Spodosol Development as Affected by Geomorphic Aspect, Baraga County, Michigan

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ABSTRACT

In midlatitude locations with steep slopes, geomorphic aspect can be an important factor in determining spatial variations in soil development. This study examines the influence of aspect on soil development in Baraga County, Michigan, as a means of explaining within-landform variability. The soils are sandy and have spodic morphologies. All are located on steep slopes (45–73%) of contrasting aspect. Ten pedons each from backslopes on north-to-northeast-(N-NE) and south-to-southwest-(S-SW) facing slopes were described, sampled, and compared using standard techniques.

Variation in slope gradient was not, statistically, a determining factor in the differential soil development found here. Aspect has strongly influenced soil development, however, with soils more strongly developed (i.e., more podzolized) on N-NE slopes than on S-SW slopes. Several soil characteristics indicative of strong podzolization were found on N-NE slopes, including higher values of solum thickness and POD index, greater losses of extractable Fe and Al from E horizons and concomitant gains in B horizons, and darker and redder B horizon colors. Soils were generally cooler on N-NE slopes in summer, with essentially similar temperatures under snowpacks in winter. Cooler temperatures and greater amounts of infiltrating water in soils with N-NE aspects may have accelerated podzolization by allowing more organo-metallic complexes to be formed and translocated. Podzolization driven by translocation of amorphous, inorganic compounds appears, however, to be nearly equivalent on sites of differing aspect.

Of the ten pedons on N-NE slopes, nine classified as Spodosols (Entic or Typic Haplorthods) and the other was an Entisol. Seven of the 10 pedons on S-SW slopes classified as Entisols (Udipsamments or Udorthents), and the remaining three were Spodosols.

Spodosols often exist in various stages of development across short distances (Alexander, 1986; Barrett and Schaetzl, 1993). This research is set within Jenny's (1941) functional-factorial model and attempts to explain these differences in soil development, differences that may have formed due to spatial variations in microclimate. The study of spatial differences in soil development is the essence of soil geography and is a focus of this paper.

Surface slope and aspect are critical factors affecting Spodosol development, due (ultimately) to variable solar radiation input at the ground or at the vegetation canopy, or both. In hilly terrain, the incidence angle of the sun varies from one location to another due to differences in local topography and the subsequent partial shading of the landscape (Lee and Baumgartner, 1966). Equatorial latitudes are virtually unaffected by this shading phenomenon because solar radiation is received from angles both north and south of (and always very close to) celestial zenith during the entire year. The effects of aspect are also negligible in polar latitudes because solar radiation is received from many directions throughout the summer daylight periods, and during the winter months it is either not received at all or is at a very low level of intensity. However, in an area of high relief located between 40° and 60° latitude, aspect becomes a major factor in the amount of solar radiation received.

North- and northeast-facing slopes differ from adjoining south and southwest-facing slopes in several climate-related categories. (Hereafter, the terms N-NE and S-SW will be used to refer to north- and northeast- and south- and southwest-facing slopes, respectively). Insolation receipt (Lee and Baumgartner, 1966), soil temperature (Franzmeier et al., 1969; Hutchins et al., 1976; Macyk et al., 1978; Hairston and Grigal, 1994), atmospheric temperature (Cantlon, 1953; Whittaker et al., 1968), soil water (Finney et al., 1962; Carter and Ciolkosz, 1991), atmospheric moisture (Cantlon, 1953; Finney et al., 1962), and wind velocity (Cantlon, 1953; Lieffers and Larkin-Lieffers, 1987) all can vary spatially within a small geographic area, due to aspect. Theoretically, these microenvironmental differences could play a vital role in the development of soils with time.

Previous studies that have analyzed soils with regard to slope orientation and microclimate have not been limited to any geographical area. Franzmeier et al. (1969) studied north and south slopes (36–62%) in eastern Kentucky and Tennessee. In silt loam parent materials over bedrock, they found darker profiles with more organic matter on north slopes. In southeast Ohio, Finney et al. (1962) found thinner A and better developed E and B horizons on southwest slopes. Losche et al. (1970) studied north and south slopes in Virginia and North Carolina. Although the soils in Virginia exhibited very little difference due to aspect, soils in North Carolina located on S slopes were redder, had a higher Fe content, contained more clay in the B horizon, and had thicker sola than did the soils on N slopes. In southeast Michigan, Cooper (1960) found shallow, intensely developed sola on south slopes, and deeper, less intensely developed sola on north slopes. On gently sloping knobs near Alberta, Canada, Macyk et al. (1978) found that aspect and microclimate had a greater effect on soil morphology and physical properties than on the chemical properties (pH, cation-exchange capacity, Fe, Al, etc.). Marron and Popenoe (1986) found that a greater degree of soil development existed on north slopes in California, as indicated by redder and more clay-rich B horizons. In the Western Tien-Shan (central Asia), Stepanov (1967) observed deeper leaching and cooler soil temperatures on north slopes compared with opposing slopes. Hairston and Grigal (1994) observed that Entisols on various slope aspects in Minnesota have different amounts of total N and organic matter.

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Abbreviations: ODOE, optical density of the oxalate extract; Fe_p, Fe content of the pyrophosphate extract; Fe_o, Fe content of the oxalate extract; Al_p, Al content of the pyrophosphate extract; Al_o, Al content of the oxalate extract; GLO, General Land Office; OC, organic C.

Of the numerous studies of soil development and aspect, we know of none that have specifically examined Spodosols. The purpose of this study was to determine if different amounts of development (i.e., greater translocation of mobile materials, thicker horizons, etc.) exist in sandy, Entic Haplorthods on sites of opposite geomorphic aspect. Pedons were described and sampled on steep slopes (45–73%) of contrasting aspect (0° to 45° vs. 180° to 225° azimuth). Morphological and chemical characteristics of paired pedons were analyzed for differences and tested for statistical significance using a paired-comparison approach.

STUDY AREA

The study area is located in NW Baraga County, Michigan, ≈46° 45′N, 88° 30′W (T50N, R34W) and covers nearly 30 km^2 (≈3 × 10 km; Fig. 1). This area was chosen because it has (i) abundant unplowed Spodosols, (ii) consistently deep and uniform, sandy parent materials, (iii) steep slopes, and (iv) a wide array of slope aspect inclinations.

The final retreat of the Wisconsin Glacier from Baraga County occurred following the Marquette readvance, ≈9900 yr BP (Futyma, 1981; Farrand and Drexler, 1985). As the margin of the Marquette ice retreated from the study area, into what is now Keweenaw Bay, ≈10 km to the north, deep deposits of sand and gravel accumulated as outwash or glaciolacustrine sediments, or both (Doonan and Byerlay, 1973). These deposits formed the Baraga Plains, which lie perched above and to the south of the study area. The northwestern edge of the Baraga Plains was subsequently dissected; the study area lies within this dissected escarpment. The escarpment has a dendritic pattern of deep, steep-sided ravines that vary from 15 to 500 m in width and 5 to 60 m in depth, all essentially dry tributaries to Menge Creek, which is the main trunk stream draining the escarpment area (Fig. 1). Ridgetops range from 5 to 30 m in width and ravine bottoms from 5 to 200 m in width. The landscape has a badlands character. The decrease in elevation from the Baraga Plains (average elevation = 400 m) to Lake Superior (elevation = 183 m) across the relatively short distance probably led to the intense dissection that characterizes the escarpment.

The soils of the study area are mapped within a Rousseau–Ocqueoc fine sand complex (sandy, mixed, frigid Entic Haplorthod–sandy over loamy, mixed frigid Entic Haplorthod), dissected, with 15 to 70% slopes (Berndt, 1988). The primary dissimilarity between the two series is that Ocqueoc soils have silty materials within a 2C horizon, which seems to indicate intermittent ponding of water subsequent to or contemporaneous with glacial retreat.

The General Land Office (GLO) survey for Baraga County was undertaken between 1846 and 1854 (Barrett et al., 1995). The GLO notes describe the study area (in 1849–1850) as broken and very hilly with many ravines and high sharp ridges. The soil was described as sandy and second-rate. Forests were dominated by hemlock [*Tsuga canadensis* (L.) Carrière], yellow birch (*Betula alleghaniensis* Britton), sugar maple (*Acer saccharum* Marshall), red maple (*Acer rubrum* L.), pine (*Pinus* spp.), and balsam fir [*Abies balsamea* (L.) Miller]. No mention was made of differential vegetative cover on slopes of opposing aspects.

Much of northern Michigan, including the study area, was logged in the late 1800s and early 1900s (Whitney, 1987). The present vegetative cover of the study area is second-growth northern hardwood forests. Common tree species include aspen (*Populus* spp.), white birch (*Betula papyrifera* Marshall), hemlock, red maple, white pine (*Pinus strobus* L.) and red pine (*Pinus resinosa* Aiton). All of the study sites were forested at the time of sampling. Understory vegetation ranged

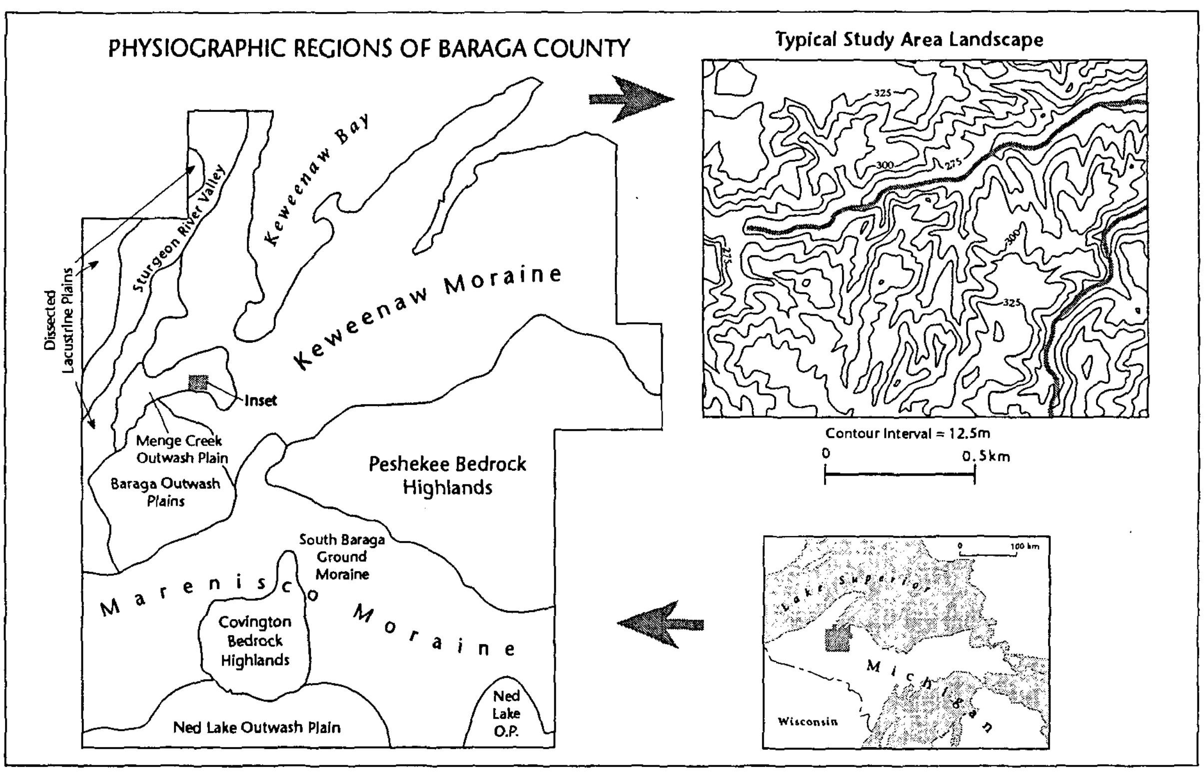

Fig. 1. Location of study area. Inset map shows typical topography, using contour lines, for a part of the study area.

from only a few mosses at some sites to thick covers of bracken fern and wintergreen at other sites.

METHODS

The Baraga County Soil Survey (Berndt, 1988) was used to identify a broad dissected escarpment at the northern edge of the Baraga Plains. A single mapping unit of Rousseau–Ocqueoc complex on this escarpment defines the study area. Numerous ravines were then field checked; hillsides were selected for further study if they had (i) an aspect either between 0° and 45° (N-NE slopes) or 180° and 225° azimuth (S-SW slopes), and (ii) a long backslope, with a gradient ≥45% and a length >25 m from top to bottom, and (iii) minimal slope curvature in plan view (nose and headwater areas [draws] were avoided). Of the many hillsides that met the criteria listed above, 20 (10 paired slopes) were selected for further study. All 20 were purposely distributed across a 10-km span of the dissected escarpment to obtain a comprehensive sample. One pedon from each of the 20 hillsides was chosen for study if it was located on a backslope at least 10 m from the shoulder or footslope and was at least 1 m from any microtopographic irregularities that may have been caused by tree uprooting (Schaetzl et al., 1990).

Once the above criteria were met, a pit was excavated and the best developed soil profile (i.e., greatest E to B color contrast, thickest horizons, and deepest solum) exposed in the soil pit was described with traditional techniques (Soil Survey Staff, 1994). Pits generally extended well into the C horizon; pit depths of 80 to 140 cm were common. Pit sites were discarded if they contained an obvious lithologic discontinuity within the solum, or if they had a >10% gravel in any horizon. (Coarse fragment contents [>2 mm] were visually estimated from the pit faces.) Thickness and dominant color of each genetic horizon were recorded for each pedon. Samples of 300 to 400 g were taken from each horizon for laboratory analysis. Each pit site was paired with another of nearly opposite aspect, yet with similar slope, parent material, and elevation, and within 1 km (often within 400 m). Paired pedons were labeled N1 through N10 for sites on N-NE slopes and S1 through S10 for site on S-SW slopes.

The POD index, a numerical index designed to assess the degree of Spodosol development, (Schaetzl and Mokma, 1988; Goldin and Edmonds, 1996), was calculated in the field at each excavated soil pit. The POD Index calculations require a profile description only, since in the calculation, E horizon colors are compared with B horizon colors to arrive at an index of relative profile development. A two-tailed Wilcoxon test for paired samples (Wilcoxon, 1949) was then applied to the POD index data to determine if a significant difference existed in the amount of soil development between the ten pairs of sampled pedons. The results of this field-based analysis showed the POD index values of soils on N-NE slopes were significantly different than the POD index values of soils on S-SW facing (data provided below). Based on this analysis, the sample size (10 paired pedons) was deemed sufficient.

Finally, soil temperature readings were taken within 5 m of each sampled pedon, at ≈2-mo intervals (17 May, 25 July, 17 Sept., and 5 Nov. 1995 and 20 Jan. 1996), at a depth of 50 cm, using a copper-constantan thermocouple attached to a hand-held thermometer. The infrequent sampling intervals were due to the remoteness and wintertime inaccessibility of the site. The 50-cm depth was selected in an attempt to avoid diurnal variations in soil temperature (Smith et al., 1964).

Soil samples were air dried and coarse fragments removed by sieving. The silt + clay percentage was determined by wet sieving after dispersing 20 to 25 g of soil in 10 mL of a weak Na hexametaphosphate (Na_2CO_3 + $[NaPO_3]_6$) solution. The remaining sand was oven dried and sieved to obtain percentages of five sand fractions. To estimate soil textures, we assumed that the silt + clay fraction was two-thirds silt. Reaction was measured in both a 1:1 soil/water ratio and a 1:1 soil/KCl ratio using an Orion 720A combination pH/ISE meter. Extractions of Fe and Al from E and B horizon samples were taken in Na pyrophosphate and acid ammonium oxalate (McKeague, 1978) on samples that had been repeatedly split in a sample splitter until a weight of 5 g was achieved. The Fe and Al contents of the extracts (Fe content of the pyrophosphate extract [Fe_p], Fe content of the oxalate extract [Fe_o], Al content of the pyrophosphate extract [Al_p], and Al content of the oxalate extract [Al_o]) were determined on a directly coupled plasma spectrometer. Optical density of the oxalate extract (ODOE) at 430 nm was determined on a 320 spectrophotometer (Perkin-Elmer, Norwalk, CT; Daly, 1982).

The Wilcoxon matched-pairs signed-ranks test (Wilcoxon, 1949) was used to test for significant differences in soil development indicators between paired pedons on N-NE and S-SW slopes. Values of significance (Student's t) were calculated for the following variables: pH (all horizons), Fe_o, Al_o, Fe_p, Al_p, Fe_o–Fe_p, and Al_o–Al_p (E and B horizons only), ODOE (E horizons), ODOE (B horizons), thicknesses of sola and horizons, hue, value and chroma of E and B horizons, depth to the top of the E horizons, depth to the top of the B horizons, soil temperatures, snowpack thicknesses, and POD indices. The calculated values of t were then compared against critical values of t in a one-tailed test for significance at $\alpha = 0.05$ (Siegal, 1956). One-tailed tests were used for all soil development data because we hypothesized that soils would be better developed on N-NE slopes. For particle-size data, which primarily reflect initial conditions and for which we hypothesized uniformity among aspects, a two-tailed test was used. A level of statistical significance of $\alpha = 0.05$ is implied unless otherwise noted.

RESULTS AND DISCUSSION

The 20 pedons studied exhibited remarkable uniformity in morphology. Most pedons had Oi-E-Bs1-Bs2-BC-C horizon sequences (Fig. 2). One pedon on N-NE

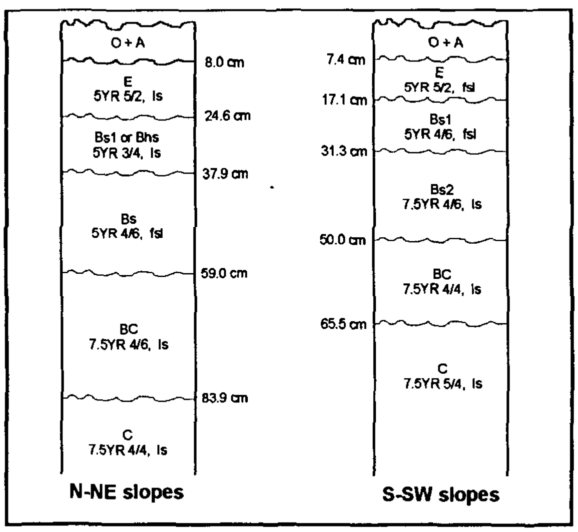

Fig. 2. Typical morphology (most common horizon sequences, colors, and textures; mean horizon thicknesses) for pedons on N-NE vs. S-SW slopes, in the study area (ls = loamy sand; fsl = fine sandy loam).

slopes had an A horizon, whereas four on S-SE slopes had A horizons. It is likely that all had A horizons prior to the widespread deforestation of the late 19th century, which resulted in frequent fires and soil erosion. All pedons had at least two B subhorizons, commonly as Bs1 and Bs2, although Sites N5 and N6 had Bhs horizons.

Parent Material Uniformity

Coarse fragment content did not exceed 10% by volume for any horizon; most horizons had <5% coarse fragments. Textures ranged from sand to fine sandy loam (Fig. 2). Most horizons contained between 70 and 90% total sand with fine sand and medium sand dominating. Lithologic discontinuities exist in 8 of the 20 pedons. Only one of these discontinuities, however, occurred within the solum (Site S3). In pedons that had lithologic discontinuities, the lower material ranged from loamy coarse sand to loam in texture and it typically was slightly more gravelly than the overlying material. Statistical analysis of the amounts of individual size fractions (very coarse sand, coarse sand, medium sand, fine sand, very fine sand, total sand, silt + clay) on a horizon basis for paired pedons failed to show significant differences for corresponding horizons on opposing slope aspects (Table 1).

Amounts of individual particle-size fractions within each pedon were also weighted by horizon thickness; horizons that occurred below a lithologic discontinuity (at Site S3) were eliminated from this calculation (Table 2). Horizon-weighted values were then summed and divided by their cumulative thickness to arrive at solum-weighted particle-size data. Statistical analyses on the weighted percentages of each size fraction (very coarse sand, coarse sand, medium sand, fine sand, very fine sand, total sand, silt + clay) show that significant differences do not exist in the solum-weighted particle-size data for paired pedons (Table 3). We conclude that the textures in the sola of sampled pedons are generally uniform and probably have similar depositional origins.

Effects of Slope Gradient on Soil Development

Jenny (1941) suggested that slope gradient inversely affects soil development, and many studies since have noted that sites with steeper slopes often exhibit less pedogenic development than do more gently sloping sites (Norton and Smith, 1930; Marron and Popenoe, 1986; Carter and Ciolkosz, 1991). Since the slope gradients (inclinations) of the 20 sites ranged from 45 to 73%, it was deemed necessary to determine what, if any, effect slope gradient may have had on pedogenesis, regardless of aspect. Thus, regression analyses were performed for each variable listed above, against slope gradient, and scatterplots were inspected to ensure that the linear regression equations were not being forced onto obviously curvilinear distributions.

None of the coefficient values in the regression equations were significantly different from zero at $P = 0.05$ and only two variables were significant at $P = 0.10$.

Table 1. Statistical differences in sand separates for paired pedons (horizon based).†

Horizons and particle-size fraction‡	Particle-size data (SD) N-NE facing slope	Particle-size data (SD) S-SW facing slope	Higher value	P (two-tail)
	g kg^{-1}	g kg^{-1}		
E horizon total sand	767 (71)	804 (63)	S-SW	0.20
E horizon vcs	12 (12)	11 (10)	N-NE	0.80
E horizon cs	58 (59)	49 (31)	N-NE	0.96
E horizon ms	238 (83)	209 (52)	N-NE	0.39
E horizon fs	367 (95)	349 (93)	N-NE	0.45
E horizon vfs	128 (50)	150 (42)	S-SW	0.45
Uppermost B horizon total sand	796 (99)	771 (62)	N-NE	0.36
Uppermost B horizon vcs	19 (21)	17 (23)	N-NE	0.86
Uppermost B horizon cs	60 (55)	50 (37)	N-NE	0.88
Uppermost B horizon ms	228 (102)	209 (69)	N-NE	0.65
Uppermost B horizon fs	353 (96)	340 (86)	N-NE	0.80
Uppermost B horizon vfs	136 (61)	155 (55)	S-SW	0.51
Second B horizon total sand	767 (116)	817 (59)	S-SW	0.52
Second B horizon vcs	11 (9)	14 (10)	S-SW	0.37
Second B horizon cs	38 (33)	53 (30)	S-SW	0.09
Second B horizon ms	180 (96)	244 (102)	S-SW	0.07
Second B horizon fs	368 (95)	372 (53)	S-SW	0.52
Second B horizon vfs	160 (61)	134 (60)	N-NE	0.09
BC or 2BC horizon total sand	805 (127)	841 (63)	S-SW	0.78
BC or 2BC horizon vcs	11 (11)	12 (7)	S-SW	0.58
BC or 2BC horizon cs	41 (45)	54 (31)	S-SW	0.26
BC or 2BC horizon ms	222 (109)	286 (124)	S-SW	0.26
BC or 2BC horizon fs	391 (93)	377 (78)	N-NE	0.09
BC or 2BC horizon vfs	140 (54)	112 (57)	N-NE	0.26
C, 2C, or 3C horizon total sand	809 (157)	828 (120)	S-SW	0.26
C, 2C, or 3C horizon vcs	4 (5)	15 (26)	S-SW	0.33
C, 2C, or 3C horizon cs	81 (151)	61 (89)	N-NE	0.67
C, 2C, or 3C horizon ms	249 (178)	267 (206)	S-SW	0.48
C, 2C, or 3C horizon fs	350 (179)	348 (127)	N-NE	0.89
C, 2C, or 3C horizon vfs	124 (92)	136 (129)	S-SW	0.67

† Based on a Wilcoxon matched-pairs signed-ranks test.
‡ vcs = very coarse sand; cs = coarse sand; ms = medium sand; fs = fine sand; vfs = very fine sand.

Table 2. Solum-weighted particle-size data for sampled pedons.†

Pedon	Sand 2.0–0.05 mm	Silt + Clay <0.05 mm	VCS‡ 2.0–1.0 mm	CS‡ 1.0–0.5 mm	MS‡ 0.5–0.25 mm	FS‡ 0.25–0.1 mm	VFS‡ 0.1–0.05 mm
	g kg^{-1} in fine earth		g kg^{-1} in sand fraction				
S1	644	349	3	19	139	285	197
S2	741	253	13	46	159	295	228
S3	694	298	16	66	191	240	181
S4	806	186	9	32	239	396	130
S5	819	166	6	31	218	420	145
S6	859	128	8	34	218	477	122
S7	778	212	7	24	144	415	188
S8	741	248	12	39	152	354	183
S9	835	88	9	81	351	310	85
S10	811	76	46	117	292	269	87
Mean	773	200	13	49	210	346	155
N1	701	291	26	114	282	192	87
N2	601	397	2	9	96	323	172
N3	892	46	36	130	352	311	64
N4	855	141	8	29	223	414	182
N5	893	93	24	72	292	400	105
N6	832	153	9	50	255	486	133
N7	850	139	7	17	190	487	150
N8	790	201	3	15	149	422	202
N9	710	273	10	43	240	309	109
N10	758	235	5	14	104	402	232
Mean	788	197	13	49	218	375	144

† Includes the E horizon(s) and B horizons of each pedon. Horizons below a lithologic discontinuity were eliminated from the calculation (Site S3 only).
‡ VCS = very coarse sand; CS = coarse sand; MS = medium sand; FS = fine sand; VFS = very fine sand.

These two variables were chroma of the uppermost E horizon ($P = 0.058$) and POD Index ($P = 0.052$). Upon further investigation, the regression results for the POD index seemed to be unduly influenced by a single value (POD index = 12 at Site N6). Removal of this value from the data changes the r from −0.44 to +0.07, and P increases from 0.052 to 0.792. In general, these results show that variations in slope gradient, for slopes as steep as these, probably have little influence on pedogenesis.

Effects of Slope Aspect on Soils

Aspect vs. POD Index

The POD index is a numerical index that assesses the degree of Spodosol development based on soil color and number of subhorizons (Schaetzl and Mokma, 1988). The POD indices were significantly greater ($P = 0.01$) on N-NE facing slopes, indicating greater soil development there. The mean POD index on N-NE facing slopes was 4.2 ± 3.4, whereas the mean POD index on S-SW facing slopes was 1.1 ± 1.2. According to Schaetzl and Mokma (1988), POD values >2 indicate that the soil probably classifies as a Spodosol, whereas a POD of <2 usually indicates that the soil, if sandy, is an Entisol.

Aspect vs. Soil Classification

Using Soil Survey Staff (1994) guidelines, color, morphology, or chemical criteria (ODOE or Fe_o and Al_o) were used to classify the 20 pedons. Nine of 10 pedons located on N-NE slopes classified as Spodosols (eight Entic Haplorthods; one Typic Haplorthod); one classified as a Typic Udorthent. Only three of 10 pedons on S-SW lopes were Spodosols (Entic Haplorthods). The remaining seven pedons classified as Entisols (five Typic Udorthents; one Spodic Udipsamment; one Typic Udipsamment).

Aspect vs. Snowpack Thickness

As illustrated by other studies (Sartz, 1972), variable depths of snow were observed on opposing slopes. On 26 Apr. and 5 Nov. 1995, snowpacks were significantly thicker ($P = 0.01$) on N-NE slopes compared with that of opposing slopes. By mid-winter (January 1996), however, snowpack thicknesses were no longer significantly different. Snowpacks in the study area can potentially affect pedogenesis and podzolization in at least two ways: (i) thicker snow covers insulate the soil and can inhibit soil freezing (Hart and Lull, 1963; Sartz, 1973; Isard and Schaetzl, 1995). On and within unfrozen soil,

Table 3. Statistical differences in soil temperatures at 50 cm, for sampled pedons.

Soil temperature	Mean and SD N-NE slopes	Mean and SD S-SW slopes	Higher value	*P* (one-tail)
°C				
May	4.9 (0.9)	8.1 (0.7)	S-SW	0.01
July	13.7 (0.8)	15.8 (0.8)	S-SW	0.01
September	11.0 (3.9)	12.3 (4.4)	S-SW	0.01
November	5.3 (0.7)	4.9 (0.6)	N-NE	ns†
January	2.0 (1.1)	1.6 (0.9)	S-SW	ns†

† ns = not significant at $P = 0.05$.

organic matter can decompose year-round, and water percolates freely, allowing organically-driven pedogenic processes to occur uninterruptedly throughout the year. The unfrozen nature of the soil also minimizes snowmelt runoff. (ii) Snow melts more gradually on N-NE slopes, which may allow more meltwater to infiltrate, rather than runoff, on these steep slopes. Snowmelt infiltration has been implicated as an important vector in the podzolization process (Schaetzl and Isard, 1990, 1991, 1996).

Aspect vs. Soil Temperature

Solar radiation inputs, which affect soil temperatures directly, are dramatically different on N-NE vs. S-SW slopes. Lee and Baumgartner (1966) document that, at 50° N latitude, south slopes of 60% gradient receive 2.7 times more annual insolation than do their N counterparts. North and south slopes sampled here had a mean gradient of 62.7 and 62.6%, respectively, suggesting that their differences in insolation receipt may be >2.7 times.

Soil temperature affects pedogenesis and podzolization in a multitude of ways (Smith et al., 1964; Stanley and Ciolkosz, 1981; Smith, 1986; Schaetzl and Isard, 1996). Soil temperatures exhibited statistically significant differences ($P = 0.01$) between N-NE and S-SW slopes in May, July, and September, 1995 (Table 3). At each of these three sampling periods, each site on S-SW slopes exhibited significantly warmer soil temperatures than its pair on N-NE slopes. The greatest mean difference in soil temperature during these months was recorded in May when S-SW slopes exhibited a mean soil temperature of 8.1 ± 0.7°, compared with 4.9 ± 0.9° on N-NE slopes. Soil temperature results similar to those described above have been documented in numerous studies (Cooper, 1960; Stepanov, 1967; Franzmeier et al., 1969; Losche et al., 1970; Hutchins et al., 1976). The S-SW slopes receive more direct-beam solar radiation during the course of a year than do N-NE slopes, probably accounting for most of the differences. On an average N-NE slope in the study area, maximum incidence angle of solar radiation occurs only once on 21 June and is only 38.8°. On S-SW slopes, solar noon incidence angles >80° exist from early April through late August, although in the narrow ravines, nearby uplands often shade the S-SW slopes during some parts of the day. The duration of this relatively intense, direct-beam solar radiation (>80°) on S-SW slopes, in conjunction with relatively short summer nights, probably lends to the warm summer soil temperatures documented on these slopes.

In winter, when snowpacks are deep, solar angles are low, and days are short, soil temperatures are more similar between N-NE and S-SW slopes. Soil temperatures measured in November (1995) and January (1996) on opposing slopes were not significantly different (Table 3), probably due to the insulating effects of deep snowpacks.

Aspect vs. Eluviation

Increased eluviation should produce soils with thicker, whiter E horizons that are more acidic and more thoroughly depleted in Fe and Al compounds than are soils with minimal eluviation. The hypothesis that eluviation, one component of podzolization, was stronger on N-NE slopes, was tested statistically by examining the above variables for the pedons on N-NE vs. S-SW slopes (Table 4).

Depths to the top of the E horizon, which reflect O + A horizon thicknesses, are a reasonable indicator of eluviation and podzolization (Stanley and Ciolkosz, 1981). This variable, however, was not found to be significantly different for soils on opposing slopes, although the mean depth was slightly greater on N-NE slopes (Table 4).

The E horizon thicknesses are an excellent reflection of cumulative eluviation; on N-NE slopes, they were significantly greater than on S-SW slopes (16.6 ± 6.1 vs. 9.7 ± 4.0 cm; Table 4). In 8 out of 10 paired pedons in this study, the E horizon of the N-NE pedon was thicker.

Table 4. Soils data related to eluviation.

Variable	Value for soils on N-NE slopes (Mean ± SD)	Value for soils on S-SW slopes (Mean ± SD)	Indicates stronger podzolization on which slope?	Level of significance† (one tail)
Depth to top of E, cm	8.0 (3.1)	7.4 (3.5)	neither	ns‡
Depth to top of B, cm	24.6 (7.2)	17.1 (5.2)	N-NE	0.02
E thickness, cm	16.6 (6.1)	9.7 (4.0)	N-NE	0.02
E pH, KCl	3.2 (0.1)	3.4 (0.2)	N-NE	0.01
E pH, H_2O	4.7 (0.4)	4.5 (0.3)	neither	ns
E hue, Munsell YR	5.8 (1.2)	6.0 (1.3)	neither	ns
E value, Munsell units	4.6 (0.5)	4.8 (0.4)	neither	ns
E chroma, Munsell units	2.2 (0.4)	2.4 (0.5)	neither	ns
Fe_o§ in E, g kg^{-1}	0.2 (0.2)	0.4 (0.2)	N-NE	0.05
Al_o§ in E, g kg^{-1}	0.2 (0.1)	0.3 (0.1)	N-NE	0.01
Fe_p§ in E, g kg^{-1}	0.1 (0.0)	0.2 (0.1)	N-NE	0.05
Al_p§ in E, g kg^{-1}	0.1 (0.0)	0.2 (0.1)	N-NE	0.01
Fe_o-Fe_p in E, g kg^{-1}	0.1 (0.1)	0.3 (0.2)	neither	ns
Al_o-Al_p in E, g kg^{-1}	0.1 (0.1)	0.2 (0.1)	N-NE	0.01
ODOE¶ of E	0.0 (0.0)	0.1 (0.1)	N-NE	0.02

† One-tailed test using Wilcoxon (1949) test.
‡ ns = not significant at $P = 0.05$.
§ Fe_o = Fe content of the oxalate extract; Al_o = Al content of the oxalate extract; Fe_p = Fe content of the pyrophosphate extract; Al_p = Al content of the pyrophosphate extract.
¶ ODOE = optical density of the oxalate extract.

Depths to the top of the B horizon, which reflect the total thickness of the eluvial zone, were also found to be significantly greater on N-NE slopes than on S-SW slopes; this conclusion also held for 8 out of the 10 paired pedons.

Soil pH data are plotted in Fig. 3 as mean horizon depth against mean H_2O pH for opposing slope aspects. Podzolization is accentuated by acidic eluvial horizons (Petersen, 1976; Buurman and van Reeuwijk, 1984), and in these soils, the E horizons were the most acidic of all, regardless of aspect. Statistical analysis of soil–KCl reactions vs. aspect revealed significant differences for only two horizons. The E horizons exhibited significantly lower ($P = 0.01$) pH values on N-NE slopes (3.2 ± 0.1) than on S-SW slopes (3.4 ± 0.2). For pH data from 1:1 soil/H_2O mixtures, E horizons on N-NE slopes were somewhat less acid than were E horizons on S-SW slopes, although the difference was not significant (Table 4 and Fig. 3).

The colors (hue, value, and chroma) of the uppermost E horizons of soils on N-NE facing slopes were not significantly different from corresponding soils on S-SW facing slopes (Table 4 and Fig. 2). The mean hue of uppermost E horizons on N-NE facing slopes was 5.8 ± 1.2 YR, compared with 6.0 ± 1.3 YR on S-SW slopes. Color values and chromas were also comparable (Table 4). Because E horizons form by the eluviation of humus and sesquioxides, one should expect to find little difference in E horizon color on opposing aspects, providing all are well developed. After the majority of the humus and Fe oxides are depleted from these horizons, the translucence of the sand grains will impart similar colors to most E horizons.

Acid ammonium oxalate extracts Fe and Al when they exist either as organically bound or inorganic amorphous materials but does not extract crystalline oxides well (McKeague and Day, 1966). In this study, relative depletion of oxalate-extractable Fe and Al (Fe_o and Al_o) occurred in the E horizons of all pedons, while B horizons gained these materials. This pattern is typical

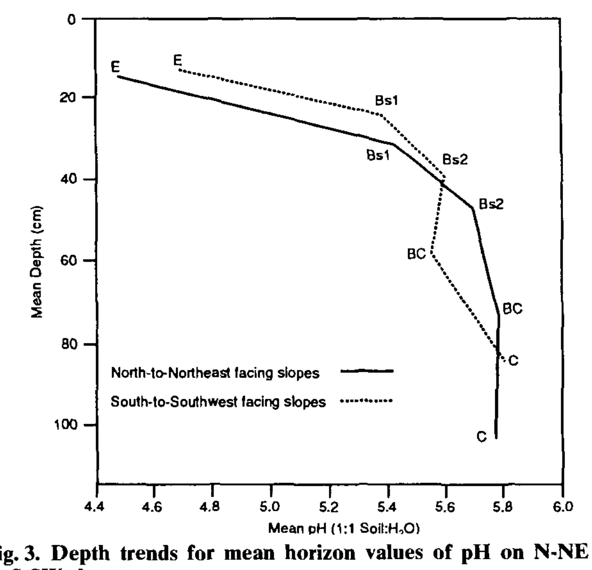

Fig. 3. Depth trends for mean horizon values of pH on N-NE vs. S-SW slopes.

of sandy soils undergoing podzolization (Kodama and Wang, 1989; Mokma, 1993; Barrett, 1995). The E horizons on N-NE slopes contained significantly less Fe_o than did those on S-SW slopes (Table 4). The mean amount of Fe_o in E horizons on N-NE slopes was 0.20 ± 0.2 g kg^{-1} soil; E horizons on S-SW slopes have more than double that amount: 0.44 ± 0.2 g kg^{-1}. Similarly, E horizons on N-NE slopes contained significantly less ($P = 0.01$) Al_o than those on S-SW slopes (Table 4).

Pyrophosphate-extractable Fe and Al indicate the presence of organically bound, amorphous Fe and Al (Aleksandrova, 1960; McKeague, 1967; Higashi et al., 1981). In this study, depletion of these materials has occurred in the E horizons of all pedons, relative to the B horizons of the same pedons. The E horizons on N-NE slopes contained significantly less Fe_p than those on S-SW slopes (Table 4). Indeed, the mean amount of Fe_p in E horizons on N-NE slopes was less than half that for comparable horizons on S-SW slopes (0.07 ± 0.0 g kg^{-1} vs. 0.15 ± 0.1 g kg^{-1}). The E horizons on N-NE slopes also contained significantly less ($P = 0.01$) Al_p than those on S-SW slopes.

The ODOE serves as a measure of podzolization because it is a surrogate for the amount of fulvic acids from each horizon (Daly, 1982) and correlates strongly with pyrophosphate-extractable C (Mokma, 1993). Spodic materials, as currently defined, have an ODOE >0.25, and this value must be at least two times the value of an overlying eluvial horizon (Soil Survey Staff, 1994). The ODOE values for the uppermost E horizons on S-SW slopes were significantly greater than those on N-NE slopes (Table 4). These data suggest that organic and fulvic acids have been eluviated more completely from the E horizons on N-NE slopes than they have on S-SW slopes.

Estimates of the Al component in allophane and imogolite, both of which are thought to be important components of podzolization in some areas (Anderson et al., 1982; Farmer et al., 1980; Gustafsson et al., 1995), can be estimated from Al_o minus Al_p (Parfitt and Kimble, 1989). Positive values of Al_o minus Al_p imply that either of these two compounds, or both, are present. Similarly, inorganic, amorphous Fe can be estimated using Fe_o minus Fe_p (Wang et al., 1986). The E horizons on S-SW slopes contained significantly more Al_o minus Al_p ($P = 0.01$) compared with that of N-NE slopes (Table 4). Lower ODOE contents in the E horizons on S-SW slopes suggests that organic acids are less active and concentrated there, which may have concomitantly led to higher amounts of nonorganically bound Al and Fe at these sites. In nearby Ontario, Wang et al. (1986) studied two Spodosol pedons and found that imogolite and other forms of inorganic Fe and Al were more common in the one that had less organic matter overall (whether expressed as Fe_p, Al_p, organic C [OC] in the solum, or root density).

The data listed in Table 4 and discussed above strongly indicate that eluviation is more pronounced on N-NE slopes. The E horizons and eluvial zones are thicker, more acidic, and more depleted of Fe and Al compounds and potentially chelating acids. The means of only 2 of the 13 variables related to eluviation were suggestive of stronger eluviation on S-SW slopes, and they were not statistically different from the values obtained for their paired pedons on N-NE slopes (Table 4). Eluviation in this case is partially a product of total infiltration, and assuming equal precipitation on corresponding sites, one can assume that the E horizons on N-NE slopes have sustained more cumulative infiltration compared with that of S-SW slopes (cf. Stepanov, 1967). This conclusion seems logical since greater evapotranspiration probably takes place on the warmer S-SW slopes (in the growing season), thus decreasing the amount of water available for deep infiltration. These data clearly support the hypothesis that more eluviation and translocation of organo-metallic complexes (i.e., podzolization) has occurred in eluvial zones on N-NE slopes than on S-SW slopes.

Aspect vs. Illuviation

Illuvial processes should be strongest and best expressed in soils that are also undergoing intense eluviation, as has been shown for N-NE slopes in the study area (Table 5). Illuviation within podzolization should result in darker, redder, and thicker B horizons (Schaetzl and Mokma, 1988). Increased amounts of Al and organic matter in the B horizon, with or without Fe, would also imply more intense podzolization and illuviation (Franzmeier and Whiteside, 1963; Barrett and Schaetzl, 1992; Soil Survey Staff, 1994). We hypothesized that illuviation was stronger on N-NE slopes and tested this hypothesis statistically by examining several variables for pedons on N-NE vs. S-SW slopes (Table 5).

The B horizon thicknesses were not found to be significantly different on opposing slopes (30.6 ± 4.1 on S-SW vs. 34.4 ± 10.0 cm on N-NE; Table 5). Although the differences in mean B horizon thicknesses were not statistically significant, 6 of the 10 paired pedons on N-NE slopes did have thicker B horizons. Two pedons on N-NE slopes had Bhs horizons; all B subhorizons on S-SW slopes were Bs horizons.

An increase in B horizon pH has been suggested as one mechanism by which organo-metallic complexes are rendered immobile, enhancing precipitation and deposition within the illuvial layer. The B horizon pH values were not significantly different between slopes (Table 5). Most pH values were near 4.2 in KCl and 5.5 in H_2O.

The uppermost B horizons on N-NE facing slopes were significantly redder (lower hue) than corresponding horizons on S-SW facing slopes (Table 5). The mean hue of uppermost B horizons on N-NE facing slopes was 4.5 ± 1.1 YR, whereas on S-SW facing slopes, the mean hue was 6.0 ± 1.3 YR. The Soil Survey Staff (1994) uses color as one criterion in the identification of spodic materials; materials with a color of 5YR or redder will classify as spodic if they also meet pH and OC requirements. All 10 pedons on the N-NE slopes had at least one B subhorizon that was 5YR or redder (three subhorizons were 2.5 YR), whereas only six of the pedons on S-SW slopes had 5YR or redder B horizons. Redder B horizons on northerly aspects have been documented by Franzmeier et al. (1969) in Kentucky and Tennessee and by Marron and Popenoe (1986) in California. They attributed the increased redness to higher concentrations of translocated clay in the B horizon, supposedly due to greater water content and greater throughflow on those slopes. Opposite findings, however, have been documented by Losche et al. (1970) in North Carolina and Cooper (1960) in Michigan. Both found redder hues on south-facing slopes, which they

Table 5. Soils data related to illuviation.

Variable	Value for soils on N-NE slopes (Mean ± SD)	Value for soils on S-SW slopes (Mean ± SD)	Indicates stronger podzolization on which slope?	Level of significance† (one tail)
B thickness, cm	34.4 (10.0)	30.6 (4.1)	neither	ns‡
Uppermost B pH, KCl	4.2 (0.2)	4.3 (0.2)	N-NE	0.03
Uppermost B pH, H_2O	5.4 (0.2)	5.5 (0.2)	neither	ns
Second B pH, KCl	4.5 (0.1)	4.4 (0.2)	neither	ns
Second B pH, H_2O	5.6 (0.3)	5.7 (0.2)	neither	ns
Uppermost B hue, Munsell YR	4.5 (1.1)	6.0 (1.3)	N-NE	0.02
Uppermost B value, Munsell units	3.1 (0.4)	3.9 (0.3)	N-NE	0.01
Uppermost B chroma, Munsell units	4.3 (1.0)	5.6 (0.8)	N-NE	0.02
Fe_o§ in uppermost B, g kg^{-1}	5.1 (2.0)	3.5 (1.1)	N-NE	0.04
Al_o§ in uppermost B, g kg^{-1}	4.7 (2.2)	3.5 (1.1)	neither	ns
Fe_o in second B, g kg^{-1}	2.3 (1.0)	1.8 (0.7)	neither	ns
Al_o in second B, g kg^{-1}	3.5 (1.7)	2.1 (0.7)	N-NE	0.01
Fe_p§ in uppermost B, g kg^{-1}	2.5 (1.5)	1.1 (0.5)	N-NE	0.01
Al_p§ in uppermost B, g kg^{-1}	2.5 (1.0)	1.4 (0.4)	N-NE	0.01
Fe_p in second B, g kg^{-1}	1.1 (0.7)	0.6 (0.5)	N-NE	0.03
Al_p in second B, g kg^{-1}	1.7 (0.6)	0.9 (0.5)	N-NE	0.01
Fe_o-Fe_p in uppermost B, g kg^{-1}	2.4 (1.5)	2.4 (1.2)	neither	ns
Al_o-Al_p in uppermost B, g kg^{-1}	2.1 (2.1)	2.0 (1.1)	neither	ns
Fe_o-Fe_p in second B, g kg^{-1}	1.3 (0.7)	1.3 (0.6)	neither	ns
Al_o-Al_p in second B, g kg^{-1}	2.0 (1.3)	1.3 (0.7)	N-NE	0.02
ODOE¶ of uppermost B	0.3 (0.2)	0.1 (0.1)	N-NE	0.01
ODOE of second B	0.1 (0.1)	0.1 (0.1)	neither	ns

† One-tailed test using Wilcoxon (1949) test.
‡ ns = not significant at $P = 0.05$.
§ Fe_o = Fe content of the oxalate extract; Al_o = Al content of the oxalate extract; Fe_p = Fe content of the pyrophosphate extract; Al_p = Al content of the pyrophosphate extract.
¶ ODOE = optical density of the oxalate extract.

(also) attributed to higher amounts of translocated clay in the B horizon on those slopes. In the Baraga County soils, however, clay translocation is an unimportant process; most of the redness is attributable to greater concentrations of amorphous materials and organo-metallic complexes (Mokma, 1993).

Both color values and chromas of the uppermost B horizons on N-NE facing slopes were significantly lower than corresponding horizons on S-SW slopes (Table 5). The mean B horizon on N-NE facing slopes has a value of 3.1 ± 0.4 and a chroma of 4.3 ± 1.0. On S-SW slopes, the B horizons are brighter (value = 3.9 ± 0.3) and grayer (chroma = 5.6 ± 0.8). The darker and grayer colors on N-NE facing slopes can again be attributed to greater concentrations of OC and organo-metallic complexes (Mokma, 1993). Daniels et al. (1987) reported greater amounts of organic matter in the B horizon (and throughout the solum) on north than on south slopes (cf. Franzmeier et al., 1969). Carter and Ciolkosz (1991) reported greater amounts of OC in B horizons on steep (25–60%) northwest slopes compared with steep (25–60%) southwest slopes; this relationship did not hold, however, for more gentle slopes. In nearby Marquette County, Michigan, sandy Spodosols on north slopes have darker (Bhs) horizons, whereas those on south slopes are less developed, with Bs horizons (Jerome, 1996).

Oxalate-extractable Fe was present in significantly higher amounts in upper B horizons on N-NE slopes than in the paired S-SW slope Bs horizons (Table 5). Al_o was also present in higher amounts on N-NE slopes, but this relationship was only significant for the second B horizon (Table 5). While significant differences in oxalate-extractable Fe and Al contents were not found for all B subhorizons, mean values on N-NE slopes were in all cases higher than for the paired horizons on S-SW slopes. This finding supports the hypothesis that increased illuviation of amorphous materials, which was also suggested by B horizon color data, has occurred on N-NE slopes. Since Al_o is generally translocated deeper in the solum than Fe_o (Mizota, 1982; Wang et al., 1986) and there exists evidence for deeper infiltration on N-NE slopes, it follows that Al_o amounts would be significantly greater in the second B horizons on N-NE slopes than in soils on S-SW slopes.

The uppermost B and the second horizons on N-NE slopes contained significantly more Fe_p and Al_p than did those on S-SW slopes (Table 5). Since Fe_p and Al_p in B horizons are both indicative of illuvial organo-metallic complexes, these data strongly suggest increased podzolization on N-NE slopes. Stanley and Ciolkosz (1981) found significant relationships between soil temperature and Fe_p and Al_p contents in Spodosol B horizons, which supports the findings here for Fe_p and Al_p in B horizons on the cooler N-NE slopes. The ODOE data also support the pyrophosphate data, with mean ODOE values for the uppermost B horizons on N-NE slopes being more than twice as high as for paired pedons on S-SW slopes (Table 5).

The ODOE values for the uppermost B horizon of soils on N-NE slopes were significantly greater (P = 0.01) than for paired pedons on S-SW slopes (Table 5). The ODOE values for the second B horizons on N-NE slopes were not, however, significantly different from those of the S-SW slopes. These data, in conjunction with darker colors and more Fe_p and Al_p in upper B horizons, suggest that the main difference in illuvial processes between N-NE and S-SW aspects lies in the intensity with which organo-metallic complexes accumulate in the B horizons.

Of the four possible measures of inorganic, amorphous materials in illuvial positions, only Al_o minus Al_p contents in the second B horizon on N-NE slopes exhibited a significant difference from their paired pedon. In this case, the second B horizons on N-NE slopes contained significantly more $Al_o - Al_p$ than did their pairs on S-SW slopes (Table 5). This finding suggests that aspect may play a more important role in affecting chelation-driven podzolization, possibly through its effects on organic matter production–decomposition processes, than on mineral weathering and translocation of Fe- and Al-rich inorganic constituents. The data also suggest that inorganic, amorphous materials are present in measurable quantities in these soils.

Aspect vs. Solum Thickness

Disparities in solum thicknesses on opposing slopes are primarily attributable to the relatively thick E horizons on N-NE slopes (Table 4 and Fig. 2). Seven of ten paired pedons on N-NE slopes had thicker sola, compared with their S-SW counterpart. Mean values, which were significantly different at P = 0.02, indicate that sola average ≈9 cm thicker on N-NE slopes (59.0 ± 9.9 vs. 50.0 ± 10.5 cm). Studies in Michigan (Cooper, 1960) and California (Marron and Popenoe, 1986; Alexander, 1995) have documented thicker sola on N or NE slopes, or both. The researchers attributed their findings to the presence of greater soil water and greater infiltration on north slopes, thus translocating more material to greater depths. Alexander (1995) found a larger proportion of shallow soils on south slopes in California. Shallower sola on N or NE slopes, or both, however, have been reported by Losche et al. (1970) for North Carolina and Small (1972) for southwest Wisconsin, where higher soil temperatures on south facing slopes were thought to promote increased chemical activity and accelerate weathering. Cooper (1960) also found that soils on south slopes were more intensely weathered than those on north slopes. For the geologically young soils in Baraga County, however, thicker sola on N-NE slopes can probably be attributed to the greater amounts of water available for translocation, rather than to weathering. Thicker E horizons in soils of N-NE facing slopes also support this conclusion and points to the importance of infiltrating water to podzolization (Schaetzl and Isard, 1991, 1996).

CONCLUSIONS

Within the study area, where parent materials and slope gradients are essentially uniform, microclimate has led to the formation of considerably different soils on opposing aspects. Soils on N-NE slopes are more strongly developed (i.e., more podzolized) than are soils on S-SW slopes. Morphological characteristics such as POD indices, colors, and horizon and solum thicknesses repeatedly indicate maximal pedogenic activity on N-NE slopes. Chemical characteristics such as extractable Fe and Al provide further evidence that soils on N-NE slopes are more intensely developed than those on S-SW slopes. Processes most responsible for this disparity are in part driven by aspect-related factors and are briefly discussed below.

Increased Accumulation of Organic Matter

Accumulation of organic material at the surface is essential for strong podzolization (Mokma and Vance, 1989). The O horizons in the study area were disturbed during logging operations and, later, by fires; hence, they are often thin and sometimes intermittent and thus cannot be used to estimate the potential for organic acid production on sites of varying aspect. Data on presettlement O horizons, unfortunately, are lacking. Nonetheless, the presence of thicker O horizons on N-NE slopes, for the many centuries since deglaciation, is probable, given the cooler, moister microclimate that exists there.

Weathering, Release of Iron and Aluminum, and Decomposition of Organic Material

Water is a necessary component of chemical weathering, and since more water and organic materials are probably available on N-NE slopes, it is likely that weathering has proceeded more rapidly and intensely on N-NE slopes. Higher soil temperatures, however, may in turn accelerate this process on S-SW slopes. This dilemma can be resolved (or avoided) by recalling that, in mid-latitude locations, well-drained Spodosols are best developed under cooler conditions (Stanley and Ciolkosz, 1981; Schaetzl and Isard, 1996), suggesting that podzolization is probably more water and infiltration limited than it is temperature limited. As an example, podzolized soils are most commonly observed in cool, wet environments like northern Michigan, and spodic development is also observed in warm, wet environments such as the southeastern USA Coastal Plain. However, soils like these rarely develop in cold, dry environments like Antarctica or in warm, dry environments like the Nebraska Sand Hills, again suggesting that podzolization is more moisture limited than temperature limited.

Translocation of Organic Carbon, Iron, and Aluminum

Infiltrating water is the primary vehicle behind translocation, and many lines of evidence indicate increased infiltration on N-NE slopes. Translocation of organometallic complexes appears to be more active on N-NE slopes than on S-SW slopes, whereas formation and translocation of amorphous, inorganic weathering products appears to be less aspect dependent.

The findings of this study can be generalized and applied elsewhere if one assumes that aspect affects primarily the energy and moisture status of soils. For sites with an abundance of moisture, when viewed in light of the energy and moisture needs of the dominant soil processes, energy may be limiting; soils on such sites may exhibit increased soil development on the warmer slopes. Conversely, in pedogenically dry areas (dry with respect to the amount of water that could be utilized by the dominant pedogenic process), moisture may be limiting. Here, the moister (poleward-facing) slopes may contain better developed soils.

In our study area, podzolization, which is a process best expressed in cool to cold climates, does not appear to be energy limited on either aspect. Instead, it is moisture and infiltration limited, explaining why soils on the moister, north-facing slopes are better developed. It remains to be seen whether this model is widely applicable or whether it holds primarily for cool, humid locations.

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