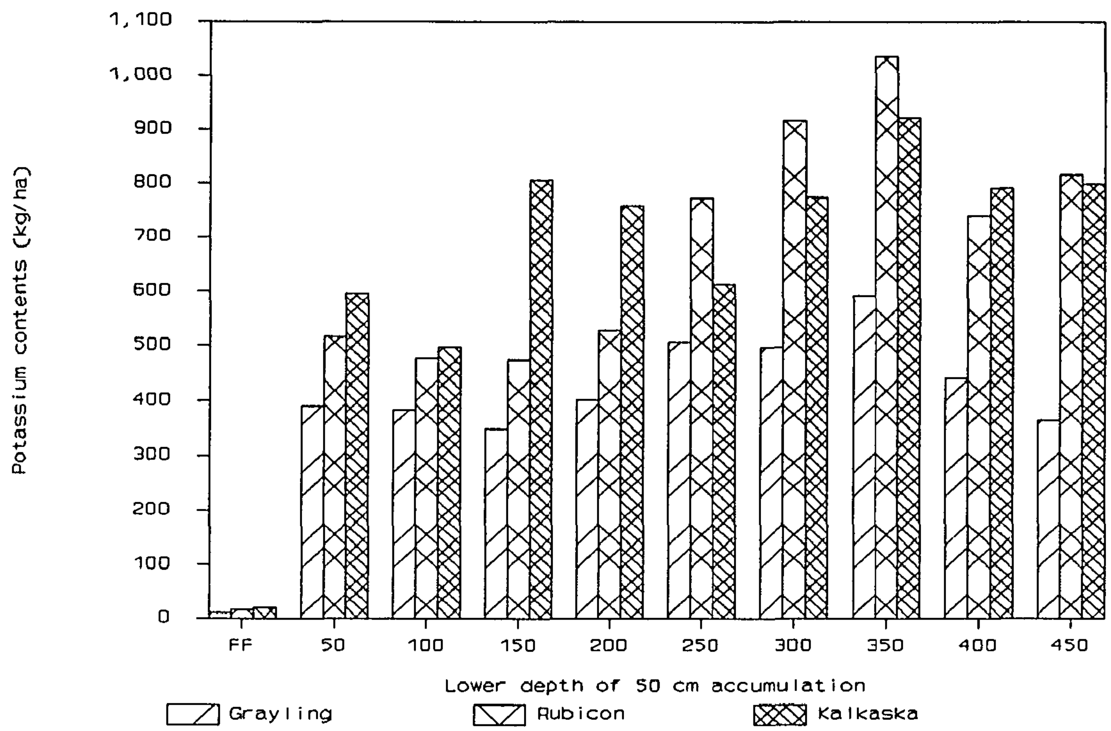


Figure 3.7. Forest floor total and acid extractable K contents grouped by soil series.

Significant series differences were found in the FF, 100-150, and 400-450 cm accumulations. The only significant differences beneath the surface 150 cm were for TKP and acid extractable K at the 400-450 cm depth. The only consistent significant series differences found by Duncan's procedure were between the Gy and Ka series. The poor discrimination between series nutrient contents was consistent with poor discriminatory power found with soil taxonomic units for stand productivity (Shetron 1972).

Nutrient and Organic Carbon Variability by Soil Series:

The series evaluations redistributed the overall variability and displayed distinct series contrasts. The nutrient poor Gy series was commonly less variable than the Rb or Ka series, while the Rb series had a higher variability than the more productive Ka series for acid extractable Ca and OC at all depths greater than 200 cm. The results for TKN, TKP, acid extractable K, and Mg were inconsistent with only 33% of the nutrient/depth combinations showing this pattern.

The Rb and Ka series displayed the greatest variability for all nutrients at a range of depths from 250-350 cm which overlaps the range that the finer textured materials were frequently encountered (150-300 cm). This pattern was most apparent for TKP and is presented in Figure 3.8. This increasing variability with depth to 350 cm occurred even when nutrient contents declined with depth.

Patterns of increasing variability with increasing soil profile depth have been found in eastern forest soils of glacial and alluvial origin (Hart et al. 1969, Mader 1963, Mollitor et al. 1980). This pattern existed, especially for the Rb and Ka series, to a depth of about 250-350 cm, below which variability decreased. The soils in the cited studies were not examined to the depth which they were in this study,

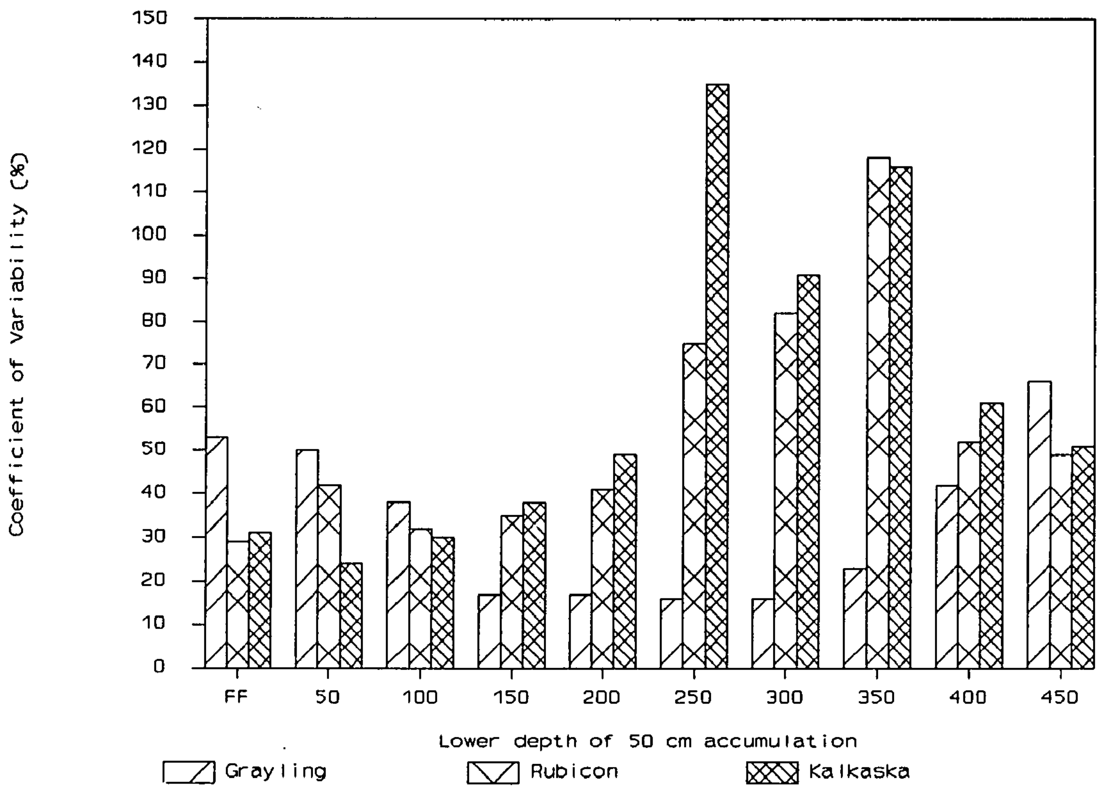


Figure 3.8. Variability of TKP contents grouped by soil series.

therefore patterns of subsolum soil variability have not been reported. Since only the Rb and Ka series had banding occurring at depths ranging from 150-300 cm, there is the implication that the variability increases apparent in Figure 3.8 are a result of this banding. This hypothesis is supported by the fact that the Gy series has no banding, and displays no variability increases with depth.

Nutrient and Organic Carbon Distributions by Phased Soil Series:

Nutrient contents evaluated by banded and unbanded soil series phases are presented in Table 3.5. The inclusion of subsolum textural strata in the soil taxonomic unit resulted in a greater number of significant differences being found as compared to the series evaluations (Table 3.3). This greater sensitivity to soil fertility differences was despite the reduction of group sample sizes because of the phasing. The one way AOV found significant differences between mean TKN contents in the FF and surface 150 cm similar to those reported in Table 3.4 for the series groupings. When examined by Duncan's multiple comparison procedure no significant differences were found between TKN contents of the banded and unbanded phases of the Rb or Ka series. Of the 23 significant nutrient or OC /depth combinations found by the one way AOV, 16 were for TKP and total or acid extractable K and Mg. The Ka phases were separated by Duncan's procedure more frequently (11 of 23) than were the Rb phases (4 of 23). Eight of the ten significant differences between the Ka phases were found with TKP and acid extractable Mg between the depths of 100-350 cm. The phosphorus in the TKP digests at depths of 250 cm and below may represent the dissolution of insoluble

Table 3.5. Mean nutrient and organic carbon contents, coefficients of variability, and results of one way AOV for soil series

	FF			0-50 cm			50-100 cm			100-150 cm			150-200 cm			200-250 cm		
	n	$\bar{x}$ kg/ha	CV %	n	$\bar{x}$ kg/ha	CV %	n	$\bar{x}$ kg/ha	CV %	n	$\bar{x}$ kg/ha	CV %	n	$\bar{x}$ kg/ha	CV %	n	$\bar{x}$ kg/ha	CV %
Nitrogen																		
Gy	3	158 a	27	3	2083 a	29	3	394 a	37	3	153 a	52	3	176	21	3	211	10
Rb	10	240 b	28	10	2206 a	31	10	635 bc	25	10	283 abc	45	10	195	80	10	200	63
RbB	6	294 b	21	6	2440 a	43	6	551 ab	65	6	264 ab	71	5	249	101	5	230	92
Ka	4	309 b	23	4	3547 b	6	4	1197 d	46	4	344 bc	31	4	245	51	4	290	81
KaB	5	426 c	29	6	3340 ab	56	6	762 cd	27	6	405 c	17	6	296	68	6	431	179
Phosphorus																		
Gy	3	11 a	53	3	799	50	3	369	38	3	223 a	17	3	219 a	17	3	212	16
Rb	10	16 b	34	10	997	38	10	491	24	10	344 bc	38	10	288 a	41	10	398	85
RbB	6	20 bc	18	6	822	49	6	501	46	6	332 abc	33	5	308 a	43	5	320	25
Ka	4	19 bc	12	4	824	9	4	585	41	4	284 ab	29	4	224 a	19	4	225	31
KaB	6	28 c	29	6	1198	17	6	658	25	6	440 c	33	6	519 b	32	6	506	135
Potassium																		
Gy	3	10 a	11	3	391	35	3	384	24	3	348 a	46	3	402 a	53	3	507	61
Rb	10	15 ab	31	10	478	27	10	455	44	10	408 ab	36	10	406 a	42	10	674	58
RbB	6	21 d	29	6	580	28	6	512	25	6	584 b	31	5	777 a b	47	5	975	99
Ka	4	17 bc	23	4	507	18	4	398	9	4	417 ab	21	4	413 a b	28	4	389	34
KaB	5	23 d	26	6	657	44	6	563	35	6	1065 c	68	6	989 b	71	6	763	69
Magnesium																		
Gy	3	12 a	41	3	422	20	3	553	21	3	486 a	29	3	495 a	30	3	1461	110
Rb	10	25 b	22	10	654	60	10	953	68	10	906 ab	51	10	1111 a	116	10	1190	63
RbB	6	29 b	35	6	691	58	6	1356	113	6	1454 bc	67	5	2117 b	80	5	2208	73
Ka	4	27 b	43	4	438	24	4	588	28	4	606 a	41	4	565 a	29	4	522	42
KaB	5	36 b	56	6	689	73	6	1115	57	6	1870 c	56	6	2024 b	54	6	8939	198
Calcium																		
Gy	3	177 a	16	3	244	50	3	176	51	3	201 a	82	3	246	77	3	2473	158
Rb	10	333 b	27	10	593	164	10	492	98	10	685 ab	110	10	3361	276	10	47290	312
RbB	6	399 bc	27	6	2523	181	6	19811	241	6	23495 c	207	5	9034	198	5	7162	138
Ka	4	425 bc	40	4	688	32	4	317	69	4	315 ab	78	4	349	54	4	374	64
KaB	5	561 c	46	6	1103	100	6	6830	226	6	15595 bc	233	6	20265	232	6	31399	157
Organic Carbon																		
Gy				3	36976	19	3	8922 a	2	3	5484	11	3	4771	11	3	3552	46
Rb				10	39257	24	10	9325 a	36	10	5111	52	10	3232	48	10	3103	50
RbB		N.D.		6	40411	29	6	10327 a	51	6	3975	48	5	4171	57	5	3066	57
Ka				4	53492	16	4	19569 b	40	4	7127	27	4	5071	15	4	4470	15
KaB				6	46089	28	6	10571 a	55	6	5414	24	6	4153	72	6	2276	36

Column means for nutrients or organic carbon contents followed by diferent letters are significantly different by

Soil series abbreviations are: Gy=Grayling series, Rb=Rubicon series; RbB= Banded phase of Rubicon series, Ka=Kal
KaB=Banded phase of Kalkaska series.

N.D. - organic carbon determinations were not made on forest floor samples.

ients of variability, and results of one way AOV for soil series groups with phases.

cm	100-150 cm			150-200 cm			200-250 cm			250-300 cm			300-350 cm			350-400 cm		
CV %	n	$\bar{x}$ kg/ha	CV %	n	$\bar{x}$ kg/ha	CV %	n	$\bar{x}$ kg/ha	CV %	n	$\bar{x}$ kg/h	CV %	n	$\bar{x}$ kg/ha	CV %	n	$\bar{x}$ kg/ha	CV %
37	3	153 a	52	3	176	21	3	211	10	3	125	30	3	160	36	3	135	36
c 25	10	283 abc	45	10	195	80	10	200	63	10	202	54	8	185	63	7	165	75
65	6	264 ab	71	5	249	101	5	230	92	5	251	124	5	273	66	5	159	50
d 46	4	344 bc	31	4	245	51	4	290	81	4	338	63	4	207	125	3	258	112
cd 27	6	405 c	17	6	296	68	6	431	179	6	236	114	6	177	86	6	120	80
38	3	223 a	17	3	219 a	17	3	212	16	3	205	16	3	262 ab	23	3	203 a	42
24	10	344 bc	38	10	288 a	41	10	398	85	10	374	90	8	286 ab	22	7	318 ab	25
46	6	332 abc	33	5	308 a	43	5	320	25	5	315	63	5	756 b	114	5	421 b	67
41	4	284 ab	29	4	224 a	19	4	225	31	4	202	8	4	170 a	45	3	206 a	15
25	6	440 c	33	6	519 b	32	6	506	135	6	347	97	6	602 b	99	6	429 b	54
24	3	348 a	46	3	402 a	53	3	507	61	3	496	49	3	593 ab	21	3	441	48
44	10	408 ab	36	10	406 a	42	10	674	58	10	602	58	8	476 a	34	7	555	52
25	6	584 b	31	5	777 a b	47	5	975	99	5	1548	142	5	1934 b	88	5	999	58
9	4	417 ab	21	4	413 a b	28	4	389	34	4	402	28	4	401 a	56	3	475	43
35	6	1065 c	68	6	989 b	71	6	763	69	6	1024	77	6	1271 b	87	6	949	64
21	3	486 a	29	3	495 a	30	3	1461	110	3	11594 ab	164	3	1495 a	51	3	8171	159
68	10	906 ab	51	10	1111 a	116	10	1190	63	10	1107 a	58	8	1354 b	100	7	1741	89
113	6	1454 bc	67	5	2117 b	80	5	2208	73	5	1910 ab	86	5	3508 ab	102	5	1674	78
28	4	606 a	41	4	565 a	29	4	522	42	4	591 a	40	4	765 a	48	3	600	33
57	6	1870 c	56	6	2024 b	54	6	8939	198	6	13960 b	132	6	17901 b	119	6	16680	131
51	3	201 a	82	3	246	77	3	2473	158	3	13535	169	3	1981	101	3	9877	162
99	10	685 ab	110	10	3361	276	10	47290	312	10	47253	312	8	15610	271	7	20491	216
241	6	23495 c	207	5	9034	198	5	7162	158	5	25741	181	5	101693	206	5	43930	218
69	4	315 ab	78	4	349	54	4	374	64	4	487	62	4	5681	178	3	612	35
226	6	15595 bc	233	6	20265	232	6	31399	157	6	43044	109	6	72697	85	6	65447	97
2	3	5484	11	3	4771	11	3	3552	46	3	3122	39	3	3025	48	3	2391	7
36	10	5111	52	10	3232	48	10	3103	50	10	3581	49	8	2798	76	7	2379	47
51	6	3975	48	5	4171	57	5	3066	57	5	4175	120	5	6348	114	5	3582	73
40	4	7127	27	4	5071	15	4	4470	15	4	3678	29	4	2474	26	3	2761	14
55	6	5414	24	6	4153	72	6	2276	36	6	2755	27	6	4174	95	6	2434	55

ents followed by diferent letters are significantly different by Duncan's multiple comparison test at an alpha = 0.10 level
s, Rb=Rubicon series; RbB= Banded phase of Rubicon series, Ka=Kalkaska series;
of Kalkaska series.
a on forest floor samples.

calcium phosphates and it is not clear whether significant differences found at these depths represent any differences in plant available phosphorus.

Figure 3.9a presents a comparison of K contents between soil series phases without subsolum textural strata. When compared to the soil series examinations in Figure 3.7, series differences in acid extractable K contents were reduced in the 100-200 cm and 300-400 cm depths. The nutrient poor Gy series shows little distinction from the unbanded phases of either the Rb or Ka series.

The inclusion of subsolum textural strata resulted in noticeable contrasts between nutrient contents in Rb and Ka

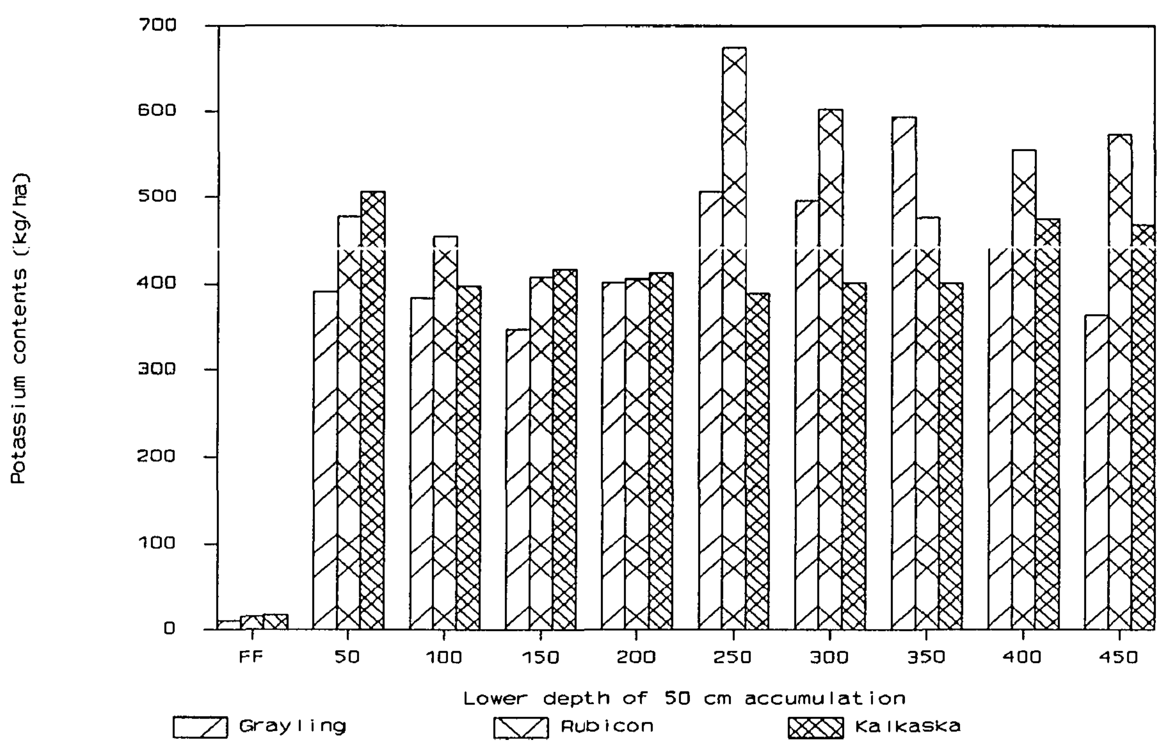


Figure 3.9a. Forest floor total and soil acid extractable K contents grouped by unbanded soil series phases.

phases. The banded phases had greater nutrient contents than the unbanded phases in 71% (42/59) of the nutrient or OC/depth combinations for Rb, and for 76% (45/59) of the nutrient and OC/depth combinations for Ka. These contrasts were most pronounced for TKP, acid extractable K, Mg, and Ca in depths below 100 cm. This trend of contrasts between banded phases of the Ka series for K contents is shown in Figure 3.9b. Greater acid extractable K contents were found in the banded phase across all depths from 0 to 450 cm, extending both above and below the range of banding depths (150-300 cm). Significant differences were found at 100-200 and 300-400 cm depths.

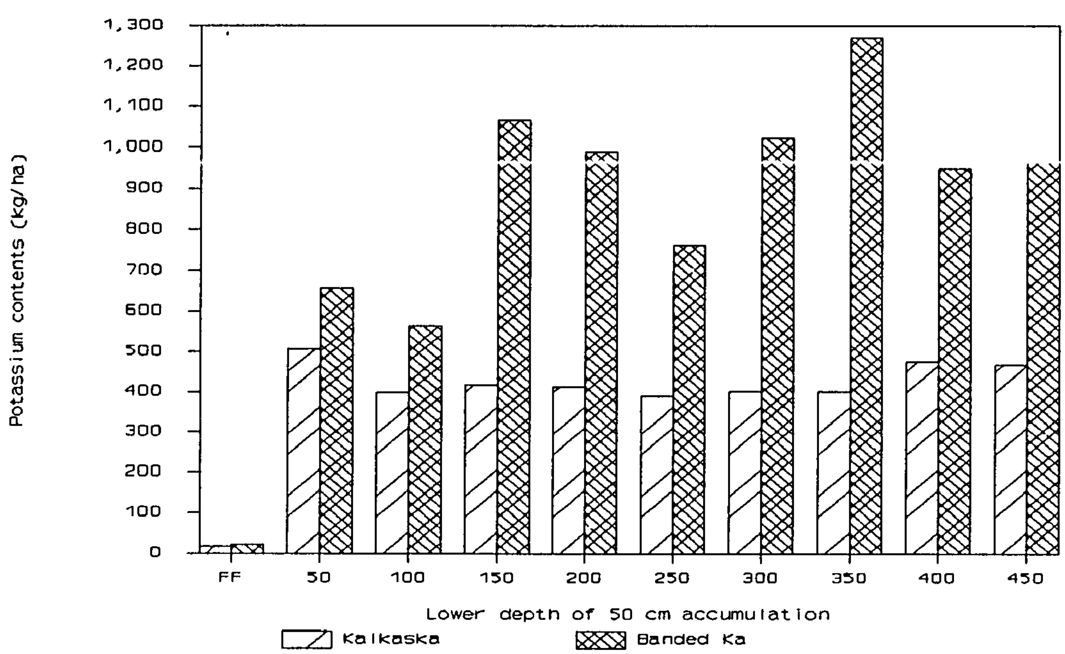


Figure 3.9b. Forest floor total and soil acid extractable K contents grouped by banded and unbanded phases of the Kalkaska soil series.

Since K, Mg, and Ca are readily leached from soils they may show illuvial increases in deeper soil horizons. It was suspected that the greater nutrient contents in the banded phases, especially at depths greater than 100 cm, was due to the parent materials having a higher nutrient status rather than to illuviation. Although the Gy series in Figure 3.9a displayed a slight increase with depth, the unbanded Ka phase in Figure 9.b showed no increase with depth.

Nutrient and Organic Carbon Variability by Phased Soil Series:

Variability of nutrient and OC contents were redistributed when examined by phased soil series. The inclusion of subsolum textural strata in the series taxonomic unit decreased the variability among the soil series phases without banding. The Rb and Ka series displayed different variability patterns when phased by subsolum textural strata. The Rb phases showed an inconsistent pattern of nutrient and OC variability. The Ka phases had a more consistent pattern, with the banded phase having a greater variability than the unbanded phase for all nutrients and OC contents and depths except TKN at 50-150 and 300-400 cm and OC at 100-150 cm. Figure 3.10a displays K content variability between soil series phases without subsolum textural strata. When compared with the soil series evaluations in Table 3.4 it can be

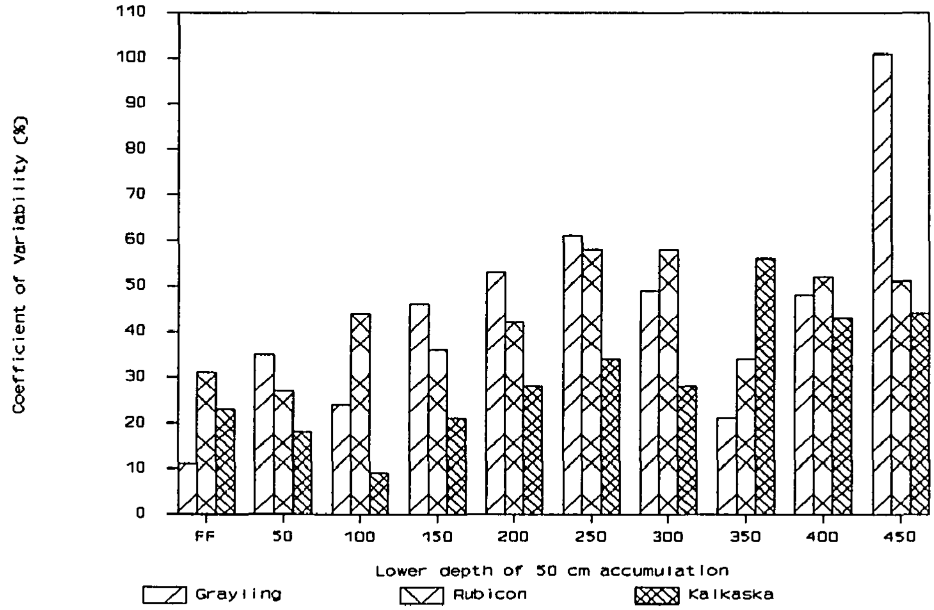


Figure 3.10a. Variability of forest floor total and soil acid extractable K contents grouped by unbanded soil series phases.

observed that the variability was reduced when the influence of subsolum textural strata was removed. This reduction in variability occurs from the surface to 450 cm, but is most evident in the 300-350 cm depth.

Variability of acid extractable K contents was greater in the banded phase of the Ka series than in the unbanded phase as shown in Figure 3.10b. A pattern of increased variability in the banded phases at all depths was observed. Other nutrients and OC displayed less distinct contrasts between phases with and without subsolum textural strata. A general pattern of increasing variability occurred, reaching a maximum at a depth of 250-300 cm and then declining.

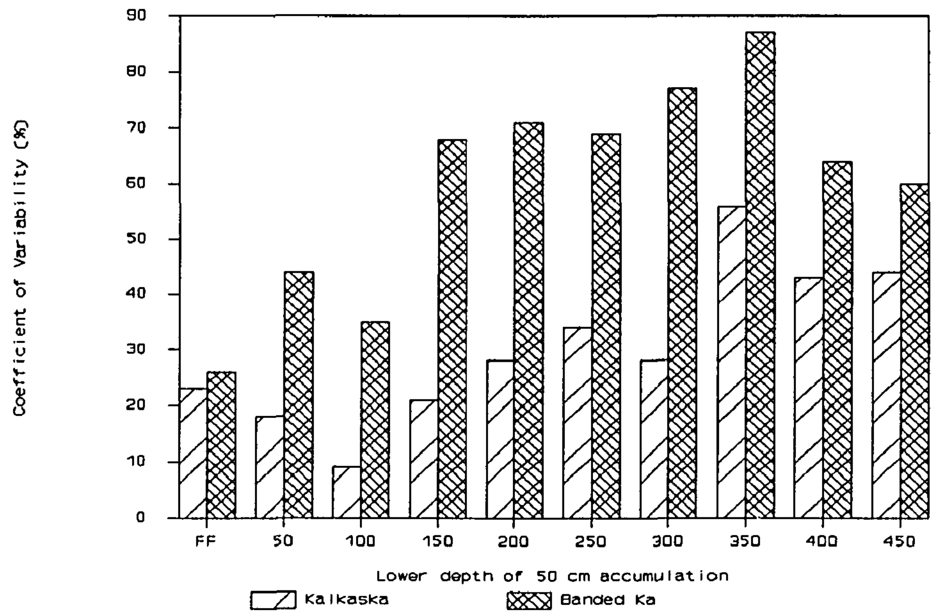


Figure 3.10b. Variability of forest floor total and soil acid extractable K contents grouped by banded and unbanded phases of the Kalkaska series.

Harradine (1949) found a decrease in variability with increasing stage of profile development in the surface 270 cm. The low variability of the Gy series as compared to the Rb and Ka series as presented in Figure 3.8 contradicts these findings. Harradine assumed that the variability was due to soil maturity or age. No mention was made of any of the other factors of soil formation; climate, organisms, parent material, and topography (Jenny 1980). The strength and intensity of banding were also suspected as influencing the variability. In Figure 3.10b it can be observed that for the Ka series, the phase with subsolum textural strata is more variable than the phase without strata. The Gy series has no occurrences of subsolum textural strata, which may be a major factor in its low variability. When the variability of the unbanded Rb and Ka phases are inspected, the Gy series has a greater variability in five of the 10 depths (Figure 3.10a).

The parent materials of all three soils have a mixed mineralogy due to glacial activity, however, the Gy series resulted from deposition of highly washed, sandy material from glacial meltwater streams or spillways. As a result the Gy series has an inherently low nutrient status when compared with the Rb and Ka series which may have till, morainal, or lake plain materials among their horizons. If influences of subsolum textural strata are removed from the Rb and Ka series, then patterns of variability with profile development generally agree with those of Harradine for the surface 250 cm (Figure 3.10a).

The increased variability in the banded soil series phases may be due to differences in texture between the band and the surrounding soil matrix (banding 'strength') or to continuity of the banding. The strength of banding is related to the thickness of the band and its texture. Some sites had well defined bands with striking textural differences from the surrounding soils, while others had poorly defined bands with only slight textural differences. The continuity of the banding was determined from the four bucket auger borings and relates to the areal extent of the banding on a site. On the ECS project 'banding intensity and continuity' was used to quantify strength and areal extent of the banding. Strength was coded by a scale of zero to five and continuity was determined by averaging the strength values from the four bucket auger borings. Table 3.6 lists the banding intensity codes. Stands having mean banding and continuity indicies ranging from zero to five were found in both Rb and Ka banded phases.

Figure 3.11 presents a comparison of acid extractable K contents by 50 cm depth accumulations across three stands with different banding intensity and continuity values. The soil pit descriptions are listed next to the figures along with horizon designations, thicknesses, and textures. It can be clearly seen that as banding intensity increases, so do acid extractable K contents in the region of the banding.

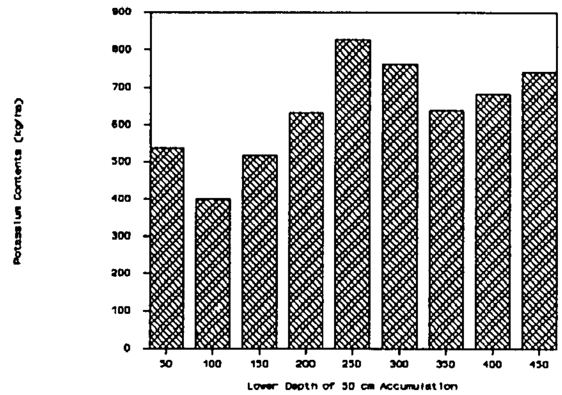
Table 3.6. Banding intensity designations.

0 -	No varves or textural stratifications.
1 -	Thin varves or LS texture, but no bands.
2 -	Bands of SL < 5 cm thick.
3 -	Bands of SL between 5 & 15 cm thick or, bands of SCL < 10 cm thick.
4 -	Bands of SL > 15 cm thick.
5 -	Bands of SCL > 10 cm thick.

Designations were determined for each bucket auger. Stand level banding intensity was average of four bucket auger intensities.

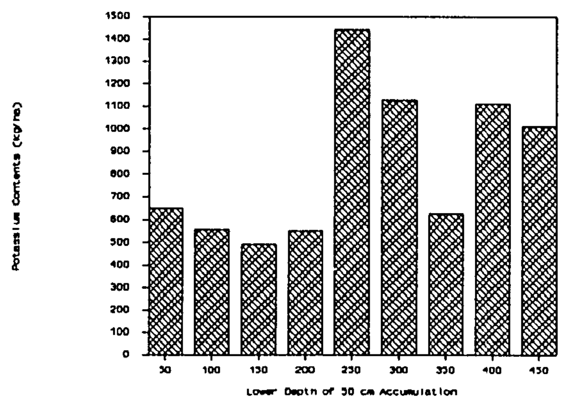
3.11a Gy Series; Banding Intensity = 1.25

Horizon	Depth (cm)	Field Texture
A	0-3.5	LS
AB	3.5-9	LS
Bw1	9-34	S
Bw2	34-47.5	S
BC	47.5-70	S
C1	70-230	S
C2	230-260	CS
C3	260-375	CS
C4	375-410	CS
C5	410-450	FS



3.11b Rb Series; Banding Intensity = 2.00

Horizon	Depth (cm)	Field Texture
AE	0-5.5	MS
BE	5.5-13.5	LS
Bs1	13.5-31	FS
Bs2	31-91	FS
Bs3	91-131.5	FS
C1	131.5-210	MS
C2	210-275	SL
C3	275-350	S
C4	350-375	S
C5	375-450	S



3.11c Rb Series; Banding Intensity = 5.00

Horizon	Depth (cm)	Field Texture
A	0-7.5	MS
E	7.5-26	MS
Bs1	26-46.5	MS
Bs2	46.5-70	MS
BC	70-97.5	FS
C1	97.5-180	S
C2	180-240	LS
C3	240-310	SiL
C4	310-340	LS
C5	340-420	MS
C6	420-450	S

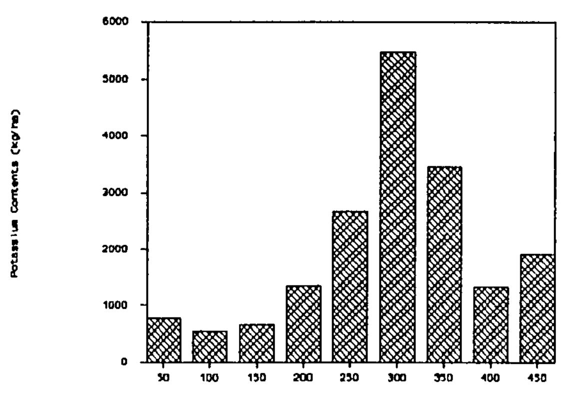


Figure 3.11. Pit descriptions and acid extractable K contents for three stands across a range of banding intensities.

Figure 3.11a presents the Gy series K contents by depth. There were no textural strata found on this site, however, there is a slight increase in K contents with depth until 250 cm. Since the effects of weathering decrease with depth and the parent materials of this soil series are uniform, any increases are likely due to illuviation or residual organic materials from roots. Figure 3.11b shows K contents and horizon descriptions for a Rb soil with moderate banding intensity and continuity. The band has a sandy loam texture and extends from 210-275 cm. The surface 0-200 cm K contents are similar to those found in Figure 3.11a, however, there are sharp increases at depths of 200-300 cm. K contents found at these depths are nearly
double that found in the these depths in the Gy series.
Figure 3.11c displays a Rb soil with a strong banding intensity and continuity. On this site a silt loam band at 240-310 cm is sandwiched between sandy loam bands at 180-240, and 310-340 cm. A dramatic increase in K contents is evident at 250-300 cm coinciding with the depth of the silt loam band.

Figures 3.11a, b, and c show proportionate increases in K contents with increasing banding intensity. Although Figure 3.11a suggests illuvial increases with depth, Figures 3.11b and c do not distinguish between illuvial increases and those due to the inherent fertility of the parent materials.

CONCLUSIONS

It is acknowledged that soil chemical data may not provide all the information needed for useful site classification systems. Pregitzer and Barnes (1984) reported that topographic, vegetational and soil factors need to be considered for successful classification of upland ecosystems. The sample size of this study was too small to adequately examine nutrient contents by ecological units which combined vegetation and soil factors.

Successful site classification systems are important tools for forest management. In order to be successful, a system must take into account factors which will most accurately predict forest growth. How the soils information will be mapped can be crucial to the accuracy and utility of derived forest land inventory systems. Soils are commonly mapped by soil series. A pivotal shortcoming of Soil Taxonomy is that many facets of the landscape are not incorporated in soil taxonomic classifications. This is true even at the lowest level of classification, the soil series. The inclusion of phases of soil series allows recognition of important landscape features (e.g. subsolum textural strata or degree of erosion) which would be overlooked by characterization to the series level alone. In addition, description of the soil landscape is incomplete unless data on impurity of soil mapping units (heterogeneity) and distinctness of soil boundaries are included (Hole and Campbell 1985).

A continuum of nutrient distributions with depth were found. TKN, TKP and OC displayed exponentially decreasing contents with depth, acid extractable K was fairly uniform in its distribution across depths, and acid extractable Mg and Ca displayed patterns of exponential increase with depth.

When the soils were grouped by soil series the Gy series had consistently lower contents than either the Rb or Ka series. CV's for the Gy series generally increased with depth to 450 cm, while the Rb and Ka series displayed patterns of increasing variability to 200-350 cm, then decreasing. This was attributed to the influence of banding.

The results reported in this chapter support the use of banding phases to produce homogeneous groupings and to increase the detection of group differences. Evaluation by banding phase for the Rb and Ka series resulted greater differentiation, with higher nutrient contents being found in the banded phases in 75% (89/118) of the nutrient-OC/depth combinations. Fifteen of the 89 banding increases were significant. Eleven of the 15 significant banding differences were found between the Ka series phases. Banding strength and continuity were thought to be the reason that variability of the unbanded phases was consistently lower than that of the banded phases. Increases in the variability of the banded phases at 200-300 cm depths coincides with depths where subsolum textural strata occurred.

Subsolum variability of banded soil phases displayed strikingly different patterns than were found (or have been reported elsewhere) for the solum. The general pattern was that of variability increase to about 300 to 350 cm, followed by a decline. Inclusion of a banding phase reduced the variability and would allow a more precise estimation of the site nutrient resource than use of only the soil series.

Stand yield showed no significant differences when grouped by soil series, however, when the banding phase was introduced significant differences were found. The link between the nutrients contained in these bands and stand growth will be examined in the following chapter.

This study provides several directions for future research. To further reduce the variability of the banded phases the intensity and continuity of subsolum textural strata need to be further investigated. Also, a consistent definition of banding intensity needs to be established. The sample size of this study was too small to allow closer examination of banding strength and continuity and answer questions such as: "Is a site banded if a single occurrence of strong banding is found on that site?", or "Would three occurrences of weak banding indicate a higher site quality than two occurrences of strong banding?".

Another direction for research involves utilization of the phased soil series evaluations with vegetational and ecological factors in an ecological classification system. Continuing work with ECS projects by MSU and the USDA Forest Service could provide such an evaluation.

The results from this study found soil series phases partitioned nutrient contents and nutrient content variabilities more satisfactorily than soil series alone. Soils evaluated a 450 cm potential tree rooting depth accounted for more variability and, therefore would allow a more precise estimation of site nutrient resources than surface soil features, and should be considered in soils with sandy surface textures and similar subsolum features. The use of phased soil series in forest land evaluation systems has a potential value that should not be ignored.

ACKNOWLEDGEMENTS

The Ecological Classification System Project was funded by the USDA Forest Service. Special thanks are extended to Mr. David T. Cleland, Soil Scientist, Huron-Manistee N.F. whose tireless efforts in behalf of the ECS project allowed this research to be undertaken, and to Dr. James B. Hart Jr. for his ideas, reviews and comments. The efforts of Dr. Carl W. Ramm for calculation of stand volume and his statistical consultations are greatly appreciated. Thanks to Dr. Donald Zak, Dr. George Host, and Mr. Steve Westin for their assistance in sample collection, and to the many individuals who assisted in field work and laboratory analysis.

Special appreciation is extended to Dr. Phu V. Nguyen for his invaluable advice and assistance.

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Chapter 4.

Relationships of Soil Fertility and Stand Growth in Glaciated Michigan Landscapes

INTRODUCTION

This study jointly examines several topics which have not been previously considered together in soil-site studies on oak and northern hardwood stands in the lake states. These topics include examination of the influence of subsolum textural strata, or bands, on stand growth; the use of acid extractable nutrients as a measure of site nutrient resources; and a soil sampling scheme which collects soils throughout the rooting depth of the forest overstory. Relationships between site fertility and stand growth were examined utilizing contents (kg ha^{-1}) of nitrogen, phosphorus, potassium, magnesium, calcium, and organic carbon accumulated by 50 cm depths as measures of soil fertility; and mean annual volume increment (MAI) to represent stand growth.

The yield of forest products and therefore, the management of forest stands are influenced by the sum of edaphic, climatic, and biological factors which affect its long-term ability to accumulate biomass. This sum of factors is often referred to as site quality. Increasing demand for forest products and a decreasing land base for timber production have led to a situation where a more agronomic philosophy of yield maximization is being applied to forestry. This philosophy is evident in more intensive forestry practices such as short rotation forestry and whole tree harvesting. More efficient and productive forest management techniques can be applied when sites are grouped into classes of similar management potential on the basis of stand growth. Increasing numbers of stands (e.g. disturbed stands, uneven-aged stands, and stands in which the desired species is not present) also occur in which direct measurements of stand growth cannot be made. Use of soil-site relationships allows estimation of stand growth on these sites (Carmean 1975, Coile 1952).

Soil-site examinations have had a long and useful history determining site quality and resulting forest growth, alone and in conjunction with examination of vegetative and ecological factors (Broadfoot 1969, Cajander 1926, Carmean 1975; Hannah and Zahner 1970, Leaf 1956, Lowry 1970; Pawluk and Arneman 1961, Pregitzer and Barnes 1984, Wilde and Scholz 1934). Many soil-site studies have examined the associations of features such as surface soil depth, subsoil texture and slope with stand growth (Carmean 1975). This reflects the goals of these soil-site examinations which were the prediction of stand growth with factors which are easily collected and analyzed. However, these factors are only indirect indices of more basic growth factors such as nutrient and moisture availability. The practical aspect of prediction was valued more than the inclusion of more fundamental growth factors. Broadfoot (1969) cautions against using variables which are effects rather than causes of tree growth and he attributes the low accuracy of his soil-site study of seven southern hardwood species to this.

There is no agreement whether soil physical or chemical properties provide better predictions of stand growth. Some researchers have found soil fertility (expressed as nutrient concentrations (ppm)) to have a more limited influence on stand growth than soil physical properties (Leaf 1956, Lowry 1970; Pawluk and Arneman 1961, Youngberg and Scholz 1950).

Relationships between stand growth and site fertility were found to be stronger when soil fertility was expressed as nutrient contents instead of nutrient concentrations (Hart et al. 1969, Mader and Owen 1961; Viro 1961, White and Leaf 1964; Youngberg and Scholz 1950, Zinke 1960). Zinke (1960) found a positive correlation between nitrogen (N) contents in the top 1.2 m (4 ft) of the soil and site index of ponderosa pine (Pinus ponderosa Laws.). Potassium contents of 30 cm (1 ft) thick soil layers to a depth of 210 cm (7 ft) were found to be significantly different from one another, and correlated to red pine (Pinus resinosa Ait.) growth (White and Leaf 1964). Viro (1961) suggests that site nutrient contents may be more appropriate for reporting soil chemical properties in soil-site studies.

Researchers have noted significant variations in stand growth associated with subsolum soil features such as sandstone strata, groundwater, and fine textured strata including bands or lenses of fluvial materials (Comerford et al. 1984, White and Leaf 1964, White and Wood 1958; and Wilde and Leaf 1955). For soils with variable subsolum properties the examination of only the top 30 cm may not be sufficient for estimating stand growth. This is especially true for deep rooted species such as red and white oak which have effective rooting depths of 450 cm (15 ft) or more in sandy soils (USDA, 1965). In their evaluation of oak sites in southern Michigan, Gysel and Arend (1953) found that moist subsolum strata at depths of 120-300 cm (4-10 ft) were important factors in oak site productivity.

The importance of subsolum soil fertility in the estimation of stand growth was shown on a potassium (K) deficient glacial outwash soil in northern New York. Red pine plantations on adjacent sites displayed a two fold difference in volume growth after seven years of equally poor growth (White and Wood 1958). A band of fine textured soil was discovered at a depth of 180 cm (6 ft) and 270 cm (9 ft) on the good and poor sites, respectively. The authors attributed the growth difference to the greater K and water supplying abilities of the band within reach of the roots. Subsequent studies revealed that acid extractable K at depths of 91-213 cm (3-7 ft) had the highest correlation to total tree height (White and Leaf 1964). On sandy glacial outwash soils in northern lower Michigan it was found that the increase in growth of red oak (site index and mean annual diameter growth) on soils which had subsolum textural bands within the rooting range was highly significant as compared to unbanded soils with similar stand characteristics[4]. The growth response of red oak was greater than that of sugar maple, presumably because of a more efficient exploitation of the subsolum bands by the deeper rooted red oak.

Few soil-site studies have been conducted on oak and northern hardwood stands in the lake states (Carmean 1975, Pregitzer and Barnes 1984, Shetron 1972; Wilde and Scholz 1934, Wilde <u>et al</u>. 1948; Youngberg and Scholz 1950), and none have examined the contributions of soil fertility beneath the surface 150 cm to stand growth.

OBJECTIVES

The objectives of this study were to determine if there is an association between soil fertility and stand growth; and if there is an association, to determine the contributions of soil fertility to stand growth of upland oak and sugar maple stands in northern lower Michigan. Other objectives were to find the set of site fertility variables which has the strongest linear association with stand growth and to

[4] D.T. Cleland, Deep Bands and Forest Growth on Kalkaska Sands. Unpublished Report.

determine whether soil sampling to a depth of 450 cm, which includes subsolum banding, has a stronger association with stand growth than sampling only the surface soils to a depth of 45 cm.

Specific hypotheses to be tested were:

1) H_0: $r_{(\text{fertility \& MAI})} = 0$

H_1: Not H_0, and

2) H_0: $r_{(\text{fertility below 45 cm \& MAI})} = 0$

H_1: Not H_0.

A final objective was to use information gained above to make recommendations on soil sampling depths for forest land inventory programs.

MATERIALS AND METHODS

Study Area:

Study plots were located in the Manistee National Forest in the northern lower peninsula of Michigan between $85^0 30'$ and $86^0 15'$ west longitude and $45^0 52'$ and $44^0 30'$ north latitude (Figure 4.1). The climate alternates between continental and semi-marine depending on the direction of individual weather patterns. The 29 year (1940-1969) mean annual precipitation was 821 mm (32 in) and the 29 year mean annual temperature was 5.8^0c (42.5^0F) (Strommen 1974). The soils series encountered on the sites (Rubicon, Kalkaska, and Grayling) were all of

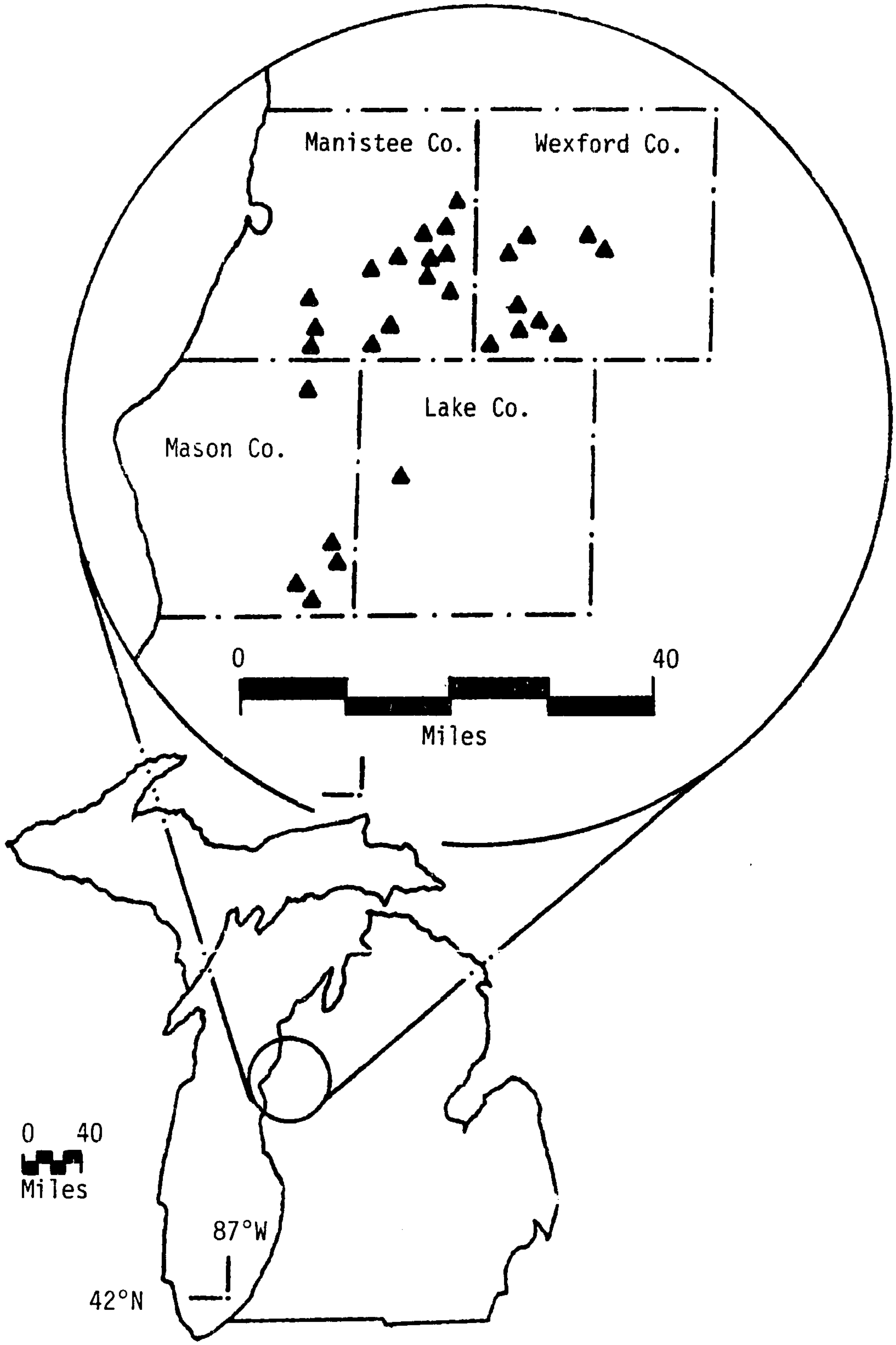

Figure 4.1. Location of sample stands.

Wisconsinian age (Soil Conservation Service 1976, 1981, 1982). The Grayling soil is a Mixed, frigid, Typic Udipsamment; the Rubicon soil is a Sandy, mixed, frigid Entic Haplorthod; and the Kalkaska soil is a Sandy, mixed, frigid Typic Haplorthod. All soils were well to excessively drained and were formed from sandy glacial drift parent materials. The more productive soils developed in or were underlain by till plain, ground moraine, and lake plain materials with textures of sandy loam or finer. Stand growth increases along a gradient of Grayling, Rubicon, Kalkaska.

Thirty stands stratified by low, moderate, and high productivity were sampled. Stands occupied by pioneer species or showing evidence of disturbance in the past 40 years were excluded from sampling. The minimum basal area of stands sampled was 18.36 m^2ha^{-1} (80 ft^2 ac^{-1}). Other stand selection criteria were that the stand must be at least 55 years old, the stand must be normally and uniformly stocked, and that the topography must be uniform and representative of upland conditions. Tree species found on the stands were sugar maple (Acer saccharum Marsh.), white ash (Fraxinus americana L.); red maple (Acer rubrum L.), red oak (Quercus rubra L.); white oak (Quercus alba L.), and the black oak group (Quercus spp.).

Sample Collection:

Samples were collected during the summer of 1983 in conjunction with an ecological classification system (ECS) project being carried out jointly by the USDA Forest Service and Michigan State University. The sampling unit was the stand. At each randomly selected stand a uniform area of one hectare or more was selected for sampling. Four randomly located points per stand were measured for overstory growth and yield. Two sets of soil samples were collected, the first was collected at the soil pit to a depth of 450 cm, and the second was collected to a depth of 45 cm.

Forest floor samples were collected with a 30x30 cm metal frame at six points (three at the pit and one each at three additional points) and systematically separated into litter, or fermentation and humus layers (Figure 4.2a). Litter samples (Oi horizon) included recognizable and nearly entire leaf material not affected by decompositional processes. Fermentation and humus layer samples (Oa and Oe horizons) consisted of finely divided decomposed organic materials extending to the upper boundary of the mineral soil.

A soil pit about 150 cm in depth was located near the center of each stand (Figure 4.2b). After pits were dug the soils were classified to the series level and equal volumes of soil were collected from each horizon. Bucket auger samples, stratified by horizon, were collected beginning at the bottom of the pit and terminating at 450 cm (Figure 4.2c). Bulk density samples were collected to allow conversion of nutrient concentrations to nutrient contents.

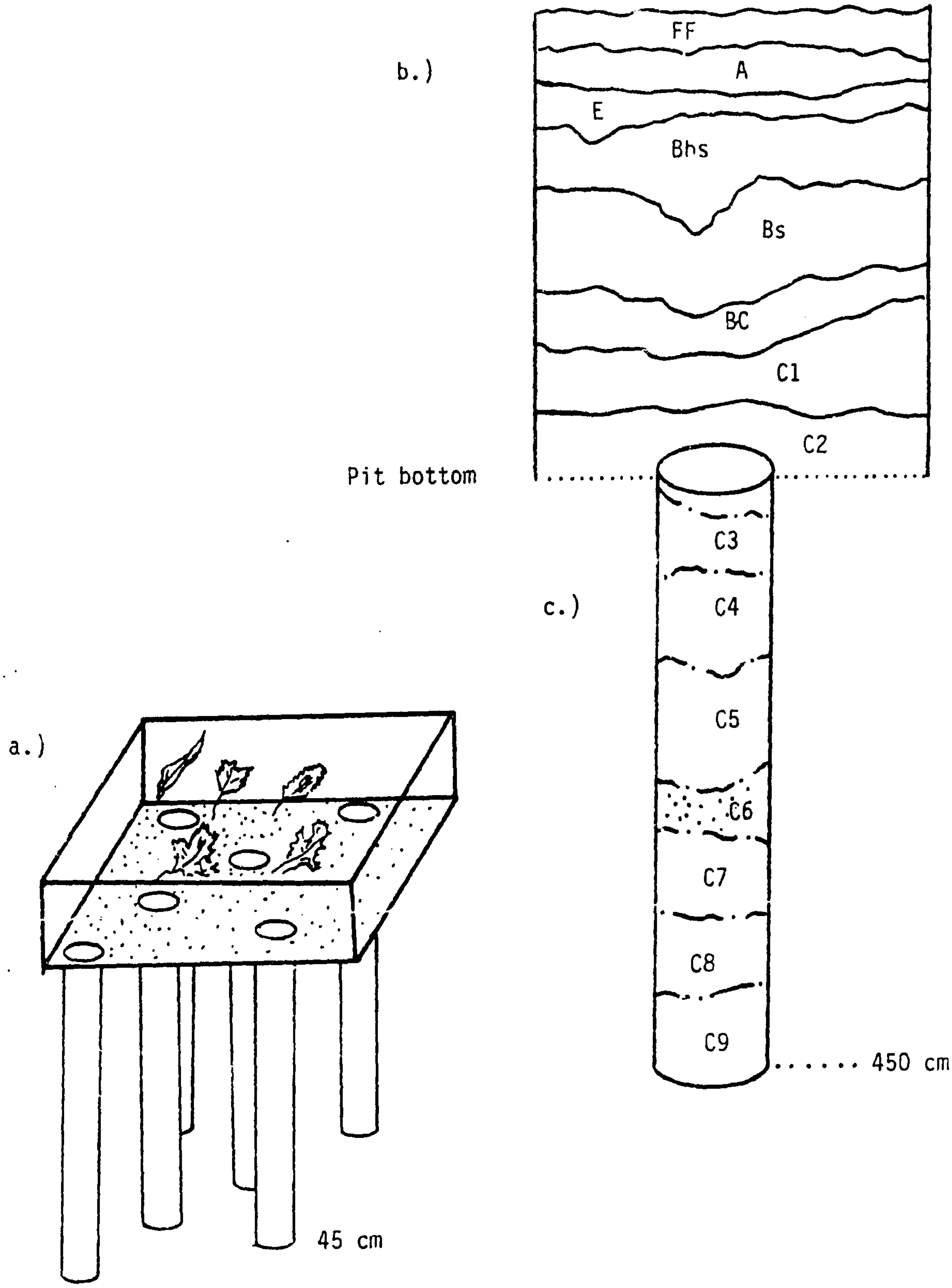

Figure 4.2. Detail of forest floor and soil sampling: a. forest floor and surface soils, b. soil pit, c. bucket auger.

Surface soil samples were collected directly beneath the forest floor samples. These were divided into surface (A and E horizons) and subsurface (upper B horizon to 45 cm. depth) layers (Figure 4.2a) and composited for analysis.

Stand Growth Measurements:

Forest growth was measured at four random points per stand using a 10 basal area factor prism. At each sample point all trees with a diameter greater than 8.89 cm (3 in) were measured for diameter at breast height (DBH), total height, and merchantable height to a 10.2 cm (4 in) top. Increment cores were taken from two trees per sampling point, across the range of DBH values, to obtain total age. Stand means were obtained by averaging measurements from the four prism points. Mean annual volume increment (MAI) was computed from the inventory data and was chosen as the site quality variable by which to express stand growth.

Laboratory Analysis:

Forest floor samples were oven dried at 70^{0}C, weighed, ground, and subsampled prior to analysis. Forest floor total Kjeldahl nitrogen (TKN) and total Kjeldahl phosphorus (TKP) digests were determined after sulfuric acid digestion (Page et al. 1982) using a Technicon[5] Auto-analyzer II and Technicon procedures (Technicon, 1977). Total cations (K, Mg, and Ca) were determined by dry ashing at 500^0C for 4 hours with ash dissolution in 8 N HCl (Wilde et al. 1972). Nutrient concentrations were converted into contents by use of areas and weights of the forest floor samples.

Soil samples were air dried, sieved to pass a 2 mm screen, and subsampled for analysis. Both coarse (>2 mm) and fine fraction weights were recorded for each sample and used to calculate horizon contents corrected for coarse fragment contents.

Commonly used agronomic soil testing procedures in which mild extractants are used to quantify 'available' nutrients have been found to be poorly related to tree growth (Adams and Boyle 1982, Leaf 1958, Thompson et al. 1977, White and Leaf 1964). Tree roots have been found to assimilate nutrients directly from unweathered soil minerals by contact feeding (Boyle and Voigt 1973, Viro 1961) and exploit the nutrient resources of a site for decades at a time. It is reasonable, therefore, that more caustic extractants will derive meaningful estimates of site nutrients important to tree productivity.

Acid extractions are thought to represent cations which replenish elements depleted by plant uptake and leaching

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[5] Use of trade names does not constitute an endorsement by either Michigan State University or the USDA.

(Page et al. 1982). Metson (1974) concluded that the rate of Mg release from soil reserves was correlated with Mg extracted by a moderately strong acid attack and was, therefore, a good guide to available Mg in continuous cropping or forest systems.

A 2 g soil sample was boiled for 10 minutes with 10 ml of 0.5 N nitric acid to extract potassium (K), magnesium (Mg), and calcium (Ca). This extraction has been shown to be associated with tree K uptake and growth in red pine (Leaf 1958, White and Leaf 1964), and with critical foliar Mg levels in radiata pine (*Pinus radiata* D. Don)(Adams 1973). Since Mg and Ca are usually extracted concurrently from soils and have many chemical properties in common (Page et al. 1982), available calcium was also determined by this method.

Cation concentrations (K, Mg, and Ca) of the boiling nitric acid extractions were determined by plasma emission spectroscopy. The extracts were brought to a concentration of 1,000 ppm LiCl to stabilize the plasma and to suppress interference. TKN and TKP were determined after sulfuric acid digestion similar to the forest floor samples.

Percent organic carbon (OC) in the soils was determined by the Walkley-Black method using 0.5 N ferrous sulfate and 1 N potassium dichromate (Page et al. 1982). Sample size varied from 1-5 g to allow greater accuracy in samples with high and low organic carbon concentrations.

Horizon concentrations were converted into nutrient contents per horizon using concentrations, soil bulk densities, and horizon depths. The contents were accumulated by 50 cm depths to circumvent problems with differences in horizon thickness. Statistical analyses were performed with the stand as the sample unit, therefore, forest floor and surface soil samples were averaged by stand.

All chemical analyses were performed in the MSU Forestry Department forest soils laboratories using 10% sample replication, National Bureau of Standards specimens, and bulk sample analysis to insure precision and accuracy.

Statistical Analysis:

Before regression analysis was performed several exploratory data analyses were performed on the data. Variables were checked to verify compliance with regression assumptions of linear X-Y relationships between independent and dependent variables and normal distributions of the dependent variable (Draper and Smith 1981). Scatterplots were generated plotting site fertility variables against MAI to inspect linearity of the relationships. The dependent variable (MAI) was tested for normality by a Chi-square goodness of fit test.

There are no "best" methods for choosing among several independent variables to find the regression equation which reveals the strongest association with the dependent variable

(Draper and Smith 1981). Variable selection was complicated by the fact that the number of independent variables exceeded the sample size for the pit soil fertility samples. Variable reduction was accomplished in several stages. First, any variables not displaying linear or transformed linear associations in scatterplots were discarded. Second, the correlation matrix of the remaining variables was examined and variables not having a significant r value with MAI were removed. Any pair of fertility variables whose correlation was greater than r = 0.80 were noted and not entered together in a regression due to multicollinearity effects (a problem in multivariate regressions when there is more correlation among independent variables than between independent and dependent variables (Draper and Smith 1981)). Third, the remaining soil fertility variables were entered into a multiple regression equation and variables not having significant regression coefficients (at an alpha = 0.10 level) were removed.

In addition to multiple regression analysis on linear and transformed linear soil fertility variables, regressions were performed on standardized soil fertility variables to generate partial regression coefficients which allow direct evaluation of relative variable contributions to the regression (Netter and Wasserman 1974). When r values > 0.80 existed between soil fertility variables, the variable with the greater contribution to the regression (as determined by adjusted R^2, SEE, and partial regression coefficient values) was chosen. After the regressions were formulated, residuals were examined for any specific violation of the regression assumptions (Draper and Smith 1981, Steel and Torrie 1980).

Principal components analysis (PCA) has the ability to overcome many of the limitations of correlated variables. The principal components generated by PCA are uncorrelated linear functions of the original variables, and multicollinearity between the principal components (PC's) is eliminated (McDonald 1980, Morrison 1976). PCA is effective at variable reduction and can reveal hidden factors which account for a large percentage of the variation in the independent variables. (McDonald 1980, Morrison 1976).

Criteria for selecting principal components from the set of generated PC's were determined, a priori, to be all PC's with Eigenvalues greater than 1, or that set of PC's which explains at least 80% of the variation in site fertility. The correlation matrix was employed in the PCA because its use is more appropriate in data sets where some variables have standard deviations of a higher magnitude, as was the case in this investigation. The Eigenvectors developed by the PCA were used to generate a set of standardized principal components for each stand. These PC's were used in a regression analysis with MAI.

RESULTS AND DISCUSSION

Exploratory Data Analysis:

When soil fertility variables of the pit samples were plotted against MAI to examine linear associations, several of the pairings displayed non-linear associations. Sigmoidal transformations improved the linearity of soil fertility and MAI associations. Scatterplots for the surface soil fertility variables and MAI also displayed non-linear associations, however, they had less scatter than the pit samples. As with the pit samples, sigmoidal transformations made many of the pairings more linear.

The results of a Chi-square goodness of fit test on MAI found that the null hypothesis of a normal sample distribution could not be rejected (Steel and Torrie 1980).

Soil fertility relationships with stand growth:

Soil sampling to 450 cm

Of the 64 possible soil fertility variables, 48 exhibited linear associations with MAI or could be transformed to variables with linear associations and are presented in Table 4.1. The collected sample size was too small to analyze this variable set by multiple regression methods. Twenty five pairs of the remaining variables had correlations with r values greater than or equal to 0.80. Of each pair of highly correlated variables the one with the highest correlation to MAI was first chosen for the regression equation. This resulted in a set of 17 variables for the initial regression analysis (Table 4.1). The discrepancy between highly correlated variables (25), variables selected (17), and variables with linear associations (48) was because some variables were correlated with more than one other variable. A series of regressions were performed, the results of one being examined before the subsequent regression was run. Highly correlated variables were randomly substituted for one another and adjusted R^2 and SEE values were utilized to determine the better overall regression. Regression coefficients were examined at each stage for statistical significance and variables with non-significant coefficients were discarded.

Evaluation by adjusted R^2, residual mean square, and SEE values resulted in the selection of a regression equation with seven fertility variables presented in Table 4.2. Examination of the residuals revealed no violations of regression assumptions. Partial regression coefficients identified total K contents in the F&H layers as having the greatest

Table 4.1. Reduction of forest floor and pit variable size for regression analysis.

Initial Variables		Variables with Linear or Transformed Linear associations		Preliminary Regression Variables
N-L[a]	Mg-L	N-L	Mg-L	N-F&H
N-F&H	Mg-F&H	N-F&H	Mg-F&H	N-200
N-50	Mg-50	N-50	Mg-50	
N-100	Mg-100	N-100	Mg-100	P-L
N-150	Mg-150	N-150	Mg-150	P-150
N-200	Mg-200	N-200	Mg-200	P-200
N-250	Mg-250	N-350	Mg-250	P-350
N-300	Mg-300		Mg-300	
N-350	Mg-350	P-L	Mg-350	K-F&H
N-400	Mg-400	P-F&H	Mg-400	K-50
N-450	Mg-450	P-50	Mg-450	K-100
		P-100	Ca-L	K-150
P-L	Ca-L	P-150	Ca-F&H	K-350
P-F&H	Ca-F&H	P-200	Ca-50	
P-50	Ca-50	P-250	Ca-100	Mg-100
P-100	Ca-100	P-300	Ca-150	Mg-200
P-150	Ca-150	P-350	Ca-200	
P-200	Ca-200	P-400	Ca-250	Ca-50
P-250	Ca-250	P-450	Ca-300	Ca-100
P-300	Ca-300		Ca-350	Ca-200
P-350	Ca-350	K-L	Ca-400	Ca-250
P-400	Ca-400	K-F&H	Ca-450	
P-450	Ca-450	K-50		
		K-100		
K-L		K-150	OC-450	
K-F&H		K-200		
K-50	OC-50	K-350		
K-100	OC-100	K-400		
K-150	OC-150			
K-200	OC-200			
K-250	OC-250			
K-300	OC-300			
K-350	OC-350			
K-400	OC-400			
K-450	OC-450			

[a] - L = Litter organic layer; F&H = Fermentation and Humus organic layers; Number following nutrient symbol is lower depth of 50 cm accumulation.

Table 4.2. Regression summaries for forest floor and pit nutrient contents accumulated by 50 cm depths and descriptive statistics.

Adj. R^2	Standard Error of Estimate	Independent Variables	Reg. Coeff. (B_i)	S.E. of Reg. Coeff.	Partial Reg. Coeff.
0.86	0.357	N 150-200[a]	0.314	0.065	0.424[b]
		P L	0.304	0.087	0.283
		P 100-150	-0.328	0.138	-0.262
		K F&H	0.091	0.018	0.526
		K 0-50	-1.6E-3	6.2E-4	-0.325
		K 50-100	0.424	0.105	0.408
		K 100-150	0.307	0.091	0.351
	B_0[c] = 0.759	F Ratio = 24.74		27 df	

Descriptive Statistics:

Variable	n	Mean	Minimum	Maximum	Standard Deviation
		------ $m^3\ ha^{-1}\ yr^{-1}$ ------			
MAI	30	2.84	1.19	4.33	0.97
		-------- Kg ha^{-1} ---------			
N 150-200[a]	29	226	15	649	169
P L	29	6	3	12	2
P 100-150	29	344	182	665	127
K F&H	29	12	5	24	5
K 0-50	29	537	275	1138	185
K 50-100	30	473	238	776	163
K 100-150	30	587	205	2400	421

[a] - Numbers represent depth of nutrient accumulation; L = litter layer; F&H = fermentation and humus layer.
[b] - Partial regression coefficients derived from regressions utilizing standardized variables (z = (x - x bar)/s).
[c] - B_0 = Y intercept of regression equation; df = total degrees of freedom for regression

contribution of the variables entered, followed by TKN in the 150-200 cm soil depth and acid extractable K in the 50-100 cm soil depth.

TKN, TKP, and total, or acid extractable K were all significantly associated with MAI. Accumulations in the intermediate depths, between the depths of 100 and 200 cm, were significant for all three nutrients. No variables beneath the surface 200 cm were entered into the regression. The strong association of total and acid extractable K contents agrees with published results finding significant associations with K contents and growth of southern hardwood and red pine stands (Broadfoot 1969, White and Leaf 1964). In the previous chapter it was found that acid extractable K began to show differences in content and variability at the 100-150 cm depth. This was especially true in soils with subsolum textural strata. The regression in Table 4.2 was interpreted as confirming the importance of intermediate soil depths in supplying nutrients for forest growth.

In a previous examination of soil fertility distribution and variability it was found that high nutrient contents were associated with the presence of subsolum textural strata. It was an expectation, therefore, that deeper soil fertility variables would be entered in the regression equation. The regression data set included stands both with and without subsolum textural strata. The inclusion of stands without subsolum banding may have obscured the influence of strata fertility on stand growth.

As a check of this hypothesis the data set was divided into two fractions, those with and those without subsolum textural strata and simple linear correlations with MAI were calculated for both fractions. Correlations of MAI with total or acid extractable K contents are presented in Table 4.3 . The r values decrease rapidly below the surface 100 cm for the unbanded stands, while they remain strong at greater depths in the banded stands. Although the sample size was too small to perform separate regressions on banded and unbanded stands, the correlation patterns suggest that different regressions would be formulated. Correlation analysis is sensitive to

Table 4.3. Correlations between MAI and forest floor total or soil acid extractable K in soils grouped by presence or absence of subsolum textural strata.

	Correlations with MAI	
Total and Acid Extractable K Accumulations	Soils w/o subsolum textural strata	Soils w/ subsolum textural strata
	n=12	n=11
Litter Layer	0.233	0.017
Fermentation & Humus Layer	0.555	0.336
0-50 cm	0.333	0.430
50-100 cm	0.481	0.695
100-150 cm	0.013	0.571
150-200 cm	-0.113	0.161
300-350 cm	-0.368	0.469
350-400 cm	-0.109	0.593

sample size, therefore, the data in Table 4.3 are only meant to display general trends.

Principal component analysis was performed on the set of 48 variables which displayed linear associations with MAI. The a priori selection criteria of 80% explanation of fertility variance was used to select principal components (PC's) from the set of generated PC's. This approach was adopted over selection by eigenvalues greater than one because it resulted in a smaller set of PC's for analysis. Eighty-two percent of the explained variance was consolidated in the first seven PC's. This represents a dramatic reduction in the dimensionality of the data from the initial 48 fertility variables. Standardized PC's were computed from the first seven eigenvectors.

The standardized PC's were entered into a multiple regression equation. Elimination of PC's with non-significant regression coefficients left an equation with three PC's. Regression summaries for this relationship are presented in Table 4.4. This regression was judged to be a poorer representation of the MAI - fertility relationship with an adjusted R^2 value 19% lower, and a SEE 56% higher than was obtained by direct examination of the pit fertility variables. Inspection of partial regression coefficients revealed that although the fourth PC explained only 8% of the variation in fertility (Table 4.5), it was a greater contributor to the regression than the second PC (which explained 15% of the

Table 4.4. Summaries for forest floor and pit principal component regression analysis.

Adj. R^2	Standard Error of Estimate	Independent Variables	Reg. Coeff. (B_i)	S.E. of Reg. Coeff.	Partial Reg. Coeff.
0.67	0.556	PC #1	0.168	0.026	0.678[a]
		PC #2	0.083	0.042	0.209
		PC #4	0.207	0.056	0.394
	B_0[b] = 2.846	F Ratio = 20.79		29 df	

[a] - Partial regression coefficients derived from regressions utilizing standardized variables (z = (x - x bar)/s).
[b] - B_0 = Y intercept of regression equation; df = total degrees of freedom for regression

fertility variation).

Table 4.5 presents the eigenvectors of the three significant PC's in the regression equation. The first PC had low loadings for TKN contents at all depths except the organic fermentation and humus layers, and low loadings for all nutrients in the litter layer. The interpretation of the first PC was that of a balanced representation for the overall nutrient status of the stand. The second PC displays a pattern of decreased or more negative loadings with depth for all fertility variables except soil TKP, which has a uniform loading across all depths. The second PC was interpreted as representing the importance of the forest floor and surface 100 cm of the soil. The fcurth PC had major loadings for TKN,

Table 4.5. Eigen values and vectors for principal components with significant regression coefficients: Forest floor and pit samples.

50 cm Nutrient accumulation	Principal Component #1	Principal Component #2	Principal Component #4
Eigen Values	17.6	7.3	4.1
% Variance	37	15	8
Eigen Vectors:			
N-L[a]	0.018	0.015	0.173
N-F&H	0.166	0.186	0.101
N-50	0.026	0.205	0.226
N-100	0.053	0.199	0.144
N-150	0.052	0.128	0.303
N-200	0.034	0.146	0.224
N-350	0.064	0.058	-0.025
P-L	0.054	-0.020	0.273
P-F&H	0.180	0.099	0.126
P-50	0.113	0.143	0.005
P-100	0.122	0.120	0.014
P-150	0.150	0.137	0.076
P-200	0.170	0.130	-0.019
P-250	0.122	-0.026	-0.191
P-300	0.143	0.024	-0.252
P-350	0.185	0.069	-0.192
P-400	0.187	0.065	-0.205
P-450	0.185	0.127	-0.205
K-L	0.047	0.147	0.112
K-F&H	0.200	0.127	-0.010
K-50	0.132	0.056	0.287
K-100	0.130	0.056	0.198
K-150	0.141	-0.042	0.253
K-200	0.118	-0.096	0.249
K-350	0.169	-0.158	0.052
K-400	0.183	-0.154	0.088

Continued

Table 4.5. Continued.

50 cm Nutrient accumulation	Principal Component #1	Principal Component #2	Principal Component #4
Eigen Vectors:			
Mg-F&H	0.152	0.229	-0.059
Mg-50	0.117	0.135	-0.212
Mg-100	0.157	0.082	-0.127
Mg-150	0.198	-0.021	-0.032
Mg-200	0.192	-0.064	0.013
Mg-250	0.172	-0.205	0.015
Mg-300	0.173	-0.201	0.033
Mg-350	0.152	-0.250	0.005
Mg-400	0.160	-0.234	0.053
Mg-450	0.144	-0.160	0.005
Ca-L	0.053	0.217	-0.029
Ca-F&H	0.161	0.236	0.019
Ca-50	0.124	0.186	-0.007
Ca-100	0.146	0.139	-0.168
Ca-150	0.165	0.022	-0.082
Ca-200	0.184	-0.031	0.005
Ca-250	0.185	-0.179	0.013
Ca-300	0.172	-0.182	-0.014
Ca-350	0.185	-0.179	0.017
Ca-400	0.147	-0.219	-0.002
Ca-450	0.140	-0.138	-0.015
OC-450	0.061	0.049	-0.224

[a] - L = Litter organic layer; F&H = Fermentation and Humus organic layers; Number following nutrient symbol is lower depth of 50 cm accumulation.

TKP, and acid extractable K. The TKN loadings were greatest for the litter layer, the 0-50, 100-150; and 150-200 cm depths. The prominent TKP loading was in the litter layer. Acid extractable K had its greatest loadings from soil depths of 0-150 cm. The loadings of PC #4 corresponded well with the fertility variables selected by the regression in Table 4.2 and was interpreted to represent the soil fertility resource at intermediate depths (50-200 cm).

Plotting the PC's with the largest partial regression coefficients revealed a reasonable separation of banded and unbanded stands. Figure 4.3 shows that stands with subsolum textural strata occur above the diagonal line which nearly bisects the plot, while stands below this line lack subsolum textural strata. Stands with bands have a high overall fertility (indicated by larger values for PC #1) regardless of fertility in the intermediate depths (indicated by values for PC #4). If the stands have a higher fertility in the intermediate depths (PC#4) then they are likely to be banded regardless of their overall fertility (PC#1).

Soil fertility relationships with stand growth:

Soil sampling to 45 cm

The selection of the "best" regression proceeded in the same fashion with the surface soil samples as for the pit

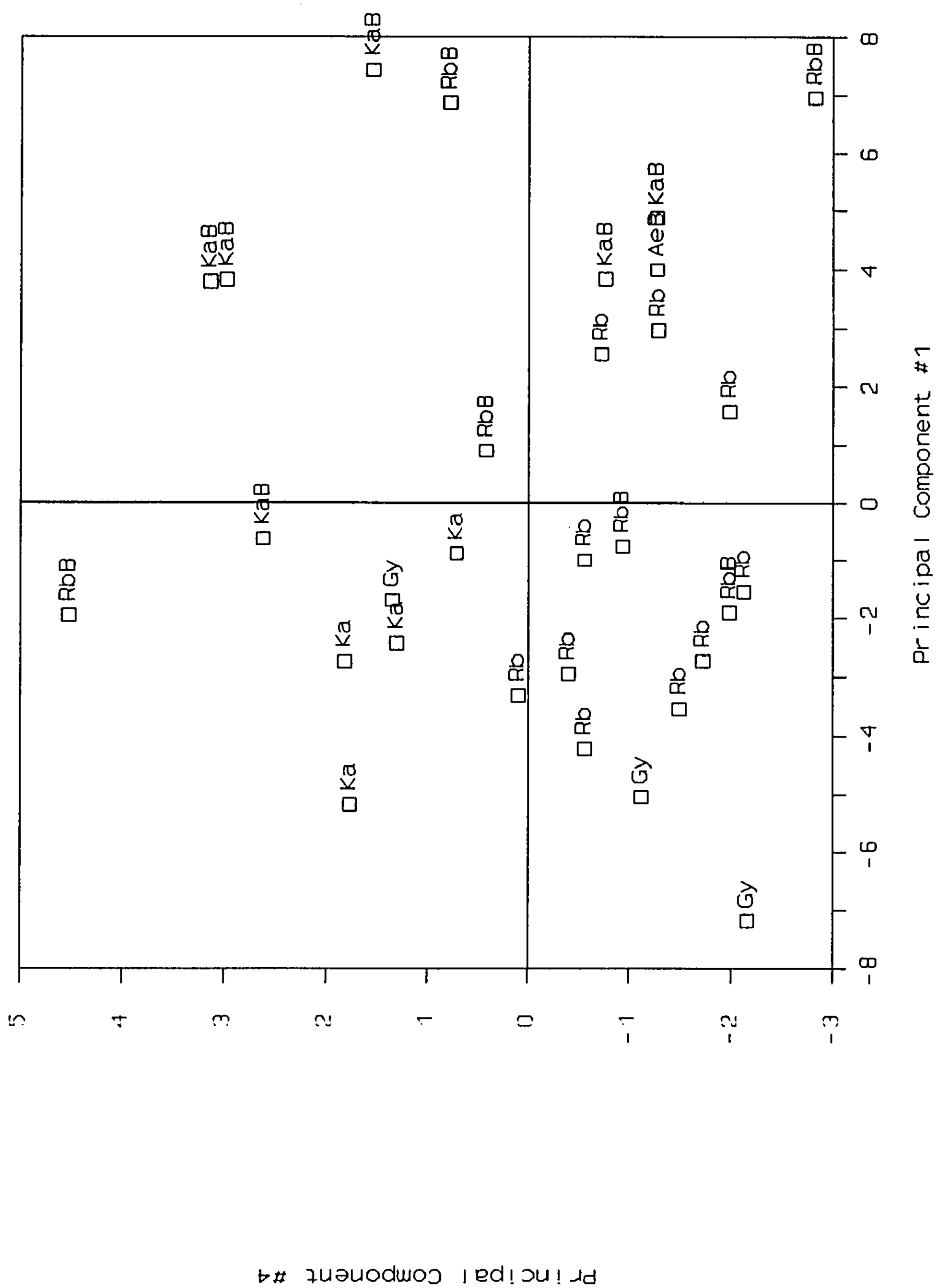

Figure 4.3. Plot of forest floor and pit principal components with strongest association with MAI.

samples, however, the fewer variables allowed a more direct analysis. Inspection of the MAI - fertility scatterplots found linear and transformed linear associations for 14 of the 22 possible fertility variables. Six pairs of fertility variables had correlations with r values greater than or equal to 0.80. Random substitution of highly correlated variables and examination of adjusted R_2 and SEE values led to the final regression equation in Table 4.6. Examination of the residuals revealed no violations of the regression assumptions.

Site fertility expressed by the surface soil samples (45 cm) represents only 10% of the soil volume represented by the pit samples (450 cm). The depth limitation of surface soil sampling may be balanced by their greater sample size which gives a better representation of landscape fertility than a single pit sample. The surface soil regression had a SEE which increased by 35% and an adjusted R^2 which decreased by 12% when compared to the pit regression in Table 4.2.

The surface soil regression had three of its four fertility variables from the forest floor, implying that the forest floor may reflect soil fertility of the intermediate depths (which were found to have strong association with MAI in the pit regression). Cycling of nutrients from intermediate soil depths to the forest floor occurs by vegetative nutrient uptake and subsequent deposition on the forest floor. The negative regression coefficient of total

Table 4.6. Regression summaries for forest floor and surface soil nutrient contents and descriptive statistics.

Adj. R^2	Standard Error of Estimate	Independent Variables	Reg. Coeff. (B_i)	S.E. of Reg. Coeff.	Partial Reg. Coeff.
0.74	0.481	P L[a]	0.666	0.144	0.622[b]
		K L	-0.425	0.187	-0.329
		K F&H	0.082	0.019	0.472
		Ca A&E	0.258	0.067	0.436
	B_0[c] = 0.747	F Ratio = 21.04		28 df	

Descriptive Statistics:

Variable	n	Mean	Minimum	Maximum	Standard Deviation
		------ m^3 ha^{-1} yr^{-1} ------			
MAI	30	2.84	1.19	4.33	0.97
		-------- Kg ha^{-1} ---------			
P L[a]	29	5	3	12	2
K L	29	6	3	14	2
K F&H	29	12	5	24	5
Ca A&E	29	603	28	8146	1589

[a] - L = litter layer; F&H = fermentation and humus layer; A&E = A and E horizons.

[b] - Partial regression coefficients derived from regressions utilizing standardized variables (z = (x - x bar)/s).

[c] - B_0 = Y intercept of regression equation; df = total degrees of freedom for regression.

K in the litter layer may be a result of K not being released through decomposition to the F&H layer or the soil. Acid extractable Ca in the A & E horizons had a significant regression coefficient which agrees with the findings of Bowersox and Ward (1972) who found Ca in the A and E horizons (which were sampled separately) was an important contributor to oak site quality in Pennsylvania. TKP in the litter had the greatest contributions of the entered variables as judged by the high partial regression coefficient. Acid extractable K and Ca were about equal in their contributions.

Principal components analysis of the surface soil fertility variables found that 82% of the variation in fertility could be explained by the first four PC's. When the standardized PC's were subjected to multiple regression analysis, only two had significant regression coefficients. The results of the surface soil PC regression are presented in Table 4.7. The PC regression had an increase in SEE of 19% a decrease in the adjusted R_2 of 11 %as compared to the direct surface soil fertility regression (Table 4.6) and was considered to be a poorer expression of the MAI - fertility relationship.

Inspection of the eigenvectors of the significant PC's in Table 4.8 revealed that the first PC had its major loadings from all nutrients in the organic fermentation and humus layers and the A and E mineral horizons, and Ca in the B

Table 4.7. Summaries for forest floor and surface soil principal component regression analysis.

Adj. R^2	Standard Error of Estimate	Independent Variables	Reg. Coeff. (B_i)	S.E. of Reg. Coeff.	Partial Reg. Coeff.
0.63	0.572	PC #1	0.267	0.039	0.777[a]
		PC #4	-0.204	0.094	0.249
	B_0[b] = 2.794	F Ratio = 25.37		29 df	

[a] - Partial regression coefficients derived from regressions utilizing standardized variables (z = (x - x bar)/s).
[b] - B_0 = Y intercept of regression equation; df = total degrees of freedom for regression

horizon to 45 cm. The first PC was interpreted to reflect the importance of forest floor and surface soil to site fertility. The fact that the litter layer does not have major loadings may imply that nutrient uptake and subsequent deposition are not greatly dissimilar between stands which differ in subsolum fertility during any one year, rather nutrient accumulations are a process that becomes more apparent over time. This would explain the high loadings of the F&H layers and the A & E horizons.

The fourth PC is more problematic in its interpretation. Positive loadings were observed for total Ca in the litter layer, for Total Mg and Ca in the F&H layer, and for TKN in the B horizon to 45 cm; none of which appeared in the PC regression in Table 4.6. Negative loadings were noted for TKP in the litter layer, acid extractable K in the A&E horizons, and for TKP and acid extractable K in the B horizon to 45 cm. Only TKP appeared in the regression equation in Table 4.6. The interpretation of the fourth PC illustrates a major drawback to principal components analysis, that is trading easily interpreted variables that may exhibit multicollinearity for uncorrelated variables which are difficult to interpret (Jackson 1983).

Plotting of the significant PC's in Figure 4.4, reveals a poorer discrimination of subsolum banding was achieved when compared to the pit PC's in Figure 4.3. This strengthens the assumption that the forest floor and surface soils give a distorted representation of subsolum fertility.

Table 4.8. Eigen values and vectors for principal components with significant regression coefficients: Forest floor and surface soil samples.

Nutrient accumulation	Principal Component #1	Principal Component #4
Eigen Values	7.9	1.4
% Variance	44	8
Eigen Vectors:		
N-L	0.129	0.071
P-L	0.160	-0.206
K-L	0.208	0.119
Ca-L	0.177	0.361
N-F&H	0.295	0.106
P-F&H	0.281	-0.133
K-F&H	0.293	-0.017
Mg-F&H	0.271	0.259
Ca-F&H	0.299	0.259
N-A&E	0.205	0.090
P-A&E	0.271	-0.137
K-A&E	0.221	-0.424
Mg-A&E	0.198	-0.066
Ca-A&E	0.265	0.106
N-B to 45cm	0.188	0.215
P-B to 45cm	0.146	-0.492
K-B to 45cm	0.207	-0.365
Ca-B to 45 cm	0.308	0.011

[a] - L = Litter organic layer; F&H = Fermentation and Humus organic layers; A&E = A and E soil horizons; B to 45 cm = B horizon to 45 cm.

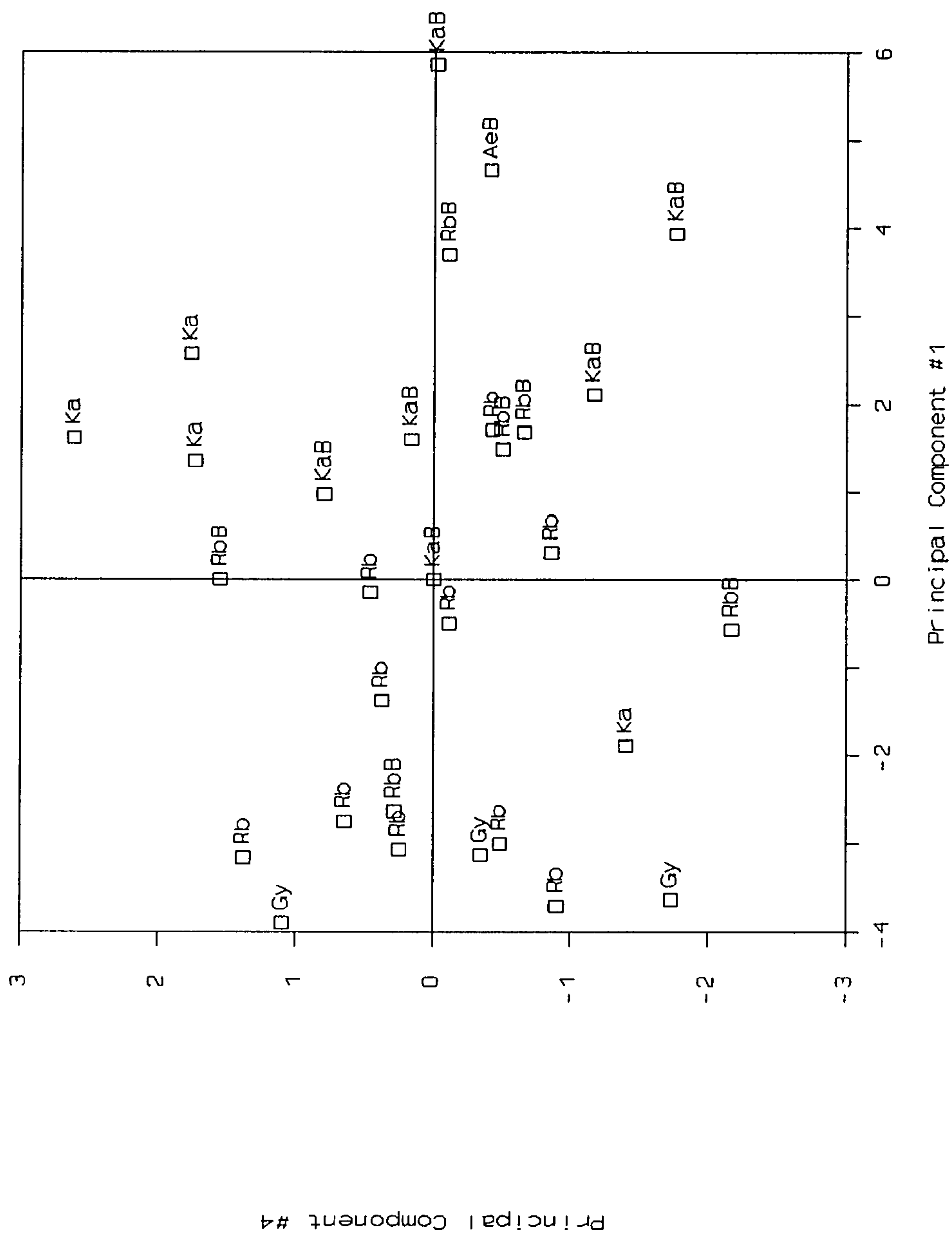

Figure 4.4. Plot of forest floor and surface soil PC's having the strongest associations with MAI.

CONCLUSIONS

It is acknowledged that factors such as temperature, light, tree genetics, and stand history play important roles in tree growth and site quality (Carmean 1975, Grigal 1984; Spurr and Barnes 1973). In addition colloidal soil separates have a great influence in the moisture and nutrient supplying power of soils making effects due to nutrients and available water difficult to separate (Coile 1952, Voigt et al. 1957, and White and Wood 1958). No attempt was made to try and separate the effects of moisture from those of fertility, or to inspect other influences on stand growth.

Results from both the pit and surface soil regressions rejected the null hypothesis of no association between MAI and fertility. Results of the pit regression rejected the null hypothesis that soil fertility below 30 cm has no association with MAI.

Carmean (1975) states that a soil-site examination can be considered successful if 65 to 85 % of the variability is explained. By this criterion both the pit (to 450 cm) and surface soil (to 45 cm) accumulations were successful estimators of MAI with adjusted R^2 values of 0.86 and 0.74, respectively. With a SEE of 0.357, the pit nutrient accumulations estimated MAI with more precision than the surface nutrient accumulations (SEE of 0.481).

The principal component regressions were marginally successful estimators of MAI as determined by Carmean's yardstick, with adjusted R^2 values of 0.67 for the pit samples and 0.63 for the surface soil samples. The pit PC's with significant regression coefficients were fairly straight forward to interpret. The eigenvector of the fourth PC had loadings which corresponded strongly with the variables chosen in the pit regression analysis. Although this PC explained less of the variation in soil fertility than the other two significant PC's, it had a strong relationship with MAI.

The pit samples had a much greater soil volume which could potentially be exploited by tree roots than the surface soil samples. However, the regressions utilizing the pit samples were only slightly stronger than those with the surface soil samples. The SEE of the surface soil regression was 35% greater than that of the pit regression, but this represents an increase of only 4% when compared to the mean MAI value. From a practical standpoint there was not a great deal of difference between the pit and surface soil regressions and the collection of surface soil samples is by far less time consuming while still providing a reasonable estimate of stand growth. It was unclear whether the performance of the surface soil samples was because they gave a better representation of site fertility due to their larger sample size, or whether they were a nutrient pool critical to stand growth. The results of the correlation analysis in Table 4.3 suggest however, that stratification of soils by banding phase may result in different and possibly more precise regressions.

Correlations of MAI with soil fertility in banded soils revealed stronger associations as depth increased, while unbanded soils had the strongest correlations in the surface depths. Splitting the samples into banded and unbanded fractions would likely result in two different regressions being developed. Unfortunately the sample size of this study did not allow separate regressions to be formulated for banded and unbanded soils.

This study is only a first step in evaluating the influences of subsolum soil fertility on site quality. The reliability of the regression estimates needs to be verified before they are used for forest land evaluation (Mc Quilkin 1976). Further investigation of the MAI - fertility relationship with regard to banding phase needs to be performed. The results presented in this paper suggest that more attention needs to be paid to subsolum features if optimal forest land evaluation is to be obtained, particularly on soils with subsolum textural strata.

ACKNOWLEDGEMENTS

The Ecological Classification System project was funded by the USDA Forest Service. Special thanks are extended to Mr. David T. Cleland whose tireless efforts of in behalf of the ECS project allowed this paper to be undertaken, to Dr. Phu V. Nguyen for sharing his expertise on laboratory methodologies; to Dr. Donald Zak for his help in soil sample collection, and to Dr. George Host and Mr. Steven Westin for collection of understory vegetation and productivity measurements, respectively. The contributions of the many individuals who assisted in laboratory analysis and preparation is greatly appreciated.

Particular appreciation is extended to Dr. C.W. Ramm, Associate Professor of Forest Biometrics for MAI data, statistical consulting, and review comments.

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Chapter 5.

Conclusions

Soil fertility was investigated across a range of regional stand productivities and the distribution and variability of nutrient and organic carbon contents to depths of 45 cm or 4.5 m were evaluated. The influence of subsolum textural strata (or banding) upon soil fertility was of particular interest. In addition, various aspects of the relationship between soil fertility and stand growth were examined. These examinations led to several notable results.

Regional examination of MAI and TKN and TKP contents in forest floor and surface soil samples found that almost 70% of the variation in MAI was explained by a regression equation with TKN and TKP contents in the A and E horizons and TKN in the fermentation and humus layers as significant independent variables. The partial correlation coefficients for all three fertility variables were similar, indicating comparable contributions of each towards explanation of variation in MAI.

Investigations of sludge application to oak stands in northern lower Michigan found fertility increases in the forest floor and surface soil (to 45 cm) persisting two years after application. When TKN and TKP means for sludge and control stands were entered into the regional regression, a significant (29%) increase in MAI was predicted as a result of sludge application. This prediction was supported by increases in basal area and diameter growth of 44% and 66%, respectively. The duration of the fertility increase due to sludge fertilization is not known, however, if site fertility increases can be maintained, long-term site quality increases are predicted.

Examination of the distribution of nutrient or organic carbon contents accumulated by 50 cm depths to a depth of 4.5 m displayed two distinct patterns. Nutrients associated with organic matter (TKN and TKP) rapidly decreased with depth, while those associated with the mineral soil (acid extractable K, Mg, and Ca) increased with depth. Forest floor contents of all nutrients were only a fraction of those contained in the mineral components to 4.5 m.

Grouping samples by soil series resulted in general patterns of increasing fertility with increasing stand growth from the forest floor to 200 cm. Below this depth the slightly less productive Rb series displayed higher nutrient contents than the Ka series. Nutrient increases beneath the 200 cm depth, most notable for the Rb series, were thought to be due to banding. The only significant series differences consistently found by Duncan's mean separation procedure were between the Gy and Ka series. The AOV on forest floor fertility variables found significant differences between soil series for all nutrients. TKN, TKP, and total Ca in the forest floor revealed significant differences between all three series. The AOV by series groups revealed a poor separation of soil series by soil fertility with only 22% of the nutrient or organic carbon/depth combinations being significantly different.

The use of subsolum textural strata (bands) to phase soil series revealed peaks in soil fertility which coincided with banding depths, implying an increased nutrient supplying power of these bands. The inclusion of the banding phase resulted in a noticeable increase in nutrient contents of the banded phase of a soil series as compared with its unbanded phase. This difference was found at all depths, most noticeably at the 300-350 cm depth. The Ka series was most successfully separated with the inclusion of the banding phase. Although the forest floor AOV again revealed significant differences for all nutrients, the mean separation by Duncan's procedure found only one significant phase difference each for the Rb and Ka series. Differences in forest floor contents may be due to differential "pumping" of nutrients from the soil by vegetation. On sites with greater soil fertility the vegetatative uptake and deposition pumps more nutrients. In this way the forest floor can reflect soil fertility. The poor separation of series phases by the forest floor may be an indication that the processes of uptake and deposition may result in a loss in the contrast between the phases.

Variability of soil fertility generally increased with depth to about 350 cm, below which variability decreased. Grouping samples by soil series resultd in a general pattern of increasing variability of soil fertility with increasing productivity. Inclusion of the banding phase partitioned nutrient content variability more successfully than did soil series evaluations. Unbanded soil series phases had a pattern opposite that of the soil series groupings for the surface 250 cm, the highly productive Ka series being less variable than either the Gy or Rb series. The banded phases displayed marked increases in variability over their unbanded counterpart. Maximum differences in variability between banded and unbanded phases were found at the 300-350 cm depth.

It was expected that phasing the soil series would have resulted in more homogeneous groups, however, this was not the case. The banded phases showed a much greater variability than the unbanded phases. An explanation for this disparity consistent with the data was that the intensity and continuity of the subsolum textural strata was highly variable. Further evaluation of this aspect of banding is needed.

MAI was successfully estimated by both pit (to 450 cm) and surface soil (to 45 cm) fertility variables. TKP in the litter layer and total K in the fermentation and humus layer were common to the two fertility regressions. The pit regressions had slightly stronger associations with MAI than the surface soil regressions. The similarities in precision of the pit and surface soil regressions may be a result of differences in sampling intensity. The more intensive sampling effort of the surface soil samples (six sampling points per stand) may represent site fertility across the landscape better than the pit samples (one pit sample per stand). Further investigation of banding influences utilizing a greater sampling intensity needs to be done. From a practical standpoint the determination of presence or absence of banding is quicker and easier than the analysis of FF samples and makes their utilization for routine forest land evaluations more likely.

Regressions with nutrient contents resulted in satisfactory estimation of site quality variables. Both regressions estimated MAI within 10% of mean values. The reliability of regression estimates needs to be verified before these relationships are used in site quality prediction.

Soil fertility variables from the forest floor to 200 cm were found to have significant associations with MAI. When subsolum textural strata were used to phase soil series, increased fertility and variability were found in banded phases as compared to unbanded phases of the same soil series. On soils with sandy surface textures subsolum textural strata can have important influences on site quality and should not be ignored in forest land evaluations.