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Topographic influences on soils and trees within single mapping units on a sandy outwash landscape

A.B. Hairston[1] and D.F. Grigal
Departments of Forest Resources and Soil Science, University of Minnesota, St. Paul, MN 55108, USA

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ABSTRACT

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Topographic variation in soil properties and forest productivity within single mapping units as defined by both forest and soil type was investigated in mature northern pin oak stands (*Quercus ellipsoidalis*) on an outwash plain in Minnesota, USA. Tree growth, soil water, and soil and forest floor nitrogen (N) were measured as indicators of productivity at three slope positions and four aspects. Differences in soil water were highly significant among slope positions ($P<0.001$), in part influenced by the shallow water table at the lower slope positions. Organic matter and total N of the surface mineral horizon also differed among slope positions ($P<0.01$). Organic matter and total N of the forest floor, and N released by anaerobic incubation from the surface mineral soil, differed among aspects ($P<0.1$). Twenty-year radial growth rate of site-index trees was significantly different among both slope positions and aspects ($P<0.1$), but total wood volume, basal area, and site index did not differ significantly with topography. Although the study sites had subdued topography and were located on single mapping units, they contained significant topographically related variation in soil properties. Stratified sampling for soil-related properties by topographic position, even in subdued terrain, would help reduce the apparent variation commonly found in these properties.

INTRODUCTION

Spatial variability hinders estimation of soil properties such as nitrogen (N) that are keys to forest productivity (Keeney, 1980). Minimizing natural variation between plots subjected to treatments is important for determining the effects of those treatments (Lloyd and McKee, 1983). Topography, one of the five soil-forming factors (Jenny, 1941), is a fundamental source of variability in soils. Forest classification schemes have routinely included topographic features (e.g. Hills, 1952; Smalley, 1984), but few studies have

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[1] Present address: 275 West Street, Suite 320, Annapolis, MD 21401, USA.

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investigated variability in soil properties in relation to topography within single mapping units.

This study investigated the link between topography, soil/site characteristics, and tree growth within single mapping units, as defined by the co-occurrence of forest cover type and soil type, in an area of subdued topography. This contrasts with the investigation of such links in areas with more rugged topography or across a region. The specific objective of this study was to determine if measured tree growth, soil N availability, and soil water were consistently related to aspect or position on slope within mapping units in a region of subdued topography.

The advantages of use of topographic information in forest management are clear. Changes in topography can be easily observed and information is readily accessible from maps; direct measurements of tree growth and soil properties are more tedious. Topographic information is becoming more accessible for management of natural resources through the burgeoning use of geographic information systems. The literature agrees that topography influences various environmental factors affecting growth (e.g. soil water, incident radiation) (Sartz, 1972), suggesting that topographic position could be used as an indicator or integrator of the effects of such factors on forest productivity (Carmean, 1975).

The disadvantages of using topographic information are also clear. Use of an additional suite of information to describe a site complicates statistical tests. In addition, simply identifying topographic position does not replace the need for some detailed measurements of soil properties or stand growth. However, topographic information could supplement or refine estimates of properties for stands or soil units by providing better information on the variation around the overall estimate for the unit. For example, if lower slope positions are reliably associated with higher N and upper slopes with lower N, then the variation in N over the entire unit is not random and this information can be considered in either intensive forest management activities or research studies (Lloyd and McKee, 1983).

METHODS

Study site and experimental design

The study was conducted in 1987 at Cedar Creek Natural History Area, Minnesota, in northern pin oak stands (*Quercus ellipsoidalis* E.J. Hill). Cedar Creek is located in the Anoka Sand Plain in east–central Minnesota (45°25′N, 93°10′W). The area has sandy to sandy loam soils derived from well-sorted glacial outwash. Upland areas are interspersed with peatlands and the area has shallow ground water. Slopes are gentle, usually less than 15%, and local relief ranges up to about 5 m. Upland soils at Cedar Creek, and at the study sites, are mapped as Alfic Udipsamments (Zimmerman series) and Typic Udipsamments (Sartell series). Annual precipitation averages 66 cm at Cedar Creek (Grigal et al., 1974) and there are approximately 2300 growing degree days above 4.5°C (Baker et al., 1985). These climatic properties interact with the sandy soils to create typically dry sites.

This study was based on a split-plot experimental design. Topographic positions were divided into four aspects, the main effects (NE, SE, SW, and NW), and three slope positions, the split plots (upper, middle, and lower). Four random blocks were established to account for expected differences in hill shapes and soil types. Each block consisted of the 12 combinations of slope positions and aspects on a single hill or depression, and on a single soil mapping unit. Two of the blocks were located on the Sartell mapping unit and two on the Zimmerman mapping unit. These two series, which dominate those mapping units, are very similar, consisting almost exclusively of fine sands and primarily differing in the presence or absence of thin (thickness less than 10 mm) bands of loamy sand in the B horizon of the Zimmerman. All slope positions within a block fell within the same mapping unit. Transects were randomly established at each aspect on a slope with uniform stand type and crown closure. One plot was established at each of the three slope positions along the aspect transect. Data were collected for four types of variables: soil/site properties, nitrogen, water, and tree growth.

Soil and site measurements

Soil was sampled to 60 cm by horizon using a closed-bucket auger. Samples were air-dried within 3 days of collection. The soil was sieved with a 2 mm sieve; no significant coarse fragments were found at Cedar Creek. Forest floor and mineral bulk density samples were collected concurrently. Forest floor was collected within a sampling ring (140 cm^2), with two samples per plot. Total forest floor depth was measured at four locations within the ring. Bulk density of the surface mineral horizon was sampled using the irregular-hole technique (Howard and Singer, 1981). Soil pH was measured in both water and 0.01 M $CaCl_2$. Particle-size distribution was determined by the modified 8 h hydrometer method (Grigal, 1973). Sand was determined by wet sieving.

Measured site variables included azimuth, slope length, and slope per cent. Azimuth was measured to the nearest 5°; slope length was estimated from existing topographic maps; slope per cent was measured with a clinometer in the immediate vicinity of the plot. Soil temperatures at 10 cm were measured concurrently with gravimetric soil water (May, July, and September). Time of measurement was recorded and used to correct the reading for daily fluctuations to a 12 noon basis. A sine curve was fitted to hourly temperatures below sod on the specific sampling dates from a site 50 km from Cedar Creek (D. Rushy, personal communication, 1988). The curve was then dampened to reflect expected ranges of temperatures at 10 cm over the growing season below a forest canopy (Tajchman and Minton, 1986).

Nitrogen measurements

Nitrogen was assessed using total Kjeldahl N and 2 week anaerobic incubations. Total Kjeldahl N (Page, 1982) was determined for forest floor and surface mineral horizons. Concentrations were converted to grams of N per square meter using soil bulk density. Anaerobic incubations were performed for surface soil horizons (Powers, 1980). After 2 weeks, incubated samples were extracted with 2 M KCl, and ammonium concentrations were determined colorimetrically (Technicon Instruments, Terrytown, NY). Samples from lower slope positions were filtered using activated charcoal to eliminate interference from dissolved organics. Concentrations were expressed in grams of NH_4 per square meter for the surface horizon. Organic matter content of surface mineral horizons was also determined, using loss-on-ignition at 450°C (Goldin, 1987).

Water measurements

Soil water content at each plot was measured three times during the growing season (May, July, and September) at four depths (surface, 0.5, 1.0, and 1.5 m). Soil water in the surface 30 cm was determined gravimetrically. Deeper soil water contents were measured with a neutron soil moisture probe (CPN Model 503). The probe was calibrated for the study area using gravimetric soil water measurements. Water concentrations were converted to depth equivalents using measured and published bulk densities (Grigal et al., 1974).

Growth measurements

Tree growth was sampled using variable-radius plots with a 10 basal area factor (BAF) prism (English). Diameters of tallied trees were measured or estimated. One site-index tree for each plot was selected and measured on the basis of relative vigor, freedom from disease, and current dominance in the canopy. Site index was calculated from published equations (Lundgren and Dolid, 1970). Increment cores including the most recent 20 years of growth were collected from the site-index tree. The cores were measured in 5 year increments using a digitizer and integrated software (Marian Erikkson and Doug Meisner, personal communication, 1987).

Plot volumes were calculated using equations from Gevorkiantz and Olsen (1955). Total height for all trees on the plot was estimated from diameter and site index using equations of Hahn (1984). To avoid bias from use of single site-index trees, average site indices for each block were used in height estimation. Basal area and average diameter at breast height were also calculated.

Data analysis

Analysis of variance was used to investigate differences in variables related to slope position and aspect. Although some exploratory regressions between measured variables were carried out, no strong linear or curvilinear relationships were found. Analysis of covariance was used because soil characteristics such as soil texture, pH, temperature, and organic matter were hypothesized to affect the variation in soil water or nitrogen with slope position or aspect. However, no covariates were significant.

Variables were checked for non-normal distributions using probability plots and for homogeneous variance using Bartlett's test. To homogenize the variance, log transformations were used for soil water content for May, July, and September. The Kruskal–Wallis (K–W) test, a nonparametric one-way analysis of variance, was used for total N concentration and content of the surface mineral soil because these variables did not meet assumptions of homogeneous variance. Outliers that were well beyond the range of the remainder of the data, or were the result of measurement error, were deleted. One outlier each was removed from July surface water to 30 cm (measurement error), organic matter of the surface mineral soil (measurement error), site index (anomalously young roadside tree), and per cent silt+clay (anomalous high value).

RESULTS

Results of this study must be considered in the context of the characteristics of the Cedar Creek area as described above; slow-growing oak stands on sandy soils with a shallow water table and gentle topography (Table 1).

Differences in soil water content among slope positions at Cedar Creek were striking. Because of the shallow water table and permeable, sandy soils, soil water content differed sharply with small changes in slope position or elevation. Cumulative soil water measurements to 175 cm in May, July, and September all differed significantly among slope positions (Table 2). Greatest differences were between the lower slope position and the two upper positions, although the LSD indicated significant differences among all positions (Table 2).

Soil water also differed significantly by aspect for all sampling dates (Table 2). However, the extremes of soil water occurred on east- and west-facing aspects, with western aspects having higher soil water content (Table 2). These results do not conform to the standard expectation that southwestern aspects tend to be the driest. At Cedar Creek, minor variations in the water table

TABLE 1

Selected means of soil water, soil nitrogen, other soil characteristics, and tree growth measures at Cedar Creek Natural History Area, MN, 1987 ($n=48$)

Variable	Mean	Standard deviation
Tree volume (m^3 ha^{-1})	199	64
Site index at 50 years (m)	17[a]	3
Radial growth of trees used for site index (mm year^{-1})	5.05	1.60
July soil water to 30 cm (% dry wt.)	10[a]	4
July soil water to 175 cm (cm)	25	15
Soil organic matter to 10 cm (g m^{-2})	5950[a]	3090
Soil total N to 10 cm (g m^{-2})	80	31
pH in 0.01 M $CaCl_2$, A horizon	4.3	0.3
Silt+clay to 60 cm (% dry wt.)	9.9[a]	3.4
Slope %	8.5	3.5

[a] Single outlier deleted, $n=47$.

TABLE 2

Soil water content (in cm within 0–175 cm soil depth) and results of tests of differences among topographic variables for Cedar Creek, MN, 1987

Date	Slope position						
	Mean				ANOVA results[a]		
	Upper	Middle	Lower	LSD[b]	F	MSE$^{1/2}$	P
May	17	19	46	0.2	76	0.247	0.00
July	15	17	44	0.1	105	0.228	0.00
Sept.	11	13	39	0.2	134	0.237	0.00

Date	Aspect							
	Mean					ANOVA results[c]		
	NE	SE	SW	NW	LSD	F	MSE$^{1/2}$	P
May	24	26	29	30	0.2	6.7	0.130	0.01
July	23	23	27	28	0.2	5.1	0.134	0.03
Sept.	19	19	24	23	0.2	4.0	0.210	0.04

[a] Degrees of freedom are 2 and 24.
[b] Fisher's protected least significant difference at the 0.05 level.
[c] Degrees of freedom are 3 and 9.

rather than exposure to solar radiation and evaporative stress apparently controlled soil water at the measured depths.

Nitrogen-related measures in the soil, including total N, anaerobic incubation, and organic matter, were more variable than soil water. Although N availability would be expected to differ with large differences in soil water, the N measures lacked clear trends among slope positions. Differences existed in total N ($P<0.05$) and organic matter content of the forest floor ($P<0.10$) and 2 week anaerobic incubations of mineral soil ($P<0.10$) among aspects (Table 3). No clear differences were found for these variables among slope positions.

TABLE 3

Means and tests of differences among soil N variables, Cedar Creek Natural History Area, 1987

Variable	Slope position						
	Mean				ANOVA results[a]		
	Upper	Middle	Lower	LSD[b]	F	MSE$^{1/2}$	P
Forest floor							
Organic matter (g m^{-2})	3140	3650	3520	480	0.6	1020	0.56
Total N (g m^{-2})	17.6	17.3	19.9	2.5	1.04	5.39	0.37
Soil to 10 cm							
Organic matter (g m^{-2})	4610	5220	7300	680	5.8	5560	0.01
Total N (% dry wt.)	0.044	0.045	0.072	0.001	9.7	0.020	0.00
Anaerobic incubation (g NH$_4$ m^{-2})	1.7	2.0	1.7	0.43	0.52	0.913	0.60

Variable	Aspect							
	Mean					ANOVA results[c]		
	NE	SE	SW	NW	LSD	F	MSE$^{1/2}$	P
Forest floor								
Organic matter (g m^{-2})	3480	2680	3920	3730	700	3.7	854	0.06
Total N (g m^{-2})	17.7	15.1	19.8	20.7	3.4[d]	4.5	1.35	0.03
Soil to 10 cm								
Organic matter (g m^{-2})	4920	6770	5470	6640	940	2.2	1690	0.16
Anaerobic incubation (g NH$_4$ m^{-2})	1.5	1.8	1.6	2.2	0.5	3.0	0.683	0.09

[a] Degrees of freedom are 2 and 24 (2 and 23 for soil organic matter).

[b] Fisher's protected least significant difference at the 0.10 level.

[c] Degrees of freedom are 3 and 9.

[d] LSD at the 0.05 level.

TABLE 4

Radial growth rate for site-index trees, volume, and basal area by slope position and aspect, and results of tests of differences at Cedar Creek Natural History Area, MN, 1987

Variable	Slope position						
	Mean				ANOVA results[a]		
	Upper	Middle	Lower	LSD[b]	*F*	$MSE^{1/2}$	*P*
Radial growth ($mm\ year^{-1}$, breast height)	5.8	4.8	4.6	3.5	2.8	0.63	0.08
Volume ($m^3\ ha^{-1}$)	193	191	212	19	1.3	40.8	0.29
Basal area ($m^2\ ha^{-1}$)	26	27	29	4	1.6	8.8	0.23

Variable	Aspect							
	Mean					ANOVA results[c]		
	NE	SE	SW	NW	LSD	*F*	$MSE^{1/2}$	*P*
Radial growth ($mm\ year^{-1}$, breast height)	4.4	5.7	5.0	5.1	4.1	3.2	0.45	0.08
Volume ($m^3\ ha^{-1}$)	201	192	197	204	57	0.031	103	0.99
Basal area ($m^2\ ha^{-1}$)	28	26	28	28	7	0.035	13.1	0.99

[a] Degrees of freedom are 2 and 24.
[b] Fisher's protected least significant difference at the 0.10 level.
[c] Degrees of freedom are 3 and 9.

However, organic matter content of mineral soil differed significantly among slope positions, increasing at lower slope positions where litter would be expected to accumulate (Table 3). Total N content ($g\ N\ m^{-2}$) of the surface mineral soil also differed among slope positions (K–W test, 5.32; $P=0.07$; assuming a χ^2 distribution with 2 df), but not among aspects (K–W test, 4.07; $P=0.25$; assuming a χ^2 distribution with 3 df) (not tabulated). Because of the strong influence of soil bulk density on measures of content, we also tested N concentration of the surface mineral soil. Concentration also showed significant differences among slope positions (K–W test, 14.6; $P=0.001$; assuming a χ^2 distribution with 2 df), but not among aspects (K–W test, 3.46; $P=0.325$; assuming a χ^2 distribution with 3 df).

Even though significant differences in the N variables among aspects were found using analysis of variance, the order of the means was not consistent. Organic matter and total N in the forest floor tended to be higher on western aspects (Table 3) where soil water was also higher; 2 week anaerobic incubations produced more N on the northwest and southeast aspects (Table 3). Many of the variables such as pH and temperatures in May, July, and September, expected to influence soil N availability, were more strongly related to slope position than to aspect. Because these variables were measured as averages for the upper 10 cm of soil, they may not have precisely reflected conditions at the interface of the forest floor and mineral soil surface where most N transformations are likely to occur.

Estimates of tree growth and productivity showed some trends with slope position and aspect, but few of the differences were significant. The radial growth rate of the site-index trees over the previous 20 years differed among both slope positions and aspects ($P<0.1$), with higher growth rates on the better-drained upper slope positions (Table 4). Northeast aspects, where the lowest average soil water contents were measured, had the lowest average growth rates. Estimates of total wood volume, basal area, and site index were more strongly related to slope position than to aspect, but these trends were not significant, even at the 0.10 level.

DISCUSSION

Soil water content clearly differed among slope positions. Although differences in some soil N measures were significant, they did not vary with topography as consistently nor as strongly as did soil water content. Because soil N measurements were averages over either a 10 cm depth or to the bottom of the A horizon, differences in N availability near the surface may have been subdued by the averaging. The magnitude of differences in soil properties is noteworthy considering that slopes are generally less than 15% in the subdued topography, and that all measurements were made within one forest type on a single soil mapping unit. Greater differences in soil properties would be expected among forest types or markedly different soils.

Although soil properties differed with topography, these differences were not strongly reflected by differences in tree growth in the northern pin oak at Cedar Creek. Although differences in tree growth measures in relation to topography were not statistically significant, they showed some trends by slope position and aspect. The lack of significance is probably related to the shallow water table, to characteristics of the present stand, and to other influences such as stand history. The pin oak stands at Cedar Creek are 40–80 years old, and are experiencing decreasing growth rates and increasing incidence of disease. Examination of the increment cores suggests that competition for light, intactness of branches, insects, and disease affected individual tree growth rates, possibly masking effects of site. Younger, more vigorous stands would be more likely to express potential site productivity and to have been subjected to fewer disturbances. Age differences in these naturally regenerated stands might also be affecting volume estimates. The relationship between volume and age is not clear without more complete data on age distributions within the stands.

Topographic differences have often been reported to be significantly related to differences in both soil properties and forest productivity, but the data for such reports are usually collected in areas of considerable local relief (e.g. Franzmeier et al., 1969; Auchmoody and Smith, 1979; Hicks and Frank, 1984; McNab, 1989). Some reports also indicate that in regions with more subdued relief, topographic variation can also be important. For example, growth responses of pine to different site preparation methods and fertilization were related to small changes in drainage and to topographic position in Louisiana flatwoods (Haywood, 1983). Frost damage to seedlings in depressions is a common topographically related problem for growth and survival (Stoeckeler, 1963). Our data add to those indicators of the potential importance of topographic variation in regions of subdued relief.

We found that the usefulness of topographic position as a direct predictor of forest productivity was limited by site-specific characteristics, and by the complex interactions of factors affecting growth. Even though topography could not wholly substitute for actual measurements of soil water, N, and other growth factors, this study demonstrated that predictable trends of such properties with topography do occur. On a whole-stand basis, variables such as soil water content and organic matter in the surface mineral soil had large standard deviations relative to their means (Table 1). These variables also showed some of the more predictable variation among slope positions. Stratified sampling based on topography would provide more precise estimates of stand averages. Information collected in this way would increase the utility of soil information or of forest stand estimates that are otherwise presented as simple averages encompassing all topographic positions. Appreciation of topographically induced variation would also help in design of efficacious experiments in forest systems.

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