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Topographic variation in soil water and nitrogen for two forested landforms in Minnesota, USA

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Abstract

Relationships between topographic position and soil water, soil nitrogen (N), and tree growth were examined on two regional landforms in Minnesota, USA. The study was conducted in northern pin oak stands (*Quercus ellipsoidalis* E.J. Hill) on an outwash plain, and in aspen stands (*Populus tremuloides* Michx.) on a ground moraine complex. Three slope positions (upper, middle, lower), four aspects (NE, SE, SW, NW) and concave and convex plan (across-slope) curvature were compared.Differences in soil water were significant ($p<0.05$) among slope positions at both locations, but they differed more strongly in the subdued outwash plain than in the steeper moraine due to a shallow water table. Only soil water in lower slope positions in the moraine differed significantly between concave and convex across-slope shapes ($p\leq0.05$). In the outwash plain, organic matter and N of the upper soil horizon were related to slope position, while organic matter and total N in the forest floor and anaerobically released N in the upper soil horizon were related more strongly to aspect. In the moraine, N variables did not differ significantly by topographic position. In the outwash plain, tree growth rates differed by slope position and aspect; in the moraine, tree volume (but not growth rate) differed by slope position ($p<0.10$). Assumptions about differences in soil properties among topographic positions that are based on generalized models should be tempered by unique influences of landform and soil materials.

1. Introduction

The association between topography and soils has long been recognized and studied (Milne, 1936; Ruhe, 1975; Jenny, 1980). For several decades, researchers have attempted to understand and quantify the relationship between topography and the availability of water and nutrients to help predict forest site productivity (Carmean, 1975). Because the majority of such studies have been carried out within a single physiographic region, comparison of results between areas is complicated by differences in both location and methodology. Few

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studies have examined this association among different regional landforms, areas where surface topography reflects a particular set of geomorphic processes.

The objective of this study was to compare soil water and soil N, two soil properties important to tree growth, among topographic positions in two contrasting landforms. Although various nutrients are required for plant growth, N was investigated because it is scarce in most parent materials and is widely regarded as an important factor limiting growth on forest soils in the northern temperate zone (Mahendrappa et al., 1986).

Availability of soil water and nutrients is usually assumed to increase downslope based on fundamental paradigms such as Milne's catena concept and Jenny's factors of soil formation (Milne, 1936; Jenny, 1980). Gravity drives downslope movement of water, sediment and organic material, and aspect modifies soil temperature and evaporative stress from sun and wind. Downslope increases in soil water or N have been frequently documented (Aandahl, 1948; Ruhe, 1975; Jenny, 1980; Schimel et al., 1985; Butler et al., 1986). Mechanistic equations have been developed to predict surface saturation zones from surface topography and soil transmissivity, blending effects of hydraulic gradient and lateral flow, based on the importance of topographic controls on water movement (O'Loughlin, 1986).

The paradigm of changes in soil water or nutrients with topography is heuristically valuable. However, characteristics of particular landforms may create conditions quite different from theory. For example, Kadmon et al. (1989) found increased soil water contents and more vegetation at higher topographic positions in the Negev desert, where bedrock ridges captured more water than lower soil-covered slopes. Barnes and Harrison (1982) found greater available soil water in surface soils on ridges than in swales in the Nebraska sandhills, attributed to differences in soil texture and plant utilization. Giblin et al. (1991) found dramatic differences in total amounts of N, P, and C along a riverside toposequence in Alaska, but high N pools were not confined to downslope positions.

Aspect has been found to influence forest productivity in some circumstances (Trimble and Weitzman, 1956, in the Appalachians; Einspahr and McComb, 1951, in Iowa) but not in others (Sartz, 1972, in Wisconsin). Distinct differences in soil moisture among aspects have been documented in dryland farming regions (Hanna et al., 1982). Plymale et al. (1987) found that a northeast-facing forest had higher N levels than a southwest-facing stand, although forest types and aspect both differed. The extent to which aspect or slope position affects soil properties or growth may depend on climate, gradient and geology.

Since some studies have shown orderly changes in soil water or nutrients with topography, differing patterns must be due to certain attributes or processes that may be peculiar to a study site or more widespread in a region or climatic zone. Using mathematical modelling, Anderson (1982) showed that hillslope topography was unimportant for soil water movement on slopes of less than 10°. A field study in silty soils in England also found little consistent relationship between topography and soil water status on 11° slopes (Burt and Butcher, 1985). Anderson and Burt (1990) suggested that phenomena such as pipeflow, where water flowing through large cracks or voids bypasses the soil matrix, could invalidate the connection between topography and soil water, even on steep slopes. This paper presents a comparison of an outwash plain site with slopes less than 10° and a moraine site with slopes greater than 10°.

Some recent studies on sedimentation and soil development have illustrated the importance of plan (across-slope) curvature as well as slope profile position and gradient, with concave footslopes maximizing sediment accumulation (Pennock and Acton, 1989; Pennock and De Jong, 1987, 1990). Soil water and organic matter would also be expected to vary with plan and profile curvature because similar hydrologic and geomorphic processes govern their movement. Other slope attributes such as slope length, total relief, and position with respect to the regional groundwater gradient affect the relationship of slope position and aspect to soil water and nutrients.

The studies cited above are widely dispersed geographically, with different climates and with vegetation ranging from desert to forest. In similar regions or climates, soil properties that are important to tree growth may vary due to differences in regional landform as well as in local topography. Basic forces such as gravity or solar radiation that underlie the association of topography and soils operate on every landform, but the extent to which characteristics of the landform translate these forces into differing patterns of soil properties is not well understood.

2. Methods

2.1. Location

The study was conducted on an outwash plain at Cedar Creek Natural History Area and on a ground moraine at Marcell Experimental Forest, Minnesota. Cedar Creek is located on the Anoka Sand Plain, an outwash plain in east-central Minnesota (45°25′N, 93°10′W). The area has sandy to sandy loam soils (Typic and Alfic Udipsamments) interspersed with peatlands, a shallow water table at 0 to 5 m, and gentle slopes. Horizons were based mostly on the presence of organic matter; there were occasional thin lenses of finer-textured soil, but surface texture rarely dropped below 85% sand and the material lacked coarse fragments. Slopes average 8.5% (5°), rarely exceeding 15%; topographic relief is about 6 m. Soil available water capacity (− 10 to − 1500 kPa) is 0.07 to 0.08 cm/cm (Grigal et al., 1974). Upland forests are mostly northern pin oak (*Quercus ellipsoidalis* E.J. Hill).

Marcell, located in the Itasca Moraine Complex in north-central Minnesota (47°31′N, 93°28′W), has steeper slopes and sandy loam to clay loam soils (Glossic Eutroboralfs). Upper soil horizons are typically sandier than underlying B horizons, which tend to have higher clay and stone contents. Slopes average 20% (11.3°), and topographic relief is about 10 m. Slope lengths at both sites did not exceed 90 m. Soil available water capacity (− 10 to − 1500 kPa) ranges from 0.18 to 0.23 cm/cm (USDA, 1987), greater than that at Cedar Creek. Forests are dominated by quaking aspen (*Populus tremuloides* Michx.) or bigtooth aspen (*P. grandidentata* Michx.), often including paper birch (*Betula papyrifera* Marsh.).

The greater topographic relief and steeper slopes at Marcell were hypothesized to more strongly influence soil properties and tree growth than would the landform of the Cedar Creek area. The parent material did not change dramatically along the slopes at either study location. Precipitation is similar at the two areas, 67 cm of annual precipitation at Marcell (USDA, 1987) compared to 66 cm at Cedar Creek (Grigal et al., 1974), but evaporative stress is higher at Cedar Creek. Cedar Creek has a longer growing season, with approximately 4100 growing degree days above 4.5°C compared to 3300 days near Marcell (Baker et al., 1985).

2.2. *Field and laboratory*

This study focused on slope position and aspect, with a split-plot experimental design that resulted in complete combinations to balance sample sizes. Slope length, gradient, and plan curvature were also assessed and included in the analysis, but were not controlled in the design. Topographic positions were divided into four aspects (NE, SE, SW, and NW) and three slope positions (upper, middle, and lower). Upper slope positions generally correspond to shoulder, middle to backslope, and lower to toeslope positions. Four randomly distributed blocks were established to cluster slope positions and aspects, presuming that soil and slope attributes are more similar closer together than farther apart. Each block consisted of the 12 combinations of slope positions and aspects on a single hill or depression. At each aspect, transects were established on a slope with uniform stand type and crown closure, and slope positions were sampled along the transect. Data were collected for four types of variables: site attributes, tree growth, soil water and soil N.

Measured site variables included azimuth, slope length, and slope percent. Sites were classed as convex or concave across-slope. Soil was sampled by horizon to 60 cm, below which few additional roots occur (Gale and Grigal, 1987). Samples were air-dried within three days of collection to minimize N transformations, sieved through a 2 mm sieve, and coarse fragment content was determined. No significant coarse fragments were found at Cedar Creek. Forest floor and bulk density samples were collected concurrently with soil samples. The forest floor was sampled within a known area (140 cm^2), combining two samples per plot. The bulk density of the surface mineral horizon was determined using the irregular-hole technique (Howard and Singer, 1981).

The tree volume was estimated using variable radius plots with a BAF 10 prism. Diameters of tallied trees were measured or estimated. One tree per plot was selected for measurement of site index (Lundgren and Dolid, 1970) and twenty-year growth rate in increments of 5 years. The total height was estimated from diameter and site index (Hahn, 1984) and plot volumes were calculated (Gevorkiantz and Olson, 1955).

The soil water content was measured at each plot at four depths (surface, 0.5 m, 1.0 m, and 1.5 m) three times during the growing season (May, July, and September). Soil water was determined gravimetrically for the surface 30 cm, and with a neutron probe (CPN Model 503) at 50, 100 and 150 cm. The probe was calibrated for each study area. Soil temperatures at 10 cm were measured on the same three dates as soil water. Temperatures were corrected for daily fluctuations to a 12-noon basis (Hairston, 1988).

Soil N was assessed by the total Kjeldahl nitrogen (TKN) procedure (Page, 1982) for surface mineral horizons and forest floor samples and by two-week anaerobic incubations (Powers, 1980) for surface mineral horizons. These measures assess potentially available N rather than instantaneous plant-available N, and were chosen to represent longer-term site productivity. Concentrations were converted to g m^{-2} to a 10 cm depth. Soil pH was measured in both water and 0.01M $CaCl_2$. Particle-size distribution was determined by the modified 8-hour hydrometer method (Grigal, 1973) for silt and clay and by wet sieving for sand. Organic matter of surface mineral horizons was determined by loss-on-ignition at 450°C (Goldin, 1987).

2.3. Data analysis

Analysis of variance (ANOVA) was used to determine the significance of differences in measurements among slope positions, aspects, and plan curvature. Assumptions of normality were checked using probability plots, and Bartlett's Test was used to detect heterogeneous variance. Abnormal values were identified from box-plots and probability plots, and no more than one outlier per variable was deleted (Hairston, 1988). Log transformations were performed on soil water measurements from Cedar Creek to homogenize variance. Slope-block interaction terms in the split-plot designs were tested because they could affect data interpretation. Soil water and soil N variables were regressed against tree growth measures, but strong correlations were not evident. Slope gradient and length were included as covariates, but did not improve statistical significance in the ANOVAs. Fisher's least significant difference (LSD) was calculated when differences were significant at $p < 0.10$. To compare landform attributes, *t*-tests were performed between corresponding variable means.

3. Results and discussion

The two landforms differed in most of the measured properties (Table 1). The moraine was characterized by higher tree volumes, generally more soil water, and higher forest floor N, although organic matter (OM) and TKN of surface soil were lower. The outwash plain had higher soil OM and the sandy soils held less water, despite a shallow water table.

3.1. Soil water

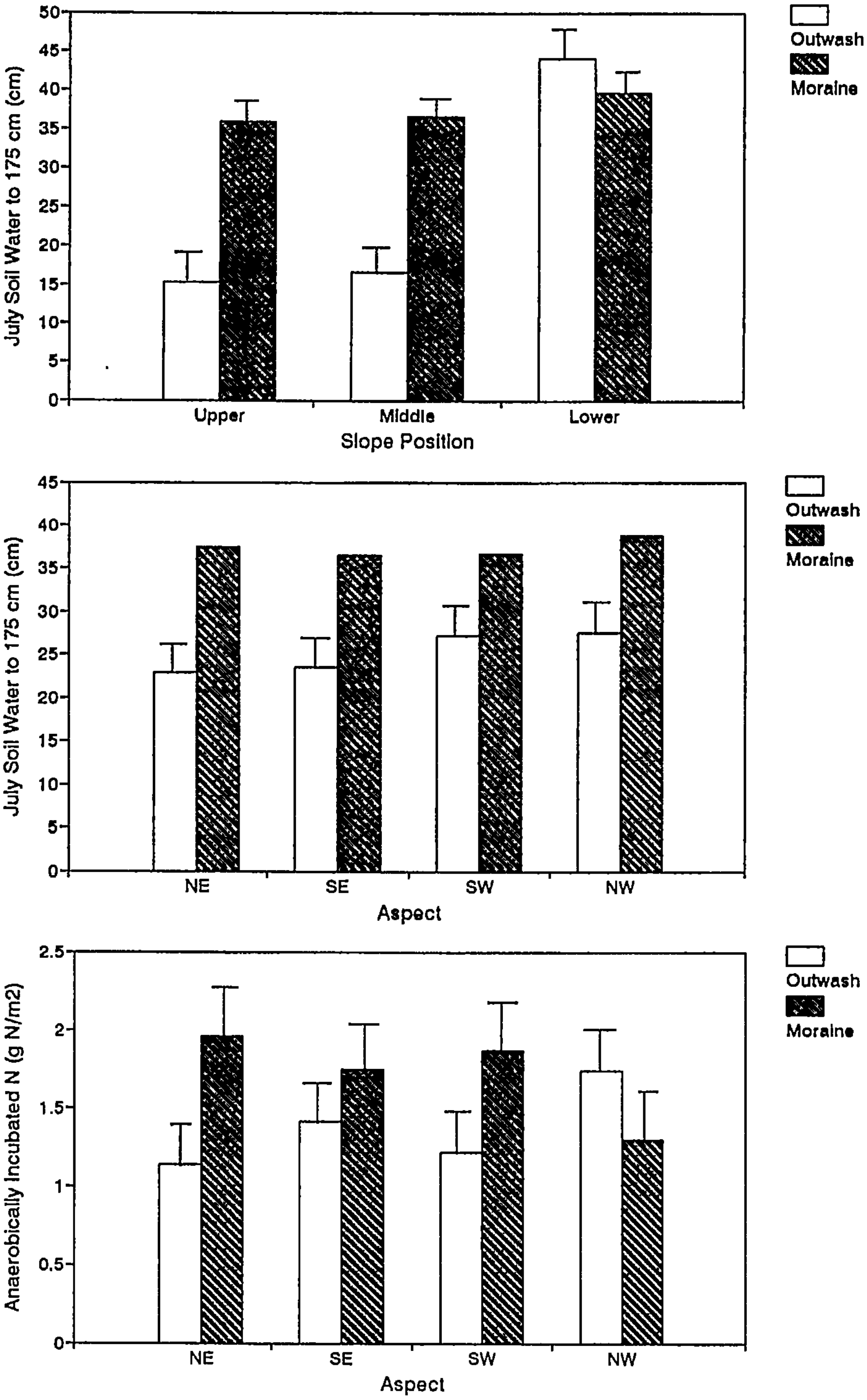
In agreement with the catena concept, soil water was higher at lower slope positions on both landforms for all sampling dates ($p < 0.05$). However, the rate of change along the

Table 1

t-Tests of means for northern pin oak stands on an outwash plain and for aspen stands on a moraine, Minnesota

Variable	Unit	Outwash Mean	Moraine Mean	*t*	df	Prob.
Tree volume	$m^3 ha^{-1}$	199	288	5.3	94	0.00
Site index	m at 50 yr	17	25	17.1	92	0.00
Radial growth	$cm\ yr^{-1}$	0.505	0.569	1.8	94	0.07
May surface soil water[a]	% dry wt	11	16	5.4	94	0.00
July soil water	$cm\ 175\ cm^{-1}$	25	37	5.4	94	0.00
Soil organic matter[a]	$g\ m^{-2}$	5721	4114	3.4	93	0.00
Soil N[a]	$g\ m^{-2}$	80	61	3.2	94	0.00
Anaerobic incubated N[a]	$g\ m^{-2}$	1.4	1.7	2.2	94	0.03
Forest floor org. matter	$g\ m^{-2}$	3442	6065	4.4	92	0.00
Forest floor N	$g\ m^{-2}$	18.3	22.2	2.6	90	0.01
% silt + clay[a]	% dry wt	9.9	34.9	12.9	93	0.00
Slope	%	8.5	20.2	9.1	94	0.00
July soil temp. at 10 cm	°C	20.1	17.7	13.3	91	0.00

[a] Surface mineral soil, 0–10 cm.


July Soil Water to 175 cm (cm)
0
5
10
15
20
25
30
35
40
45
50
Upper
Middle
Lower
Slope Position
Outwash
Moraine
July Soil Water to 175 cm (cm)
0
5
10
15
20
25
30
35
40
45
NE
SE
SW
NW
Aspect
Outwash
Moraine
Anaerobically Incubated N (g N/m2)
0
0.5
1
1.5
2
2.5
NE
SE
SW
NW
Aspect
Outwash
Moraine

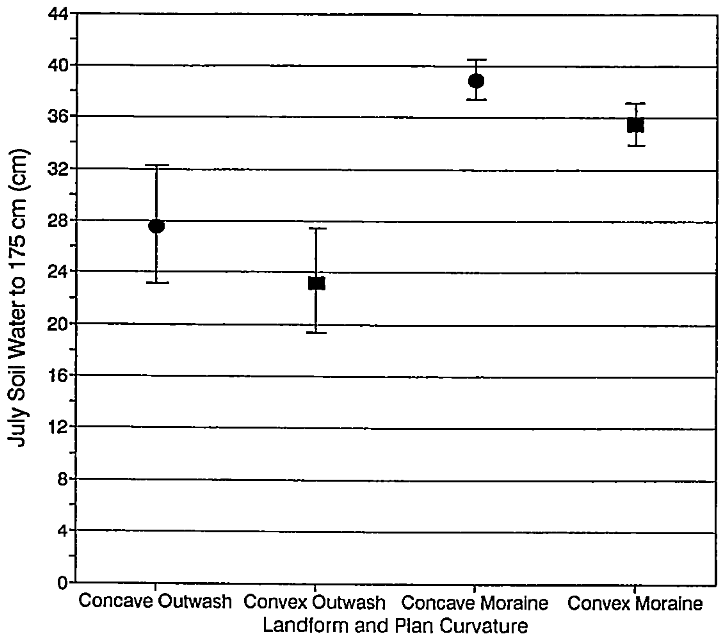


Fig. 2. Soil water storage for concave and convex plan curvature on an outwash plain and moraine in Minnesota in July. Error bars show values of least significant difference. Only the moraine values are significantly different ($p < 0.05$).

slope differed markedly for the two areas, as illustrated by the July measurements (Fig. 1). Additionally, the relationship was not consistent over time or among blocks in the moraine; interaction prevented clear interpretation of the ANOVA. In contrast, soil water varied consistently with slope position through the growing season and among blocks in the outwash plain. The uniformity of the soil materials in the outwash plain probably contributed to the consistency of the relationship, while the shallow water table enhanced the effect of small differences in relief.

Highest soil water contents in July were on the western aspects on the outwash plain ($p < 0.05$) but there were no significant differences on the moraine (Fig. 1). Similar results were observed for the May and September sampling dates. Slightly higher water content on western aspects in the outwash plain may have been related to adjacency to wetlands.

Soil water differed between across-slope concave and convex positions in the moraine but not in the outwash plain ($p < 0.05$) (Fig. 2). When the effect of plan curvature was examined within slope positions, only the lower slope positions in the moraine differed. Maximum soil water was at concave lower slopes, consistent with the findings of Pennock and De Jong (1987).

Fig. 1. Soil water storage and anaerobically released N with respect to topographic position on two landforms in Minnesota in July. Upper error bars depict Fisher's least significant difference. Where absent, differences were not significant ($p < 0.10$).

3.2. Soil nitrogen

For plots at the same slope position and aspect, soil N was more variable than soil water on both landforms. Few of the soil N measures differed significantly among slope positions, and only differences in N from anaerobic incubation were significantly different among aspects for both landforms ($p < 0.10$) (Table 2). The pattern of variation differed with landform, however (Fig. 1). The northwest aspect had the highest N from anaerobic incubation in the outwash plain, but the lowest in the moraine. The relationship on the moraine was complicated by interactions among slope positions and blocks, precluding clear conclusions about the strength of the relationship.

In the outwash plain, forest floor organic matter (OM) and TKN also differed significantly with aspect, and OM and TKN of the surface mineral soil differed by slope position (Table 3). Lowest forest floor OM occurred on the southeast aspect, and highest forest floor TKN occurred on the northwest aspect (Table 3). None of these variables was significantly different on the moraine. The opposite effect was seen for plan curvature. Soil OM and N were significantly higher in concave positions in the moraine, but no significant effects were found in the outwash plain ($p < 0.05$).

Although N levels did not vary consistently, soil temperature, expected to influence N, was quite consistent between landforms for both slope position and aspect. On both landforms, temperatures in July were lowest at 10 cm for lower slope positions, where, incidentally, soil water increased (Table 3). Relationships with aspect were also consistent and logical, with the southwest aspect being the warmest and northern aspects being cooler (Table 3). Despite the consistency in patterns, temperatures did not differ significantly by aspect in the outwash plain, nor by slope position in the moraine. The processes affecting

Table 2
Probability[a] of significance of differences in soil properties among four aspects and three slope positions on two landforms in Minnesota

Variable	Slope position		Aspect	
	Outwash	Moraine	Outwash	Moraine
Forest floor				
Organic matter (g m^{-2})	0.27	0.71	0.06	0.91
Total N (g N m^{-2})	0.29	0.93	0.03	0.27
Surface soil (0–10 cm)				
Organic matter (g m^{-2})	0.03	0.32	0.24	0.42
Anaerobic incubated N (g N m^{-2})	0.61	0.31	0.09	0.09
Soil temp. July (°C at 10 cm)	0.00	0.57	0.29	0.03
Soil water (to 175 cm soil depth)				
May soil water (cm)	0.00	0.93	0.01	0.45
July soil water (cm)	0.00	0.04	0.03	0.48
September soil water (cm)	0.00	0.05	0.04	0.76

[a] Probabilities based on random block/split plot analysis of variance.
Degrees of freedom for tests of aspect were 3, 9 and for slope position were 2, 24.

Table 3
Selected forest floor and soil properties at four aspects and at three slope positions for northern pin oak stands on an outwash plain and aspen stands on a moraine, Minnesota.

Variable	NE	SE	SW	NW	LSD[a]	*F*	Prob.
Forest floor organic matter (g m^{-2})							
Outwash	3480	2680	3920	3730	640	3.7	0.06
Moraine	6660	5860	5620	6090	na[b]	0.2	0.91
Forest floor total N (g m^{-2})							
Outwash	17.7	15.1	19.8	20.7	2.8	4.5	0.03
Moraine	24.2	20.5	18.7	25.5	na	1.6	0.27
July soil temp. at 10 cm (°C)							
Outwash	19.9	20.1	20.3	19.9	na	1.6	0.29
Moraine	17.5	17.9	18.0	17.2	0.5	4.7	0.03
	Upper	Middle	Lower		LSD[a]	F	prob
Soil organic matter (g m^{-2})							
Outwash	4610	5220	7300		1630	4.0	0.03
Moraine	4110	3660	4580		na	1.2	0.32
Soil total N (g m^{-2})							
Outwash	65.9	81.5	92.6		18.4	3.1	0.06
Moraine	61.4	53.0	67.5		na	1.2	0.32
July soil temp. at 10 cm (°C)							
Outwash	20.7	20.5	19.0		0.4	36.8	0.00
Moraine	17.8	17.6	17.5		na	0.6	0.57

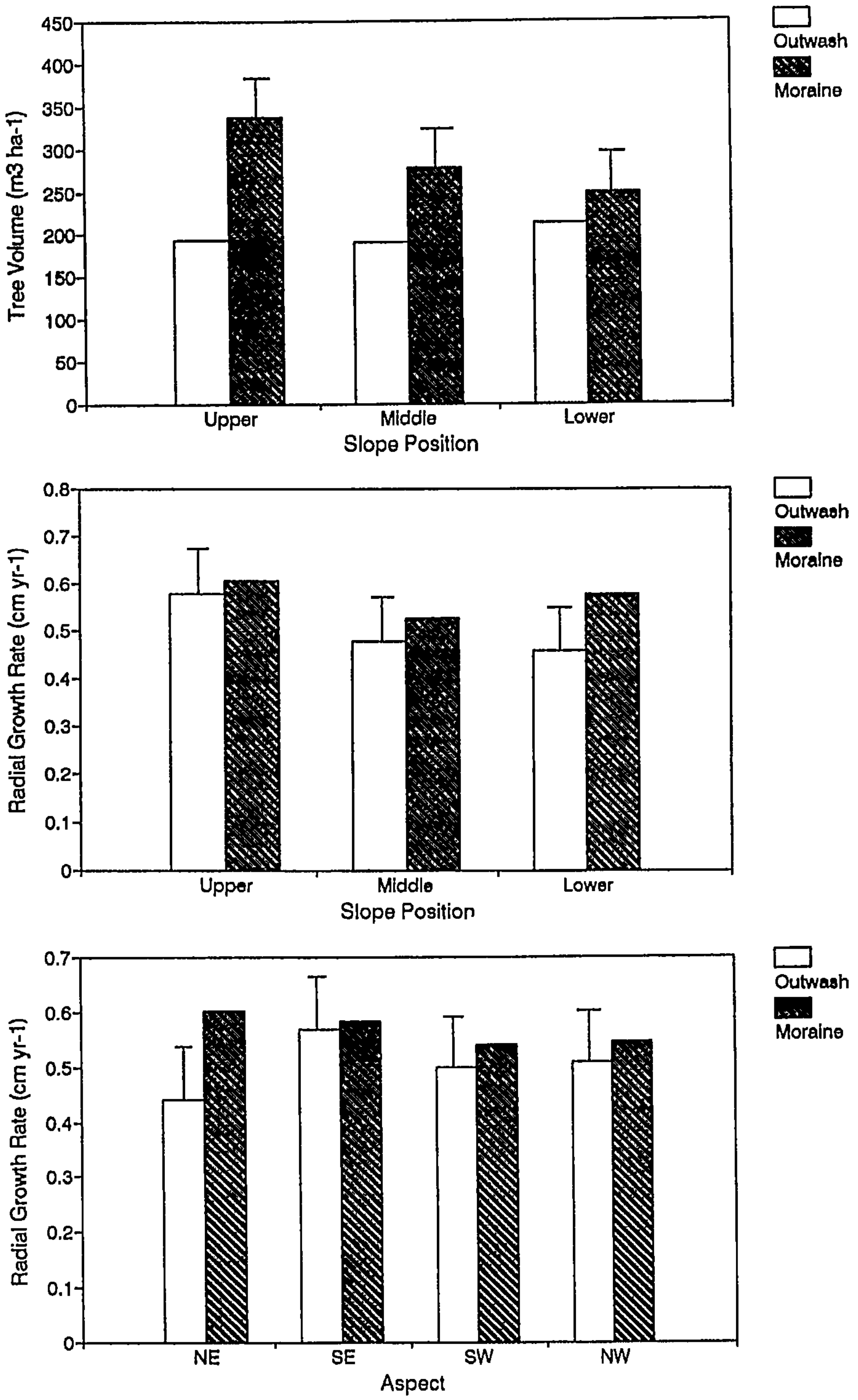
[a] Fisher's protected least significant difference at the 0.10 confidence level.
[b] LSD is not calculated where differences are not significant.

soil N may depend on temperature, but temperatures nearer the surface or biotic factors may be more influential than temperatures at 10 cm.

3.3. Tree growth

Tree radial growth was related to both slope position and aspect in the outwash plain but did not differ significantly in the moraine (Fig. 3). Radial growth rate was significantly lower at lower slope positions in the outwash plain ($p < 0.10$), and highest in upper slope positions at both locations. Poor drainage could be inhibiting growth at the lower slope positions. Growth rates on the northeast aspect were highest on the moraine, but lowest on the outwash plain, although patterns for the remaining aspects were similar (Fig. 3).

Stand volume decreased at lower slope positions in the moraine, but tended to increase on the outwash plain (Fig. 3); similar trends occurred for basal area. These differences were statistically significant on the moraine, but not on the outwash plain, in contrast to differences in radial growth rate ($p < 0.05$).


450
400
350
300
250
200
150
100
50
0
Tree Volume (m3 ha-1)
Upper
Middle
Lower
Slope Position
Outwash
Moraine
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Radial Growth Rate (cm yr-1)
Upper
Middle
Lower
Slope Position
Outwash
Moraine
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Radial Growth Rate (cm yr-1)
NE
SE
SW
NW
Aspect
Outwash
Moraine

Differences in growth characteristics of species and in stand history between the two landforms probably contributed to the irregular growth results relative to topography. The northern pin oak stands on the outwash plain were older and tended to be more unevenly stocked than were the aspen stands on the moraine. Stand age (i.e., years since disturbance) was an important factor in N dynamics on the outwash plain (Zak et al., 1991); such factors could also influence topographic effects.

Tree growth was not closely correlated with the measured soil water or soil N. Although these factors are required for growth, they may not have been limiting at the sites studied, or tree growth may be varying at different scales than were the soil water or soil N attributes measured (Levin, 1992). Light competition, insects, and disease also have major effects on growth and were not measured in this study.

4. Conclusions

Differences in patterns of soil water, soil N, and tree growth relative to topography appeared to depend more strongly on soil properties and landform hydrology than on steepness of slope or amount of relief. Although the moraine landform at Marcell Experimental Forest had greater relief, soil water and N were more strongly related to topography on the outwash plain at Cedar Creek (Table 2). The shallow water table in the outwash plain contributed to strong effects of slope position on soil water, but plan curvature seemed to have little effect in the gentle topography. The fine-textured B horizon in the moraine was observed to limit vertical infiltration, and may have influenced the importance of plan curvature, at least in lower slope positions where significant differences in soil water occurred.

Soil properties varied with topography on both the outwash plain and the moraine, as would be inferred from concepts such as the soil catena and Jenny's soil-forming factors. However, the strength of variation of the different soil properties differed between the landforms, so that variables significantly different among topographic positions on the outwash plain did not differ in the moraine (Table 2). Although this is a case study and not universal proof, these results strongly argue that relationships of soils along a slope or in a landscape cannot be assumed. General relationships such as downslope increase in soil water tend to be valid; however, the rate of change and subsequent effects on plant growth are strongly influenced by soil characteristics such as horizon textures and by geomorphic setting, slope shape in plan and profile, and hydrologic flowpaths (Zaslavsky and Rogowski, 1969; Barnes and Harrison, 1982; Pennock and Acton, 1989). The net effect of inputs such as rainfall or nutrients on growth must take into consideration soil and landform characteristics.

Topographic effects obviously extend beyond their influences on soil properties, and include effects from microclimate (Callaway et al., 1989). However, greater topographic relief does not always translate into stronger influences as would be assumed when applying

Fig. 3. Stand volume and tree growth with respect to topographic position on two landforms in Minnesota. Upper error bars depict Fisher's least significant difference. Where absent, the differences were not significant ($p < 0.10$).

strictly mechanistic models. O'Loughlin (1986) noted the notorious variability of saturated hydraulic conductivity within soil units and additional variation within a soil catena, and relied on calibration with measured data to determine effective transmissivity. Predictions may be improved if underlying spatial patterns are known rather than assumed homogeneous.

Another important result of this work is that the choice of measure can affect the observed strength of the relationship to topography. Several different variables were measured to assess soil water (to 30 cm and 175 cm depths) and N (mineral soil and forest floor TKN and OM, soil N from anaerobic incubation). Each of these evaluates a different facet of the factor, and different relationships with topography result. N from anaerobic incubation was most strongly related to aspect, while soil OM tended to vary with slope position and associated soil water. These results demonstrate that studies of topographic effects depend on the variable being measured as well as the topographic characteristics of the landform.

Generalized predictions of landscape properties based on established paradigms fall short when applied to specific locations. Exceptions may outnumber cases conforming to the rules. Validation and verification of all models, even the most widely accepted conceptual models, must be carried out.

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