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Randall J Schaetzl
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Randall J. Schaetzl*

ABSTRACT

Soils in northern lower Michigan, all formed in sandy glacial outwash, were examined to determine the effects of vegetation and fire frequency vs. climate on their development. To accomplish this, soil development was quantified for 13 pedons that span a region known as the Grayling Fingers. Next, a GIS was used to examine spatial interrelationships among the following data sets for the Fingers area: soils, climate, and presettlement vegetation. The 13 sampled pedons span a major pedologic ecotone between an area of strongly expressed spodic morphology (with hardwood forests, low fire frequencies, and deep snowpacks) and one where soils are Psamments. The Psamment area is dominated by jack pine and oak barrens, which frequently burned in presettlement time, and have much less snow cover in winter. The texture and mineralogy of all pedons are generally similar, thereby ruling out parent material as a controlling factor in their development. The relationships among vegetation patterns and soil development remain unclear in this area. Spatial relationships among snowfall amounts and snowpack thicknesses, however, correlate extremely well to soil development patterns. Thus, I conclude that in this region, patterns of soil development are related primarily to the influence of snowmelt infiltration and its previously documented impact on podzolization. Overstory vegetation may provide a strong, reinforcing influence or may be reacting in turn as a dependent variable to soil development and soil moisture during spring, as impacted directly by snowmelt infiltration.

The functional-factorial (state factor) approach of Jenny (1941) has repeatedly shown value in studies of soil geography and distribution (Ponomareva, 1958; Phillips, 1998; Barrett, 1999, 2001). By determining the variability in one or more of the five state factors across space, the reasons for soil variability, at many scales, can be deduced (Crocker, 1952; Parsons and Herriman, 1975; Nettleton et al., 1986; Schaetzl, 1991a). Although no substitute for pedon-scale, process-based analyses (Ranger et al., 1991), functional-factorial analyses of soils in a spatial context can provide valuable information about the character and variability of pedogenic processes (Schaetzl, 1991b; Bockheim et al., 1996; Franzmeier et al., 1996; Langley-Turnbaugh and Bockheim, 1997).

This study uses detailed, pedon-scale analysis set within a geographic framework whereby I examine trends in soil development across the region in a GIS. Soil development and variability across a 30 000 km^2 area in northern lower Michigan, known as the Grayling Fingers, were studied using the functional-factorial approach; pedon-scale data were used to provide details on soil development for parts of the landscape.

On one side of this region are some of the best-developed Haplorthods in the Great Lakes region. On the other side, only ≈55 km distant, the landscape is dominated by Psamments with little spodic development. Because well drained, sandy parent materials of a uniform age [≈13 000 kilo annum (ka)] dominate the region, I was able to hold the factors relief, parent material, and time constant; only vegetation and climate vary spatially. Ascertaining which of these last two soil-forming factors is most closely associated with this strong pedogenic gradient will advance our understanding of podzolization, here and elsewhere.

Thus, the purpose of the study is to (i) quantify soil development across the study area, and (ii) seek spatial interrelationships among soil development patterns and those of contemporary climate and presettlement vegetation.

Podzolization Theory

Podzolization is a pedogenic process in which organic carbon, Fe, and Al, in some combination, are translocated from the upper profile to an illuvial horizon (DeConinck, 1980; Buurman and van Reeuwijk, 1984; Courchesne and Hendershot, 1997; Lundstrom et al., 2000). Soils dominated by podzolization tend to have thin A horizons and light-colored, eluvial (E) horizons over Bh, Bs, Bsm, and/or Bhsm horizons in which amorphous compounds of Fe and Al have accumulated (Mokma and Evans, 2000). Two schools of thought exist to explain the podzolization process. In the first, Fe and Al sesquioxides form soluble organometallic complexes with organic molecules (chelates). These compounds are translocated by infiltrating water and precipitate as the microbes break down the organic (fulvic acid) molecules, as the chelates become saturated with metals, or at a water table or slowly-permeable layer (DeConinck, 1980; Buurman and van Reeuwijk, 1984). Observations that Al and Fe can exist in Spodosols as amorphous inorganic compounds such as imogolite and allophane have led to an alternate, proto-imogolite theory of podzolization (Farmer et al., 1980; Anderson et al., 1982; Farmer, 1982). In this theory, Al, and probably Fe, is first translocated into the B horizon as proto-imogolite sols; later processes involve migration and precipitation of organic matter onto the already-deposited Fe and Al. In all likelihood, some components of both theories are active in most Spodosols, but perhaps some sort of hybrid theory is closest to reality (Wang et al., 1986; Jakobsen, 1991; Ugolini and Sletten, 1991).

Spodosols tend to be best expressed under vegetation that produces acidic litter which fosters slow decomposition, resulting in thick O horizons which release abundant fulvic and low molecular weight acids (Vance et al., 1986). The acid litter also discourages the activity of soil fauna which, via pedoturbation, would otherwise

Dep. of Geography, 314 Natural Science Building, Michigan State Univ., East Lansing, MI 48824-1115. *Corresponding author (schaetzl@msu.edu).
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Abbreviations: ka, kilo annum; PSD, particle size distribution.

destroy the horizonation that typifies Spodosols. The litter of certain types of coniferous trees is particularly acidic, promoting podzolization more rapidly than that of others (Nielsen et al., 1987; Madsen and Nørnberg, 1995). Thus, any environment in which the growth of certain types of trees is encouraged should also promote podzolization, via the indirect litter effect. Likewise, fire destroys litter and in so doing slows or even stops podzolization (Schaetzl, 1994; Barrett, 1997).

In a classic study, Mokma and Vance (1989) related rates of podzolization to a continuum of three distinct vegetation–soil associations, widespread throughout the Great Lakes region (Abrams et al., 1985; Almendinger, 1990) (Fig. 1). Jack pine (*Pinus banksiana* Lamb.) is a fire climax species and its open, barrens-like stands tend to burn frequently (Simard and Blank, 1982; Weber, 1987). In the Great lakes region, jack pine stands are commonly associated with Typic, Spodic, and Lamellic Udipsamments (Radeloff et al., 1999). Recurrent fires in these stands not only promote continued jack pine regeneration, but burn the litter and retard podzolization processes (Brown, 1966). On the other end of this continuum, northern hardwood stands, dominated by sugar maple (*Acer saccharum* Marshall), American beech (*Fagus grandifolia* Ehrh.), basswood (*Tilia americana* L.), yellow birch (*Betula alleghaniensis* Britton) and aspen (*Populus* spp.), along with scattered conifers like white pine (*P. strobus*) and eastern hemlock [Tsuga canadensis (L.) Carriere] rarely burn. Lack of fire fosters high amounts of standing and dead biomass (i.e., thick litter accumulations), which in turn promote podzolization (Lorimer, 1977; Mokma and Vance, 1989; Shotola et al., 1992; Barrett et al., 1995). Soils beneath Michigan's northern hardwood forests tend to be strongly-developed Typic and Lamellic Haplorthods (Fig. 1). Mokma and Vance further suggested that pine-dominated stands (red pine, *P. resinosa*, and white pine) are intermediate in fire frequency and soil development. Entic and Lamellic Haplorthods are presumably associated with these type of pine stands (Fig. 1).

The vegetation-soil associations documented by Mokma and Vance (1989) are widespread throughout the Great Lakes region. Together, they form a realistic continuum, replete with internal feedback mechanisms acted out within the constraints of the landscape such as soil drainage class, texture, and slope (Fig. 2a). For example, fire frequency affects stand type and litter thickness, which in turn impacts soil development, which can also impact forest composition. The system interactions shown in Fig. 2a are designed to reflect the theoretical underpinnings of Mokma and Vance's (1989) paper for the soil-vegetation system on Michigan's sandy up-

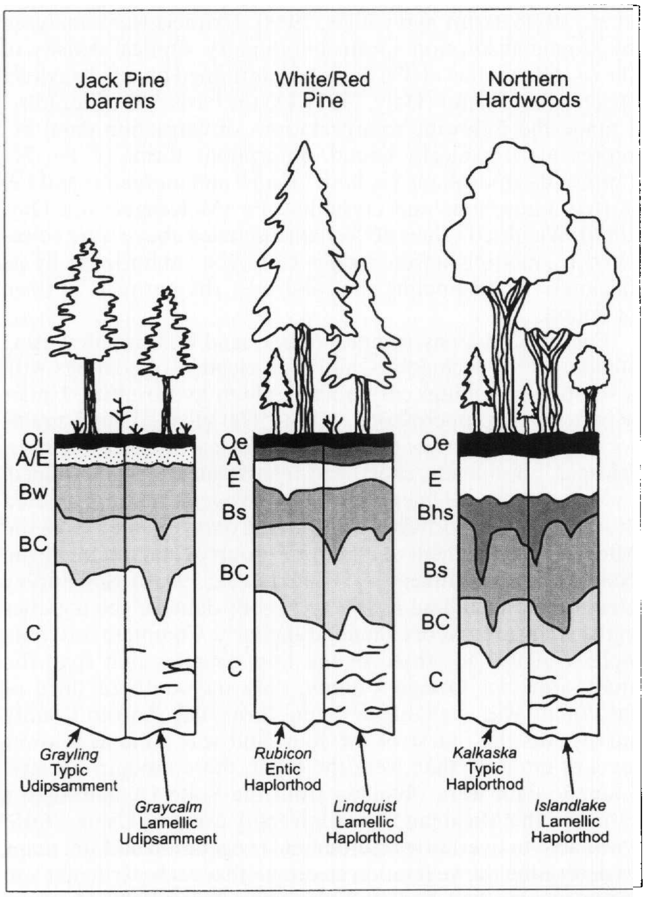

Fig. 1. Typical soil horizonation–forest overstory associations in Michigan and the Great Lakes region, on sandy landscapes. After Mokma and Vance (1989).

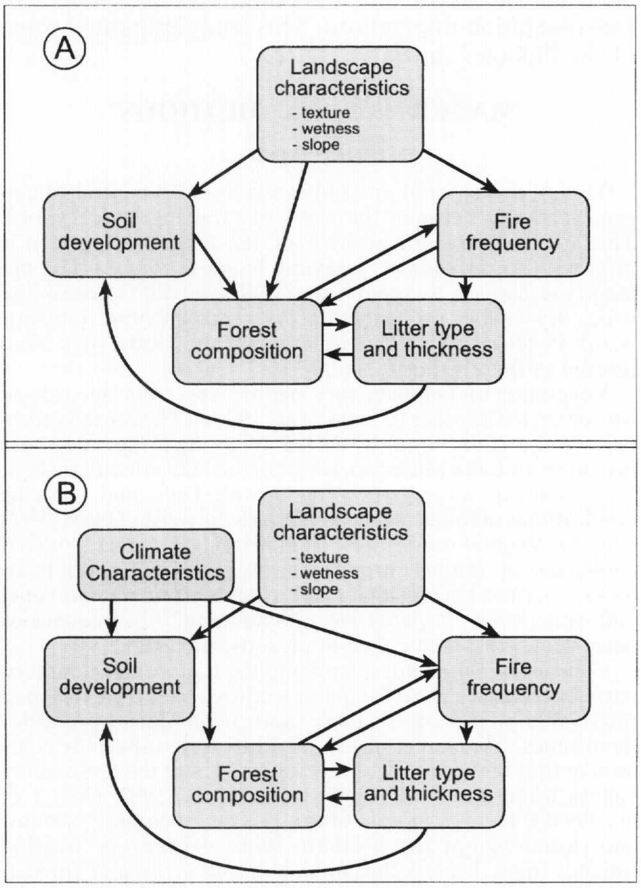

Fig. 2. Two models of extrinsic and intrinsic feedbacks for soil and vegetation systems of northern Michigan in particular, and the Great Lakes region in general. Model A is based largely on Mokma and Vance (1989), whereas model B is that model, but modified based on the findings of Schaetzl and Isard (1991, 1996).

lands. The system lacks, however, a direct climatic input mechanism.

Alternatively, Schaetzl and Isard (1991, 1996) have argued that the most important factor governing rates of podzolization in the Great Lakes region centers on inputs of water provided to the soil via snowmelt. For example, strongly podzolized, sandy Haplorthods in the northern Great Lakes area receive 3 to 5 times the infiltration during snowmelt than do Entisols farther south (Schaetzl and Isard, 1996). Only during snowmelt, while the vegetation is dormant, are soil profiles wet for extended periods of time and receiving large pulses of (snowmelt) water. Schaetzl (1990) and Schaetzl and Isard (1996) argued that slow, steady influxes of cold snowmelt water are particularly effective in the podzolization process. Soils with potential for large inputs of snowmelt water (due to thick snowpacks) also are less likely to be frozen, due to the insulating effects of the snowpack (Baker, 1971; Ellis, 1980; Isard and Schaetzl, 1995, 1998). This theory holds at mesoscales (across tens to hundreds of km^2) as well as at microscales. At mesoscales, differences in snowfall create spatial variability in snowmelt potential. At microscales, pits and depressions on the forest floor accumulate more snow than mounds, and pit soils are less likely to freeze, leading to accelerated podzolization in the pits (Schaetzl, 1990). Figure 2b incorporates the ideas presented by Schaetzl and Isard into the Mokma-Vance model of soil-vegetation interactions. This study examined some of the linkages shown in Fig. 2b.

MATERIALS AND METHODS

Study Area

This study centered on landscapes in north-central Michigan, generally between the cities of Grayling and Gaylord. This area is characterized by high, flat-topped uplands; it is informally known as the "Grayling Fingers" (Fig. 3). The uplands are capped by loamy sand and sand till, whereas the wide, dry valleys are underlain by sand alluvium. Uplands stand 45–60 m above the valleys. All the study sites were located in these valleys.

Vegetation and climate vary significantly from one side of the region to the other (Comer et al., 1995a). The northwestern part of the study area, by virtue of its high elevation and proximity to Lake Michigan, is within the lake effect snowbelt. Here, soils are strongly-developed, with Typic and Lamellic Haplorthods dominating the uplands (Schaetzl and Isard 1991) (Fig. 3). Vegetation on these Haplorthods is typically mixed coniferous-deciduous northern hardwoods, with eastern hemlock, American beech, sugar maple, red oak (*Quercus borealis*) and white birch (*B. papyrifera*) dominating. Fire frequencies here were, presumably, low in presettlement time.

Contrasting landscapes dominate the eastern and southern parts of the study area. Frequent wildfires historically shaped the vegetation patterns on these sandy plains during presettlement times (Higman et al., 1994). Fires were especially common in the southern part of this region, where the large sandy valleys trend east-west (Simard and Blank, 1982; Comer et al., 1995a). Here, a mosaic of dry prairie, open pine barrens, and closed canopy dry northern forest existed on Grayling (mixed, frigid Typic Udipsamments) and Graycalm (mixed, frigid Lamellic Udipsamments) soils (Fig. 3). [In the north–south trending valleys between the Fingers, however, fires were less common and the vegetation was more mesic (Comer, 1994)]. Snowfall is considerably less here than in the snowbelt, and continuous snowpacks are established much later in the fall.

Red and white pine forests, seen as intermediate in fire frequency (Mokma and Vance, 1989) were common in the central parts of the study area during the 1800s, but are less common now, except as plantations (Fig. 4).

Methods

Thirteen sites in dry Finger valleys were chosen as representative of the variability that exists in the well drained sandy soils of the Grayling Fingers (Fig. 3). Upland sites were not sampled because I wanted to control for texture as much as possible among the 13 sampled pedons; parent material textures on the uplands vary from sand to sandy loam, and coarse fragment contents range from 2–25%. Soil pits were dug at the 13 sites and a POD Index calculated. The POD Index is a numerical index of spodic development based on field-measured attributes; increasing POD values correlate to stronger soil development (Schaetzl and Mokma, 1988; Goldin and Edmonds, 1996). At each site, the vegetation was described and each pedon sampled by genetic horizon. Samples were air-dried and sieved to remove coarse fragments. The fine earth fraction was analyzed in the laboratory for pH (2:1 water:soil) and particle size distribution (PSD) by pipette and dry sieving (Soil Survey Laboratory Staff, 1996). Organic matter content was determined by loss on ignition (8 h at 430°C) (Davies, 1974). Extractions for Al and Fe were performed on E and B horizons (not BC horizons) using acid ammonium oxalate (Fe_o, Al_o), sodium pyrophosphate (Fe_p, Al_p), and sodium citrate-dithionite (Fe_d) (Soil Survey Laboratory Staff, 1996). Because the nature of Al_d is not well understood, I do not report those data (McKeague and Day, 1966; McKeague et al., 1971; Parfitt and Childs, 1988). Extracts were analyzed by atomic absorption spectrophotometry. Optical density of the oxalate extract at 430 nm was determined on an ultraviolet spectrophotometer (Daly, 1982). On the basis of the literature, I made the following interpretations of extraction data: Fe_p represents organically-bound, amorphous forms of Fe; Fe_o represents amorphous Fe, both organic and inorganic; and Fe_d is free amorphous and crystalline Fe (McKeague and Day, 1966). Weighted values of the data discussed above were calculated by multiplying the values (for each subhorizon) by its thickness, and summing the total over the entire B horizon or solum.

For most horizons, samples of fine sand were isolated using standard PSD techniques, and then cleaned of coatings with a solution of sodium citrate and sodium hydrosulfite. Under a petrographic microscope, 300 to 600 cleaned sand grains were classified into one of four mineralogical categories (quartz, feldspar, hornblende, chert) and relative amounts determined.

Maps of presettlement (circa 1840) vegetation were created in ArcView GIS software, using digital data obtained from the Michigan Department of Natural Resources and the Michigan Natural Features Inventory (Comer et al., 1995b). Soil Survey Geographic Database (SSURGO) soils data for the counties in the study area were examined similarly. Complete soils data were available for three of the four counties that span the study area; for Otsego County, only the southern third of the county was available in digital form. The Antrim County survey was the oldest of the four, and was done at a lower level of intensity than were the other, more modern surveys. Climatic data were obtained from the State Climatologist's office on the Michigan State University campus. Using a GIS, I was able to overlay (presettlement) vegetation and soil maps to determine the vegetation coverage that each particular soil series or map unit had, and vice versa, circa 1840. The area utilized for this procedure encompassed all the Grayling Fingers and a border of <10 km on all sides.

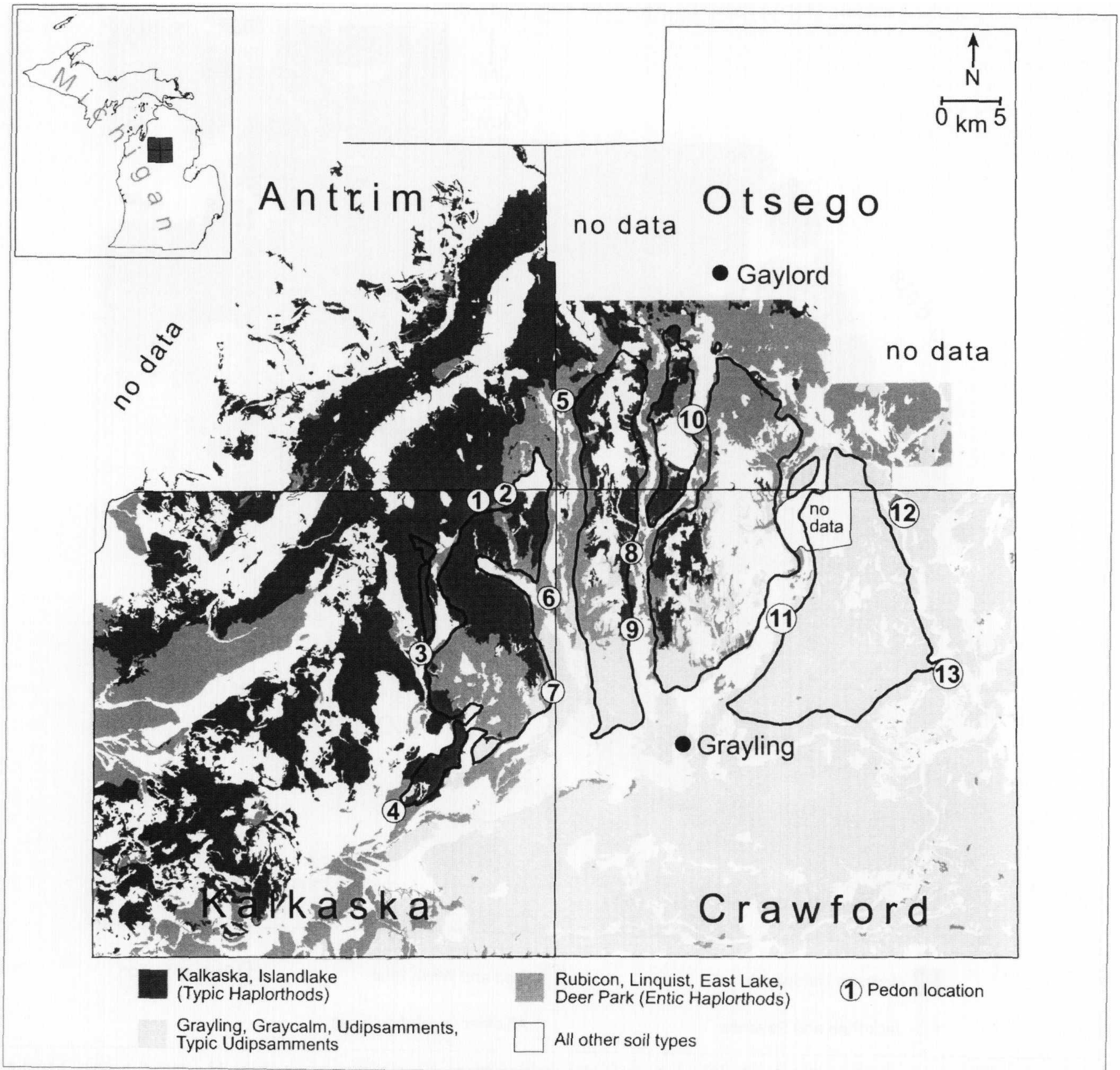

Fig. 3. Outline of the Grayling Fingers, overlain onto a map of soil development. Also shown are county names and the locations and numbers of the 13 sampled pedons, based on county-level, digital Soil Survey Geographic Database (SSURGO) data from the National Resources Conservation Service, East Lansing, MI.

RESULTS AND DISCUSSION

Soil Morphology and Classification

The 13 pedons examined have coarse sand, loamy sand, or sand textures (Table 1). All have formed in sediments carried by glacial meltwater during the waning stages of the Port Huron readvance, circa 13 ka, with possible reworking by meteoric runoff from postglacial streams. Lithologic discontinuities often occur within the lower solum and C horizon of the pedons, but this should not have markedly impacted podzolization in the very uniform materials above. These discontinuities and the stone lines that are often associated with them confirm the variability of past fluvial environments. Nonetheless, the particle size control section of most pedons is dominated by medium and fine sand, which attests to the uniformity of the last pulses of water that deposited the sands in the valleys of the Grayling Fingers.

Spodic development in the 13 pedons ranges from strongly developed Typic Haplorthods (e.g., Pedons 1, 6, and 8) to weakly developed Udipsamments (pedon 13) (Tables 1, 2). Among the well-drained sandy soils in this region, those in the Kalkaska series (sandy, mixed, frigid, Typic Haplorthods) are the most strongly developed (Schaetzl and Mokma, 1988) (Fig. 1). Grayling soils are the most weakly developed, often lacking

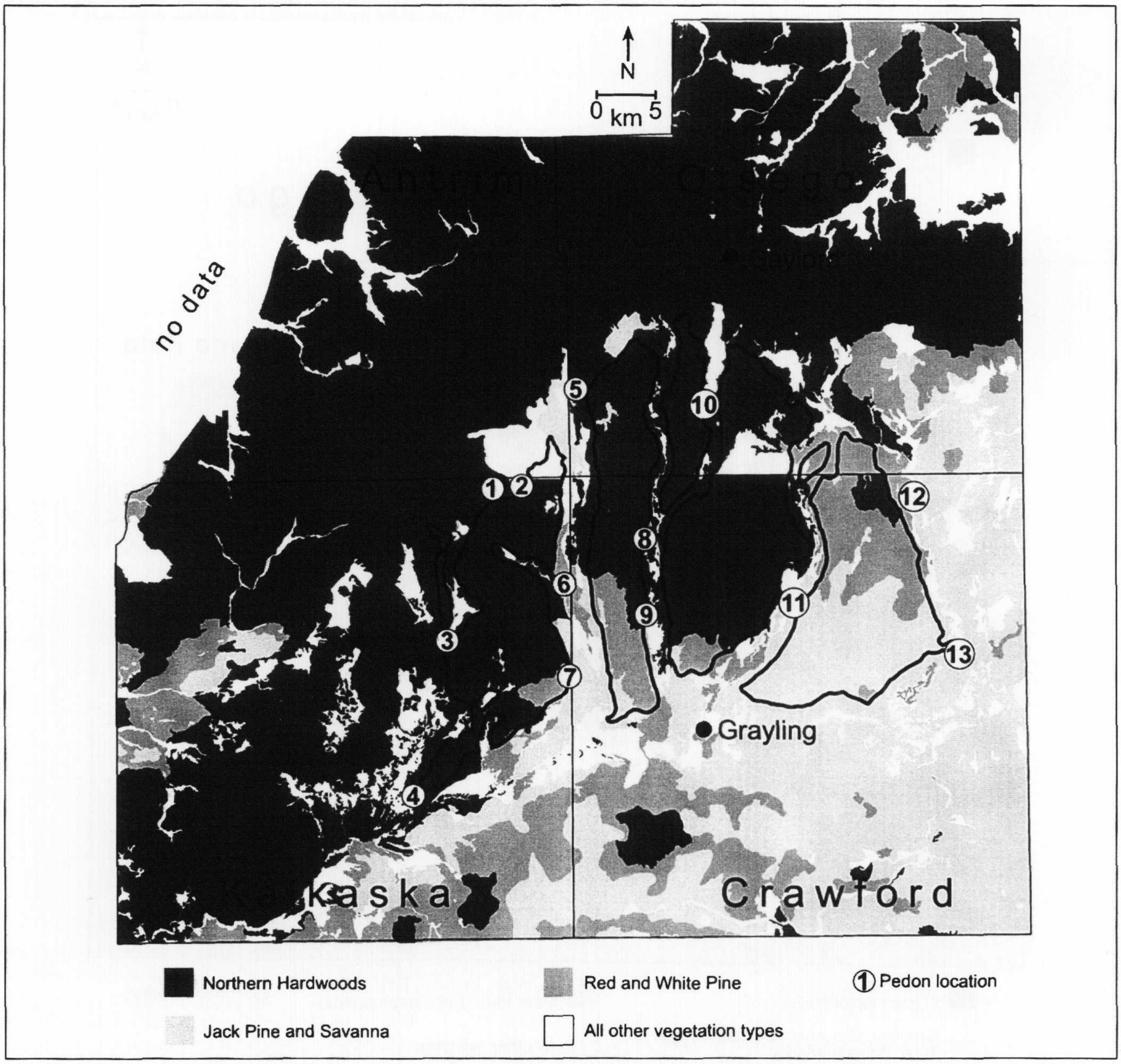

Fig. 4. Presettlement (circa 1830) vegetation for the study area, also showing the locations and numbers of the 13 sampled pedons, based on digital vegetation data obtained from the Michigan Department of Natural Resources.

E horizons (Fig. 1). Intermediate in development are soils within the Rubicon series (sandy, mixed, frigid Entic Haplorthods). I consider each of these series more or less equivalent to its lamellic counterpart. Although thin lamellae do allow the soil to retain more plant available water, the overall impact on podzolization in the upper solum is negligible; often the lamellae are simply Fe-rich bands, rather than textural lamellae (Schaetzl, 1992, 2001). Equivalent series without/with lamellae, respectively, are: Kalkaska/Islandlake, Rubicon/Lindquist, and Grayling/Graycalm. Series with lamellae thick enough to classify as an argillic horizon were avoided, but do occur to a limited extent in the study area.

Across the study area, spodic development increases from the southeast to the northwest (Fig. 5). This trend is illustrated in several ways. First, county soil maps of the region were mosaicked together and queried for well-drained, sandy mapping units that fell into each of three categories: (i) strongly developed Spodosols (Typic Haplorthods), (ii) moderately developed Spodosols (Entic Haplorthods), and (iii) weakly developed Udipsamments. These data show a clear regional trend (Fig. 3). Typic Haplorthod mapping units (i.e., Kalkaska–Islandlake) are clustered in the northwest, while Entisols dominate the eastern and southeastern parts of the study area. On the uplands, large areas of loamy sand parent materials exist, potentially complicating what

Table 1. Morphology and selected physical properties of representative pedons.

Pedon & horizon	Depth	Munsell color (moist)	Coarse fragments (>2 mm)	Very coarse sand (2.0–1.0 mm)	Coarse sand (1.0–0.5 mm)	Medium sand (0.5–0.25 mm)	Fine sand (0.25–0.125 mm)	Very fine sand (0.125–0.053 mm)	Silt (2–50 m)	Clay (<2 m)	Texture class
	cm		est. % by volume	%							
Kalkaska series (sandy, mixed, frigid Typic Haplorthods). POD Index† = 1.5, Native vegetation‡ = beech, sugar maple, yellow birch.											
1 – Oi	0–3										
1 – A	3–16	7.5YR 2/0	0	0.7	13.0	52.8	18.5	3.3	11.6	0.0	Sand
1 – E	16–24	5YR 4/3	0	0.5	15.5	54.1	14.8	2.6	12.4	0.0	Sand
1 – Bhs	24–31	5YR 2.5/2	0	1.7	12.1	50.2	17.1	2.2	13.2	3.5	Loamy sand
1 – Bs1	31–58	7.5YR 4/6	0	0.8	11.0	58.0	21.9	3.4	4.9	0.0	Sand
1 – Bs2	58–85	5YR 5/8	4	1.9	16.0	62.5	16.2	0.8	2.5	0.0	Sand
1 – Bw	85–128	10YR 4/6	4	0.8	7.3	59.3	29.3	1.5	1.8	0.0	Sand
1 – 2E/Bt	128–160+	10YR 4/6 (E) 7.5YR 4/4 (Bt)	8	1.1	14.1	58.7	21.6	2.6	2.0	0.0	Sand
Rubicon series (sandy, mixed, frigid Entic Haplorthods). POD Index = 3, Native vegetation = beech, sugar maple, yellow birch.											
3 – Oi	0–9										
3 – A/E	9–27	7.5YR 5/2	2	1.1	17.6	60.4	14.5	1.5	5.0	0.0	Sand
3 – Bs1	27–41	7.5YR 4/6	2	1.4	14.7	60.5	17.7	2.3	3.5	0.0	Sand
3 – Bs2	41–54	7.5YR 4/6	2	1.8	12.9	63.6	18.1	2.7	1.0	0.0	Sand
3 – Bsm	54–105	7.5YR 4/6 & 10YR 5/6	2	0.8	11.3	66.2	19.7	1.1	0.9	0.0	Sand
3 – BC	105–148	10YR 6/6	2	0.2	7.3	54.6	36.0	1.2	0.8	0.0	Sand
3 – C	148–270+	10YR 6/4	2	0.4	12.7	61.6	23.3	1.1	0.9	0.0	Sand
Deer Park series (mixed, frigid Spodic Udipsamments). POD Index = 0, Native vegetation = hemlock, white pine.											
4 – Oi	0–9										
4 – A	9–13	10YR 2/2	2								
4 – E	13–23	10YR 4/3	2	3.5	23.2	51.9	13.8	1.9	5.7	0.1	Sand
4 – Bs1	23–43	7.5YR 4/6	2	3.8	19.8	51.9	17.6	2.7	4.3	0.0	Sand
4 – Bs2	43–60	10YR 5/8	4	3.8	18.7	54.1	20.4	1.5	1.5	0.0	Sand
4 – Bs3	60–87	10YR 6/6	4	2.6	19.1	59.9	17.4	0.6	0.5	0.0	Sand
4 – 2BC	87–146	10YR 6/4	2	2.0	7.6	57.2	32.9	0.4	0.0	0.0	Sand
4 – 3C1	146–158	10YR 5/6	8	5.9	29.0	53.6	10.0	0.5	1.0	0.0	Sand
4 – 3C2	158–180+	10YR 6/3	2	0.2	4.0	76.9	18.4	0.3	0.3	0.0	Sand
Kalkaska series (sandy, mixed, frigid Typic Haplorthods). POD Index = 2, Native vegetation = red pine, white pine.											
6 – Oi	0–4										
6 – A	4–9	N 2/0	0	0.7	19.7	64.2	11.6	0.6	3.3	0.0	Sand
6 – E	9–20	7.5YR 4/2	0	0.7	17.5	62.0	13.7	1.2	3.7	1.2	Sand
6 – Bs1	20–41	5YR 3/4	0	1.0	14.0	63.7	15.4	1.2	4.8	0.0	Sand
6 – Bs2	41–62	10YR 4/6	0	0.2	10.3	71.5	16.1	0.7	0.1	1.0	Sand
6 – BC	62–126	10YR 5/4	1	0.1	3.0	65.0	30.7	0.8	0.5	0.0	Sand
6 – C	126–165+	10YR 6/4	1	0.2	2.6	49.5	46.0	1.4	0.0	0.4	Sand
Kalkaska series (sandy, mixed, frigid Typic Haplorthods). POD Index = 6, Native vegetation = northern hardwoods.											
8 – Oi	0–4										
8 – A	4–11	10YR 2/2	2	0.2	17.3	57.7	14.0	1.3	9.4	0.0	Sand
8 – E	11–28	7.5YR 4/2	2	3.2	19.8	58.1	12.4	1.3	5.3	0.0	Sand
8 – Bhs	28–37	2.5YR 2.5/2	2	1.4	15.5	57.3	16.1	0.8	8.8	0.0	Sand
8 – Bs1	37–53	7.5YR 4/4	2	2.6	19.3	61.1	13.3	1.0	2.7	0.0	Sand
8 – Bs2	53–152	10YR 5/6 & 10YR 6/4	6	0.6	8.9	61.2	26.9	1.5	1.0	0.0	Sand
8 – BC	152–174	10YR 6/4	2	1.8	8.0	57.3	29.5	0.9	2.5	0.0	Sand
8 – 2Bhsm	174–194	2.5YR 2.4/4	40	8.5	30.1	46.7	7.7	2.3	4.7	0.0	Clay sand
8 – 2C	194–215+	10YR 6/3	4	2.8	30.2	59.3	6.4	0.1	1.2	0.0	Sand

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Table 1. Continued.

Pedon & horizon	Depth	Munsell color (moist)	Coarse fragments (>2 mm)	Very coarse sand (2.0–1.0 mm)	Coarse sand (1.0–0.5 mm)	Medium sand (0.5–0.25 mm)	Fine sand (0.25–0.125 mm)	Very fine sand (0.125–0.053 mm)	Silt (2–50 m)	Clay (<2 m)	Texture class
	cm		est. % by volume	%							
Rubicon series (sandy, mixed, frigid Entic Haplorthods). POD Index = 0, Native vegetation = upland conifers.											
9 – A/E	0–10	10YR 3/2 & 10YR 4/2	4	1.1	13.3	59.6	16.0	1.4	8.6	0.0	Sand
9 – Bs	10–31	5YR 4/4	4	2.1	11.5	56.5	21.3	2.4	6.2	0.0	Sand
9 – Bw	31–50	7.5YR 4/6	4	1.9	13.6	59.3	20.2	1.4	2.4	1.3	Sand
9 – BC	50–101	10YR 5/6	6	0.6	11.1	63.5	20.7	1.0	3.2	0.0	Sand
9 – C1	101–136	10YR 5/4	10	2.5	17.5	59.6	16.1	1.0	3.4	0.0	Sand
9 – C2	136–178	10YR 5/4	4	5.1	27.4	54.9	10.6	0.2	1.7	0.1	Sand
9 – 2C	178–275+	10YR 6/4	2	0.3	5.6	56.3	36.0	1.3	0.5	0.0	Sand
Deer Park series (mixed, frigid Spodic Udipsamments). POD Index = 0, Native vegetation = grassland.											
12 – Oi	0–8										
12 – A	8–17	10YR 3/1	2	1.3	28.4	56.6	5.4	0.7	7.5	0.0	Sand
12 – Bw1	17–48	10YR 4/6	2	2.7	21.6	61.2	8.8	1.3	4.2	0.2	Sand
12 – Bw2	48–61	10YR 5/8	2	2.1	18.7	64.2	10.1	0.7	4.2	0.0	Sand
12 – BC	61–96	10YR 6/4	2	1.8	12.3	70.1	14.7	0.8	0.4	0.0	Sand
12 – 2C	96–139	10YR 4/4 & 10YR 5/4	35	7.9	28.3	51.1	5.9	1.5	5.4	0.0	Sand
12 – 3C	139–150+	10YR 5/2 & 10YR 5/3	25	9.6	43.1	38.2	3.8	1.8	3.6	0.0	Clay sand
Grayling series (Mixed, frigid Typic Udipsamments). POD Index = 0, Native vegetation = pine savanna.											
13 – Oi	0–4										
13 – A	4–12	10YR 3/2	2	0.8	22.3	60.8	7.2	0.6	8.2	0.1	Sand
13 – Bw1	12–35	7.5YR 4/6	2	1.6	19.9	64.3	8.4	0.7	5.2	0.0	Sand
13 – Bw2	35–73	10YR 5/6	2	2.3	21.7	66.0	8.7	0.1	1.2	0.0	Sand
13 – BC	73–86	10YR 5/4	6	2.3	28.0	63.4	5.3	0.2	0.8	0.0	Sand
13 – 2C	86–103	10YR 5/8	60	9.0	38.6	45.2	3.9	0.6	2.8	0.0	Clay sand
13 – 3C1	103–119	10YR 5/3	8	3.2	37.0	49.9	6.6	0.7	2.7	0.0	Clay sand
13 – 3C2	119–136	10YR 6/3	4	0.9	11.6	75.4	11.3	0.2	0.7	0.0	Sand
13 – 3C3	136–152	10YR 4/4	19	6.4	11.7	60.4	16.3	1.5	3.8	0.0	Sand
13 – 4C	162–180+	10YR 5/3	68	17.8	28.9	41.4	7.1	2.0	2.9	0.0	Clay sand

† POD is a soil development index, from Schaetzl and Mokma (1988). Larger values indicate greater degree of spodic development.
‡ On the basis of digital data on Michigan's presettlement vegetation (Comer et al., 1995b).

Table 2. Chemical and mineralogical properties of representative pedons.

Pedon & horizon	Depth	Organic matter	pH	Quartz	Feldspar	Hornblende	Chert	Fe_d	Fe_p	Fe_o	ODOE‡	Al_p	Al_o
	cm	%		— % of fine sand fraction† —				— % dry soil —			% abs.	% dry soil	
Kalkaska series (sandy, mixed, frigid Typic Haplorthods). POD Index = 1.5, Native vegetation = beech, sugar maple, yellow birch.													
1 – A	3–16	4.2	4.7					0.07	0.02	0.01	0.10	0.00	0.01
1 – E	16–24	1.7	4.2	90.7	4.7	2.5	2.2	0.05	0.01	0.01	0.07	0.01	0.01
1 – Bhs	24–31	3.3	4.0	88.8	4.7	3.7	2.8	0.75	0.17	0.18	0.97	0.14	0.14
1 – Bs1	31–58	1.5	6.1	89.7	4.8	2.2	3.3	0.25	0.07	0.04	0.20	0.20	0.22
1 – Bs2	58–85	0.5	6.6	90.5	5.3	1.5	2.7	0.05	0.03	0.02	0.07	0.07	0.10
1 – Bw	85–128	0.3	6.7					0.05	0.01	0.01	0.04	0.06	0.08
1 – 2E/Bt	128–160+	0.3	6.9	87.0	7.0	3.5	2.5						
Rubicon series (sandy, mixed, frigid Entic Haplorthods). POD Index = 3, Native vegetation = beech, sugar maple, yellow birch.													
3 – A/E	9–27	4.2	4.3	90.0	5.7	3.0	1.3	0.03	0.00	0.00	0.00	0.00	0.00
3 – Bs1	27–41	2.1	4.6	83.0	6.0	9.3	1.7	0.48	0.16	0.33	0.34	0.18	0.32
3 – Bs2	41–54	1.1	5.6	84.7	5.7	9.0	0.7	0.19	0.04	0.12	0.13	0.13	0.34
3 – Bsm	54–105	0.7	5.5					0.11	0.03	0.06	0.10	0.09	0.16
3 – BC	105–148	0.3	6.4	87.0	7.3	3.3	2.3						
3 – C	148–270+	0.2	6.5	86.7	3.7	8.0	1.7						
Deer Park series (mixed, frigid Spodic Udipsamments). POD Index = 0, Native vegetation = hemlock, white pine.													
4 – A	9–13												
4 – E	13–23	0.9	5.0	87.7	7.3	4.7	0.3	0.12	0.03	0.05	0.07	0.03	0.04
4 – Bs1	23–43	1.4	5.5	82.0	6.0	10.0	2.0	0.32	0.08	0.16	0.14	0.17	0.30
4 – Bs2	43–60	0.6	5.4	83.0	7.7	6.3	3.0	0.10	0.02	0.04	0.07	0.07	0.16
4 – Bs3	60–87	0.3	5.6					0.05	0.01	0.02	0.03	0.03	0.08
4 – 2BC	87–146	0.2	6.0	82.0	8.7	6.3	3.0						
4 – 3C1	146–158	0.2	6.2	86.0	5.3	6.0	2.7						
4 – 3C2	158–180+	0.1	6.7										
Kalkaska series (sandy, mixed, frigid Typic Haplorthods). POD Index = 2, Native vegetation = red pine, white pine.													
6 – A	4–9	4.4	4.0					0.04	0.01	0.01	0.06	0.02	0.02
6 – E	9–20	0.6	6.1	86.0	8.2	3.3	2.5	0.04	0.01	0.01	0.04	0.00	0.01
6 – Bs1	20–41	1.8	6.1	87.3	6.5	3.3	2.8	0.29	0.06	0.06	0.36	0.18	0.24
6 – Bs2	41–62	0.5	6.9	89.3	4.0	4.0	2.7	0.05	0.02	0.01	0.06	0.07	0.13
6 – BC	62–126	0.3	7.2	87.3	5.4	3.7	3.7						
6 – C	126–165+	0.2	7.5	84.2	8.5	4.3	3.0						
Kalkaska series (sandy, mixed, frigid Typic Haplorthods). POD Index = 6, Native vegetation = northern hardwoods.													
8 – A	4–11	7.0	5.8										
8 – E	11–28	0.8	4.9	85.9	5.6	5.9	2.6	0.07	0.02	0.02	0.06	0.00	0.02
8 – Bhs	28–37	1.8	5.1	82.3	6.0	9.3	2.3	0.36	0.16	0.19	0.55	0.13	0.16
8 – Bs1	37–53	1.4	5.1	85.0	4.7	9.0	1.3	0.16	0.06	0.07	0.25	0.17	0.18
8 – Bs2	53–152	0.4	5.6	86.0	9.0	4.3	0.7	0.07	0.02	0.02	0.07	0.06	0.10
8 – BC	152–174	0.3	6.3	88.3	5.0	2.7	4.0						
8 – 2Bhsm	174–194	4.5	5.2					0.43	0.07	0.13	1.00	0.38	0.71
8 – 2C	194–215+	0.4	6.7	84.3	6.3	5.0	4.3						
Rubicon series (sandy, mixed, frigid Entic Haplorthods). POD Index = 0, Native vegetation = upland conifers.													
9 – A/E	0–10	4.7	6.2	90.0	3.3	5.7	1.0	0.11	0.04	0.05	0.13	0.04	0.04
9 – Bs	10–31	1.7	5.4	84.3	4.0	9.7	2.0	0.38	0.11	0.18	0.25	0.17	0.27
9 – Bw	31–50	1.1	5.4	82.3	5.3	10.3	2.0	0.24	0.05	0.11	0.13	0.04	0.20
9 – BC	50–101	0.3	5.7	86.6	3.3	5.0	5.0						
9 – C1	101–136	0.3	6.2	87.0	4.3	6.0	2.7						
9 – C2	136–178	0.2	7.0										
9 – 2C	178–275+	0.1	6.5										
Deer Park series (mixed, frigid Spodic Udipsamments). POD Index = 0, Native vegetation = grassland.													
12 – A	8–17	3.8	5.2	84.7	6.7	7.7	1.0						
12 – Bw1	17–48	1.2	5.4	81.3	4.3	11.3	3.0	0.26	0.06	0.13	0.10	0.12	0.18
12 – Bw2	48–61	0.6	5.5	81.3	5.3	8.3	5.0	0.15	0.03	0.06	0.05	0.08	0.13
12 – BC	61–96	0.3	6.5	84.7	5.0	6.6	3.7						
12 – 2C	96–139	1.4	8.1	90.0	2.7	5.7	1.7						
12 – 3C	139–150+	0.3	8.5										
Grayling series (mixed, frigid Typic Udipsamments). POD Index = 0, Native vegetation = pine savanna.													
13 – A	4–12	2.4	5.5	81.9	4.7	10.0	3.3						
13 – Bw1	12–35	1.1	5.1	83.2	5.5	7.4	3.9	0.21	0.05	0.07	0.09	0.11	0.13
13 – Bw2	35–73	0.3	5.5	83.0	6.3	8.0	2.7	0.05	0.01	0.03	0.03	0.04	0.07
13 – BC	73–86	0.3	6.8	84.0	5.7	6.0	4.3						
13 – 2C	86–103	0.4	6.3	83.0	6.7	7.0	3.3						
13 – 3C1	103–119	0.4	6.4										
13 – 3C2	119–136	0.2	6.4										
13 – 3C3	136–152	0.3	7.3										
13 – 4C	152–180+	0.3	8.2										

† Relative percentages of mineral grain counts. Grains of unknown origin are not included in the sample *n*.
‡ ODOE = optical density of the oxalate extract; abs. = absorbance.
§ POD is a soil development index, from Schaetzl and Mokma (1988).

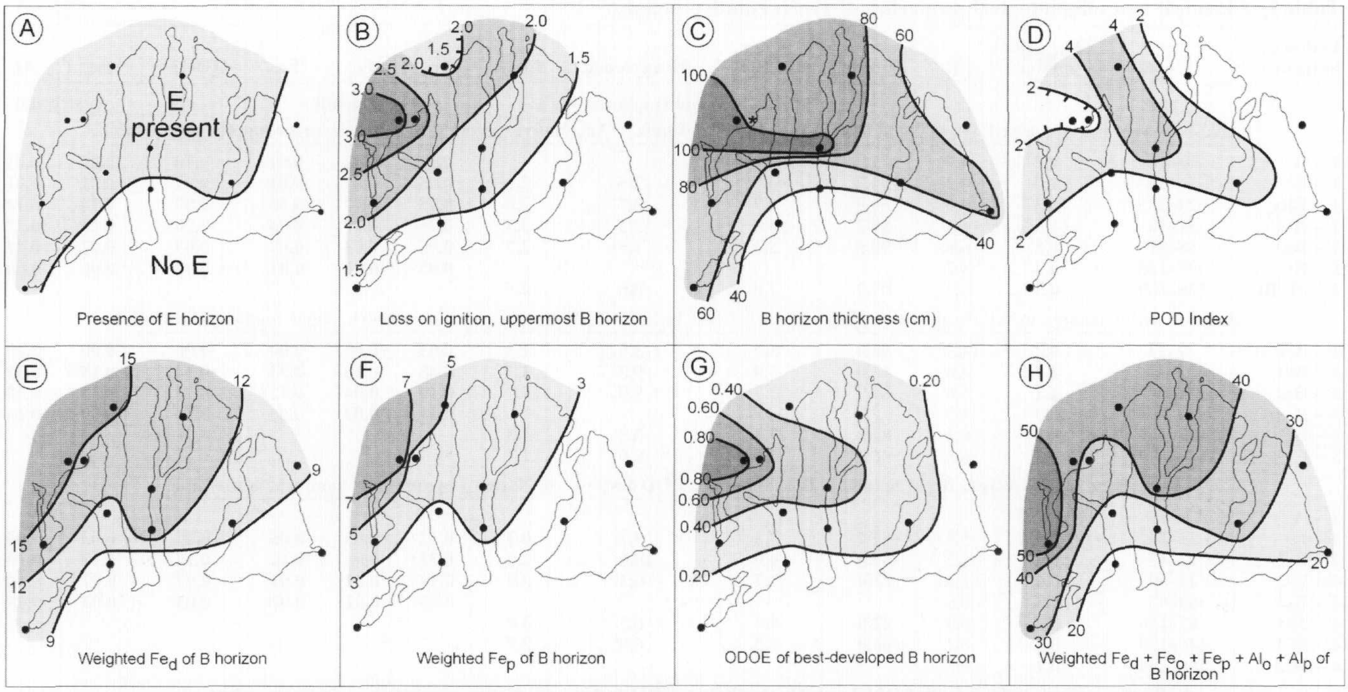

Fig. 5. Isoline maps of chemical and morphologic data from the 13 pedons studied in the Grayling Fingers area. Weighted values are determined by multiplying horizon-based data (%) by horizon thickness (cm), and summing across all pertinent horizons. Darker shading implies better development. The 13 pedons are all in the valleys between and adjacent to the upland Fingers. Thus, trends shown here may not be exactly reflected on the variable parent materials and landscapes of the Fingers proper. Isolines fitted by hand.

is a clear regional northwest-southeast trend in soil development. However, trends in soil development on the uplands are similar to that in the valleys: spodic development increases from the southeast to the northwest (Fig. 3). Second, various chemical and morphologic data from the 13 pedons were plotted and isolines drawn (Fig. 5). Although this northwest–southeast trend in podzolization intensity had been mapped previously and continues beyond the limits of the study area (Schaetzl and Isard, 1991), the zone of maximum rate of change per unit distance, that is, pedogenic gradient, lies within the Grayling Fingers. Thus, the combined database of soil maps for the region clearly shows a strong regional trend in soil development, which by virtue of the fact that all the soils are essentially the same age, corresponds to a map of podzolization intensity for the past 13 ka.

Pedogenic Factors Across the Region

Strong spatial trends in soil development in the Grayling Fingers region must coincide with at least one of the five pedogenic factors. All 13 sites examined are formed in sandy outwash of the same age, and thus time or soil age is ruled out as an explanatory factor. Of the 13 pedons, 12 were well or excessively drained; Pedon 11 was moderately well-drained (Table 1). All 13 pedons are dominated by sand; solum-weighted sand contents range from 91.8 to 98.0%, with most pedons having ≈96–97% sand (Fig. 6; Tables 1, 2). Solum-weighted silt contents range from 3.3 to 11.6%, with most pedons near 7 to 9%. Thus, parent material uniformity seems to rule out texture as a geographic variable that could have led to the strong regional pattern of soil development seen here.

Mokma and Vance (1989) found that the elemental composition of C horizons of Grayling, Rubicon, and Kalkaska soils from this region did not vary markedly, although the Grayling soils did have very low amounts of elemental Fe, Al, and Ca. Because such analyses include not only primary minerals but also grain coatings, I performed grain counts as a means to assess mineralogy directly, on the assumption that soils with more Fe-bearing, silicate minerals might have stronger spodic horizon development. In all cases, the general trends in mineralogy across the Fingers were subtle and the direction of change did not match that of soil development (Fig. 6). Thus, I conclude that the quartz-dominated mineralogy of the sands is sufficiently comparable across the region that mineralogy did not directly lead to the soil patterns observed today.

The effects of the vegetation and climate factors are more difficult to isolate for this region. In the northwest part of the Fingers, two factors that can lead to strong spodic development coincide, namely thick, lake effect snowpacks and fire-intolerant northern hardwood forests (Schaetzl and Isard, 1991, 1996; Mokma and Vance, 1989). In the southeastern part of the region, soils enter spring much drier due to thin snowpacks, setting the stage for more xeric summertime conditions and a greater likelihood of fire, two coincidental factors that retard spodic development. Thus, there are several potential interactive and/or feedback mechanisms among climatic and vegetative systems in the Grayling Fingers

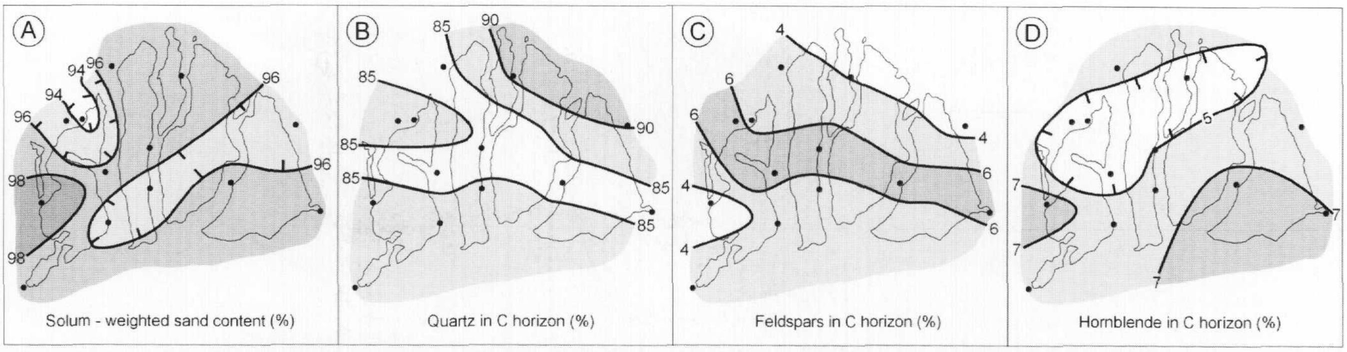

Fig. 6. Isoline maps of parent material texture and mineralogy, for the 13 pedons studied in the Grayling Fingers area. Weighted values are determined by multiplying horizon-based data (%) by horizon thickness (cm), and summing across all pertinent horizons. Darker shading implies conditions that might or should promote podzolization. Isolines fitted by hand.

region, making it difficult to isolate soil development from vegetation and climate factors (Fig. 2).

Vegetation-soil relationships, as illustrated by the areal coverage of each major soil association with major vegetative communities present at the time of European settlement, are generally consistent with current understanding of the soil-vegetation ecology of the area (Table 3). Jack pine was found almost exclusively on Udipsamments (Grayling and Graycalm). Similarly, more hectares of red and white pine forest occurred on Udipsamments than on Haplorthods, casting some doubt on the pine forest-Entic Haplorthod developmental pathway and/or association of Mokma and Vance (1989). Typic and Lamellic Haplorthods (Kalkaska and Islandlake series) commonly supported northern hardwoods, although the dominant forest cover on Spodosols of intermediate development was also northern hardwoods. From the data in Table 3, one might draw an initial conclusion that soil–vegetation associations in the Fingers region circa 1830 agree with those reported in nearby areas (Abrams, 1985; Higman et al., 1994; Host et al., 1988; Mokma and Vance, 1989). Upon detailed inspection, however, it becomes apparent that northern hardwoods are overrepresented on all landscapes, as they are the dominant cover type on the Kalkaska-Islandlake and Rubicon-Lindquist soils, and also occur on nearly 30 000 ha of dry Psamments (Table 3). In contrast, jack pine was not found on any of the well-developed Spodosols, and thus appears underrepresented on the landscape. On soils of intermediate development, in the central part of the Fingers, northern hardwoods were again the predominant cover type. Thus, the expected vegetation patterns, based on the model of Mokma and Vance (1989), did not materialize when the maps of soils and presettlement vegetation were overlain.

It is important to note that the vegetation pattern shown in Fig. 4 represents only one temporal snapshot and may not be indicative of the mean pattern across the Holocene. Vegetation patterns shift dramatically after disturbance and subtly as climate changes. Thus, it is difficult to discern the exact pedogenesis-vegetation pathways in this region, although the model presented in Fig. 2 (A or B) seems appropriate. It certainly is possible, but cannot be definitively demonstrated here, that vegetation in this region is acting as a wholly or partially dependent variable and not as an independent variable. In short, it cannot be determined whether vegetation patterns are a function of soils and climate, or vice versa. Fire frequencies have similar dependency problems, as they may be reacting to vegetation type (e.g., fire is more common in jack pine stands, but jack pine stands are in turn dependent upon, and promote, fire) or to climate. Decreased snowfall in eastern and southeastern parts of the study area tends to lead into edaphically drier spring and summer seasons, which in turn could promote fire.

The relationships among most climatic parameters and soil development are generally weak across the Fingers, with the exception of snowfall and snowpack, for which it is more strong spatially than even that of vegetation. Mean annual temperature varies by $<1°C$

Table 3. Matrix of areal coverage of soils and vegetation assemblages in the study area, circa 1840.†

	Northern hardwoods‡	Red and white pine§	Jack pine¶
Kalkaska and islandlake#	751 724 (24.5%)	12 109 (0.4%)	0 (0.0%)
Rubicon and Lindquist††	225 951 (7.4%)	208 696 (6.8%)	17 961 (0.6%)
Grayling and Graycalm‡‡	29 121 (0.9%)	331 927 (10.8%)	488 744 (15.9%)

† Numbers within the table are hectares in the study area with that particular soil–vegetation assemblage, and the percentage of the study area with that particular soil–vegetation assemblage.
‡ Includes stands interpreted by the Michigan DNR as "northern hardwoods", "beech–hemlock", "beech–sugar maple–yellow birch", "conifer/hardwood", "aspen–paper birch", "silver maple–red maple", and "white pine–beech–red maple".
§ Includes stands interpreted by the Michigan DNR as "red pine–white pine", "hemlock–white pine", "red pine–jack pine", and "red pine–oak".
¶ Includes stands interpreted by the Michigan DNR as "jack pine", "savanna", and "pine barrens".
# Typic Haplorthods, sandy. Islandlake is like Kalaska except that it has thin lamellae at depth.
†† Entic Haplorthods, sandy. Landquist is like Rubicon except that it has thin lamellae at depth. Includes "Entic Haplorthods" mapped on US Forest Service land.
‡‡ Udipsamments. Graycalm is like Grayling except that it has thin lamellae at depth. Includes "Typic Udipsamments" mapped on U.S. Forest Service land.

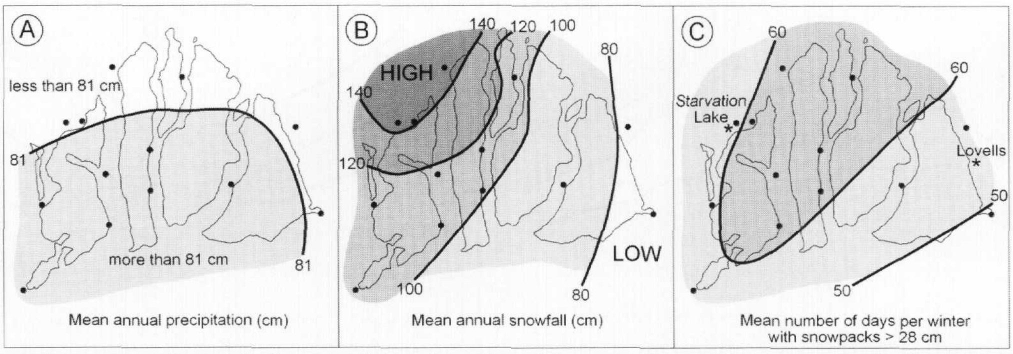

Fig. 7. Isoline maps of mean annual precipitation, snowfall, and number of days per winter with deep snowpacks, in the Grayling Fingers area. Sources: Michigan Department of Agriculture (1974) and Norton and Bolsenga (1993). Darker shading implies conditions that might or should promote podzolization.

across the region (Michigan Department of Agriculture, 1974), and mean annual precipitation is equally constant, varying by <1 cm from east to west (Fig. 7).

As expected, however, snowfall and snowpack data correlated closely with soil development patterns (Fig. 3, 5, 7) (Schaetzl and Isard, 1991). Both snowpack amounts, persistence, and date of first arrival increase to the northwest, which is in strong spatial agreement with spodic development patterns. Patterns between vegetation and spodic development are less evident. Local residents report that it is not uncommon for Starvation Lake, in the northwestern part of the study area, to have 60+ cm of snow on the ground, while Lovells, in the southeast, is essentially devoid of snowpack (Fig. 7). The thicker lake effect snow in the northwestern part of the Fingers results in more reliable and persistent snowpacks, which in turn reduces the likelihood of soil freezing (Isard and Schaetzl 1998). The slow, steady release of snowmelt waters, often continuing uninterrupted for days through fresh litter rich in organic acids, is therefore able to infiltrate into unfrozen soil; this process has been directly implicated as a strong vector of podzolization (Schaetzl and Isard, 1991, 1996). Influxes of snowmelt water are often the largest infiltration events of the year in the Fingers, where intense thunderstorms are not common. Data from Stoner and Ugolini (1988) attest to the importance of intense, prolonged infiltration events in podzolization.

CONCLUSIONS

Data suggest that climatic factors related to snowfall are strongly linked to spodic development patterns in northern lower Michigan, and by extension the entire Great Lakes region. Although vegetation patterns, and with them links to fire frequency and O horizon character, are also coincident with soil development patterns, the strongest spatial associations on sandy uplands appear to be among snowpack thicknesses, snowmelt infiltration totals, and soil development.

My results in no way undermine the model of Mokma and Vance (1989), which leans heavily on overstory vegetation and fire frequency as predictive variables in soil development (Fig. 2A). Vegetation character, O horizon thickness, and mesicness of the site can and do impact soil development. It is possible, however, that vegetation patterns are not working independently in this landscape. Rather, vegetation type and fire frequencies could simply be reacting to (i.e., dependent upon) spatial patterns of soil development and snowmelt infiltration. Because climate cannot be viewed as a dependent variable and because of the strong spatial linkages between snowpacks and soil development, I conclude that, on spatial and time scales equivalent to those examined here, the importance of snowmelt infiltration on podzolization can hardly be overestimated.

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