The Distribution of Spodosol Soils in Southern Michigan: A Climatic Interpretation

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Abstract. **This study describes and explains the geographic distribution of Spodosol soils (Podzols) on a regional scale. We employ a spatially-based, functional-factorial model of soil formation and, by holding four factors constant, are able to examine the effects of climate on soil genesis and distribution. Analysis of soils data for the southern peninsula of Michigan reveals that well and moderately well-drained, sandy Spodosols are found primarily in the northern half of the region in association with mixed coniferous-deciduous forest. Within this "Spodosol province," degree of soil development varies markedly. Differences in degree of soil development among sandy sites appear to be independent of present-day (or presettlement), regional vegetation patterns and may be related to variations in climate. Infiltration and "soil freezing potential," calculated using a hydrologic model, as well as air temperature records, are analyzed to ascertain which climate factors best correspond to observed trends in Spodosol development. Soils with strong spodic development exist in areas of northwestern southern (lower) Michigan that commonly experience deep lake-effect snows. Deep snowpacks in early winter inhibit soil frost, allowing for unrestricted infiltration of meltwater into the mineral soil during the spring snowmelt period (March and April). Correspondence between areas of increased autumn infiltration and strong Spodosol development suggests that wet soil conditions at the onset of winter also have impact on soil development, probably by inhibiting soil frost. Whereas the overall distribution of Spodosols is related to a coniferous component in the forest, variation in the degree of Spodosol development appears to be related to the frequency of years with high amounts of snowmelt infiltration, which intensifies the podzolization process.**

Key Words: infiltration, snowmelt, forest hydrology, podzolization, pedogenesis, soil geography.

THE aim of soil geography is to explain and record the development and distribution of soils on the earth's surface (Bridges 1981). A geographic approach to the study of soils is perhaps one of the oldest and most time-honored methods of gaining insight into soil genesis and history. Many late nineteenth- and early twentieth-century soil scientists were either educated as, influenced by, or worked closely with geographers (Tandarich et al. 1988) and thus demonstrated a distinctly geographic approach to their research.

Initial soil studies of a geographic nature were simply descriptive exercises in mapping and often failed to explain how the soil patterns observed had originated, because adequate models of soil formation had not yet been formulated. Later, pedologic/geographic scholars (Dokuchaiev 1893; Jenney 1941; Marbut 1951) provided a paradigm through which soil formation and distribution could be studied and interpreted. This framework functioned by linking soil properties to "state factors" of the environment. Through an analysis of the spatial variation in these factors, a better understanding of soil distributions was obtained. This principle can be applied at any scale of study, from global patterns to small-scale variation across a hillside.

The state factor theory, also called the functional-factorial approach (Jenny 1941), holds that soils are a function of five major soil-forming

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factors: climate, vegetation (organisms), relief (topography), parent material, and time. Jenny (1941), in his monograph on soil formation, stressed that although the functional-factorial approach:

> reveals the dependence of soil properties on soil-forming factors,... the conversion of such fundamental knowledge to specific field conditions is impossible unless the areal distribution of the soil formers is known. Clearly, it is the union of the geographic and the functional method that provides the most effective means of pedological research (262).

Working within the functional-factorial paradigm, explanation of the spatial variability of soils can be accomplished if several state factors are held constant and one or two are left to vary systematically across the landscape (*sensu* Jauhiainen 1973). Systematic variations in soil properties are then assumed to be primarily due to the one or two spatially varying factor(s).

When examined regionally, three of the five state factors (climate, organisms, and time) usually change gradually, whereas the remaining two factors (topography and parent material) generally vary in a more complex fashion that often cannot be shown on small-scale maps. Since time is a passive factor, the application of the functional-factorial approach to the mapping of soil distributions at global scales often results in generalized associations (spatial "links") between soils and vegetative-climate assemblages (cf. Sibirtsev 1901; James 1922; Volobuyev 1959; McCann 1979; Buol et al. 1989). Examples of these generalizations are the association of Udoll soils (Brunizems) with tallgrass prairie vegetation and subhumid climates, and the general correspondence of Spodosols with coniferous forests of subarctic climates.

Restriction of the area of study to an intermediate scale allows for a generalized association between a soil type and one state factor, as in the "coniferous forest soil" region mentioned above. This type of scale reduction allows for an analysis of relationships among smaller scale patterns of soil properties and spatial variations in one of the factors, provided that the impact on the soil of the remaining three state factors can be held constant.

We use this paradigm to analyze soil patterns in southern Michigan. First, we recognize the spatial coassociation between Spodosols and mixed coniferous-deciduous forests in northern lower Michigan. Second, we minimize variations in three state factors (parent material, topography, time) by examining only well-drained, sandy soils in a region where soils have had sufficient time to develop Spodosol morphology. Finally, we relate spatial variation in degree of soil development to climate patterns (*sensu* Jauhiainen 1973). Thus we use maps of soil distributions and environmental state factors to better understand soil processes (Simonson 1959). After we confirm the geographic links between factors and processes, extrapolation to other areas where processes are less understood can be accomplished and soil-geographic knowledge is advanced.

Patterns in Southern Michigan

Vegetation Patterns

A floristic boundary or "tension zone" has long been known to exist in lower Michigan (Livingston 1903; Nichols 1935; Potzger 1948; Braun 1950; Barnes and Wagner 1981). This zone is a relatively diffuse boundary between two major vegetation associations (Elliott 1953; Brewer 1982) (Figs. 1, 2). Forests south of the tension zone consist primarily of broadleaf deciduous species such as *Acer saccharum* (sugar maple), *Fagus grandifolia* (beech), and *Quercus* (oak). North of the tension zone, *A. saccharum, F. grandifolia, Pinus strobus* and *P. rubrum* (white and red pine), *Tsuga canadensis* (eastern hemlock), and *Betula lutea* (yellow birch) species are associated in a mixed coniferous-deciduous forest assemblage. But on dry, sandy sites north of the tension zone, nearly pure stands of pine were noted by federal land surveyors and early settlers (Fig. 2).

Because of the dramatic changes that have occurred in forest composition and physiognomy during the last 150 years, this discussion will focus on the vegetation patterns thought to exist at the time of European settlement. We recognize that vegetation, like climate, has been in a state of flux since deglaciation, and that soil patterns may be partially reflective of these earlier, rather than modern, vegetative patterns. With this caveat, we also recognize that general vegetation assemblages, as indicated in Figures 1 and 2, have not fluctuated markedly over the last few thousand years.

The presence, location, and abruptness of the tension zone have been associated with

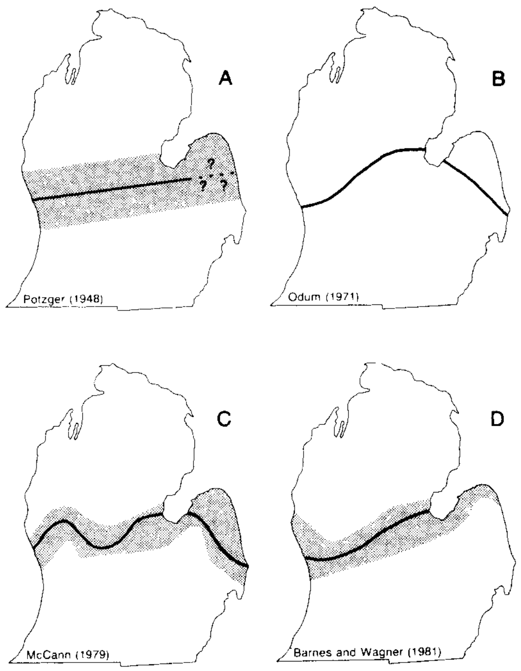


Figure 1. Location of the floristic tension zone in Michigan, marking the boundary between mixed coniferous-deciduous forests to the north and predominantly deciduous forests to the south. References to the original maps are provided in the lower left hand corner of each subfigure.

Figure 2. Presettlement vegetation patterns generalized for the southern peninsula of Michigan, after Marschner (1946).

selected environmental factors (surficial sediments, climate), effects of disturbance, and competition among tree species (Livingston 1903; Elliot 1953; McCann 1979; Brewer 1982; Medley and Harman 1987, 1989). Most studies, however, emphasize edaphic controls on the location of vegetation communities in lower Michigan (Veatch 1931). It is generally concluded that coarser-textured soils in northern regions favor coniferous species whereas the dominance of loamy soils south of the tension zone allow deciduous forest species to outcompete conifers (Livingston 1905; Medley and Harman 1987).

Prior to European settlement, sites with well-drained, sandy soils in lower Michigan were dominated by open, almost park-like *Quercus* forests (Veatch 1931; Brewer 1982). North of the tension zone, *Pinus* and *Quercus,* and to a lesser extent *T. canadensis,* were dominant on sandy soils (Veatch 1931; Elliott 1953).

Soil Patterns

Spodosols[1] in the Great Lakes region have their southernmost extent in Michigan. The southern limit of Spodosols in Michigan was recognized long ago as a major boundary between two pedologic "provinces," a northerly one dominated by podzolization processes in sandy materials and a southern zone where lessivage (clay translocation) overwhelms other processes in finer-textured, loamy materials. Early maps (Fig. 3) showed that northern lower Michigan was dominated by Spodosols (Podzols), with Alfisols (Gray-Brown Podzolic soils) covering extensive areas of southern lower Michigan, reflecting these two contrasting suites of pedologic processes.

In northern lower Michigan Spodosols are most common on sandy soils. Similar parent materials in southern Michigan typically lack a spodic horizon. The latter soils, formed under oak or oak-hickory forests, usually have a weak B horizon that may be slightly enriched in clay (Miles and Franzmeier 1981).

Maps of the distribution of Spodosols in lower Michigan depict a southern limit of these soils (Fig. 3) that roughly coincides with the floristic tension zone (Fig. 1) (Brewer 1982). This correspondence provides the basis for dividing lower Michigan into two soil-vegetation zones: (1) a northern, "Spodosol province" of Spo-

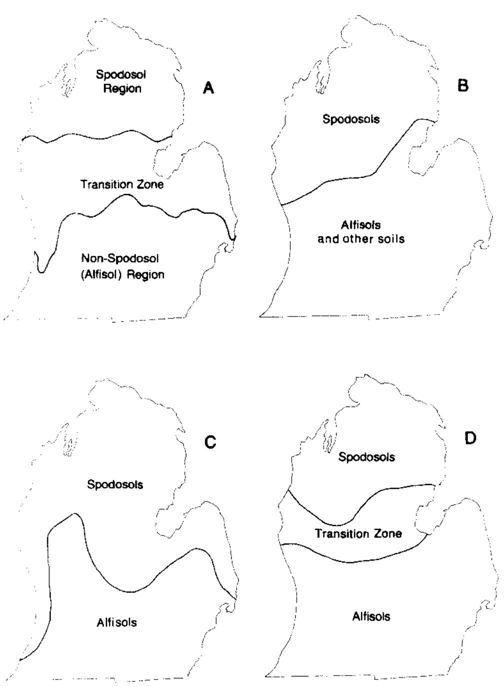


Figure 3. Location of the boundary between Podzols (Spodosols) and non-Podzols (non-Spodosols) in lower Michigan. Generalized from maps by (A) Veatch (1931), (B) Kellogg (1936), (C) Wilde (1946), and (D) Veatch (1953).

dosols, sandy parent materials, and mixed coniferous-deciduous forest and (2) a southern region of Alfisols, loamy sediments, and deciduous forest (Veatch 1931; Wilde 1933; Messenger 1966; Mokma and Vance 1989).

Podzolization

Podzolization processes that produce acidic soil profiles (Spodosols) are strongly-expressed on forested, sandy soils in northern lower Michigan (Gardner and Whiteside 1952; Brewer 1982). Podzolization is the term applied to a suite of acid-leaching processes that produce Podzol or Spodosol soil profiles (DeConinck 1980; Ugolini and Dahlgren 1987). These processes are best expressed in coarse-textured soils (Gardner and Whiteside 1952; Messenger et al. 1972; Vance et al. 1986). Podzolization processes can be summarized as follows: (1) decay of organic materials in upper horizons (O and A) produces acids capable of chelating Fe and Al cations, thus rendering them mobile within the soil profile and (2) these organometallic complexes are translocated into the B horizon and precipitated (Messenger et al. 1972; DeConinck 1980; Vance et al. 1986; Ugolini and Dahlgren 1987). The resulting soils have whitish E horizons depleted of Fe and Al, overlying dark, reddish brown spodic (Bs) horizons that have experienced illuviation (gains) of Fe and Al (Elliott 1953). Vertical percolation of water through the soil profile is the driving force behind the translocation of the organo-metallic complexes. A regional comparison of soil development under different climates in Finland suggested that podzolization increases with increasing "climatic humidity" and leaching (Jauhiainen 1973).

Podzolization is accelerated under coniferous vegetation (Wilde 1933; Messenger et al. 1972), which produces more acidic litter than do broadleaf trees. For this reason, podzolization and the Spodosol profile have been associated worldwide with coniferous and mixed coniferous-deciduous forests. This generalization applies in Michigan, where soils with spodic-like characteristics in northern sections of the state are often associated with *Pinus* or *Tsuga* forests (Veatch 1931; Wilde 1933), or mixed coniferous-deciduous stands (Mokma and Vance 1989).

Methods

In this study we use Soil Conservation Service (SCS) data to show the spatial variation in degree of development of dry, sandy Spodosols in lower Michigan and examine the importance of certain climate factors to the podzolization process by comparing their spatial and temporal distributions to patterns of Spodosol development. Restricting the analysis to the northern, mixed-forest province allows for an examination of the effects of climate on the spatial variation in soil development, independent of vegetation influence. We fully acknowledge the impact that local organisms, topography, parent material, and site history can have on the podzolization process (cf., Cann and Whiteside 1955; Crampton 1982; Mokma and Vance 1989; Schaetzl 1990). The analysis that we have undertaken focuses on broad-scale patterns that cannot be adequately explained by examining site-specific examples.

The variability in the "time" soil-forming factor across lower Michigan is relatively unimportant to a regional analysis of Spodosol development, as on highly permeable, sandy parent materials, weathering proceeds extremely rapidly, such that Spodosol morphology can develop within 8000 years in Michigan (Franzmeier and Whiteside 1963a, b). Except for areas immediately adjacent to Lakes Huron and Michigan, all of lower Michigan has been subaerially exposed for at least 9000 years (Farrand and Eschman 1974). Thus, major differences in soil development across the Spodosol province can be ascribed to spatial variations in climate factors (Messenger 1966), not time.

Soils Data

We tabulated the areal extent of soil series (hectares) on a county-level basis from published and forthcoming SCS soil surveys. We restricted the compilation to well and moderately well-drained soils in sandy (or "sandy over loamy," "sandy over clayey," etc.) textural families in order to minimize the effects of drainage and parent material on soil development. Where soils occurred as complex mapping units (containing more than one soil series), we assumed that all soil series had equal areal dominance. Mapping units designated as "beaches" or "pits, sandy" were not included in the data set because the youthful character of these soils has probably overwhelmed other soil-forming factors. The soils were divided into two main groups: non-Spodosols (Typic, Spodic, Alfic and Aquic Udipsamments, Psammentic Hapludalfs, and "dune land") and Spodosols (Typic, Entic, Alfic, Aquic, and Aqualfic Haplorthods). Typic Haplorthods were then separated from those Spodosol series that are less developed. For purposes of mapping, areal extent of these soil classes for each county was converted to the percentages of dry, sandy soils that are Spodosols and those that are Typic Haplorthods. Based on the above two maps and on older, smaller-scale, state-wide soil maps, we derived regions of varying "strength of podzolization" (Fig. 4).

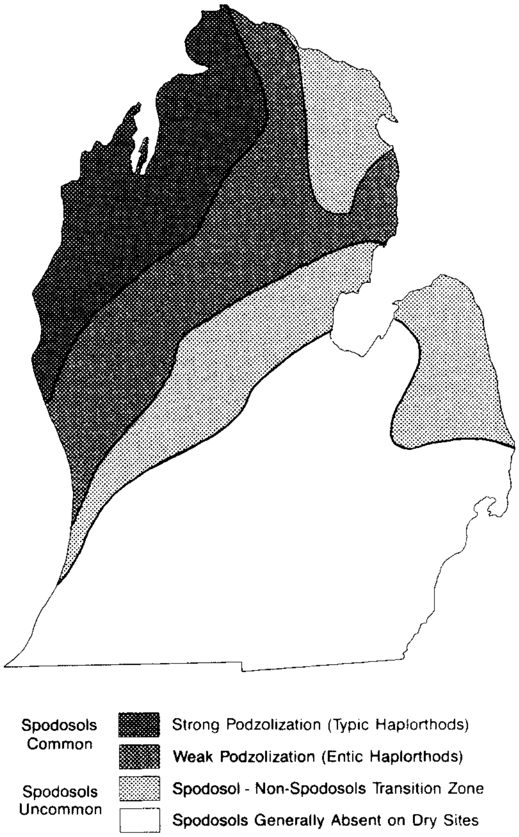


Figure 4. Zones of varying "strength of podzolization" for dry, sandy soils in lower Michigan.

Climate Factors

In most soils, temperature affects the rate of chemical and biochemical reactions (Smith 1986) and water is the primary agent of translocation (Buol et al. 1989). Therefore, podzolization is strongly influenced by the climate factors that control the heat content of the upper soil horizons and the chemistry and the amount of water that is translocated through the soil. Although air temperatures correspond reasonably well with temperatures of forested O and A horizons, the amount of precipitation that falls on a forest is not equivalent to the quantity of water that infiltrates into the mineral soil, since 10–35 percent of the water that falls is intercepted by the forest canopy and litter layer and is returned directly to the atmosphere

Table 1. Throughfall and Stemflow Equations Utilized in the Hydrologic Model

Equation[a]	Season[b] dormant/growing	Precipitation type[c] liquid/solid	Forest type[d] mixed/deciduous	References[e]
T = 0.853P − 0.36	Dormant	Liquid	Deciduous	1, 5, 10
T = 0.846P − 0.39	Growing	Liquid	Deciduous	1, 5, 10
S = 0.056P − 0.11	All seasons	Liquid[f]	Deciduous	1, 5, 8, 12
T = 0.814P − 1.92	All seasons	Liquid	Mixed	3, 6, 8, 12
S = 0.045P − 0.41	All seasons	Liquid[f]	Mixed	3, 8, 12
T = 0.95P	Dormant	Solid	Deciduous	7
T = 0.70P	Dormant	Solid	Mixed	2, 5, 9, 11, 12

[a] T = throughfall, P = gross precipitation, S = stemflow; all values in millimeters.
[b] The growing or "leaf-on" season is defined for deciduous forests in southern Michigan as 10 May–20 October. The dormant or "leaf-off" season is defined as 21 October–9 May.
[c] The model assumes that precipitation reported in the National Weather Service records falls in a liquid form (rain) if the mean daily temperature (MDT) is greater than or equal to 0°C. Snow (solid precipitation) is assumed on days in which the MDT is less than 0°C.
[d] The model used equations for deciduous forest for NWS stations south of the floristic tension zone as interpreted by McCann (1979). Stations north of this boundary are assigned mixed coniferous/deciduous forest equations. See Figure 1 for the location of this tension zone.
[e] Although each author calculated throughfall or stemflow coefficients unique to their study area, there is a general correspondence among coefficients for each season, vegetation type, and precipitation type. General references are as follows: 1, Brown and Barker (1970); 2, Hansen (1969); 3, Helvey (1967); 4, Kolesov (1985); 5, Leonard (1961); 6, Mahendrappa and Kingston (1982); 7, Maule (1934); 8, Rogerson and Byrnes (1968); 9, Satterlund and Haupt (1970); 10, Trimble and Weitzman (1954); 11, Wood (1937); 12, Voigt (1960).
[f] Stemflow is not computed for inputs of solid precipitation.

(Wood 1937; Voigt 1960; Leonard 1961; Swank et al. 1972; Helvey 1967). For this reason we developed a hydrologic model that computes infiltration (water passing through the litter layer and into the mineral soil). This model combines a water-budget model with SCS snowmelt and runoff models (USDA-SCS 1971).

The model's algorithm incorporates daily precipitation (total) and temperature (mean) data and functions as follows. The amount of water reaching the forest floor via stemflow and canopy throughfall is calculated using equations from forest hydrology literature (Table 1). The model assumes that precipitation falls as rain only when the mean daily temperature is greater than or equal to 0°C; otherwise, snow is assumed. The model allows for water storage in both the litter layer and the snowpack. If a snowpack exists and the mean daily air temperature is above freezing, snowmelt is calculated as a linear function of the mean air temperature (Garstka 1964) and is added to the litter layer. When a snowpack does not exist, potential evaporation from the litter layer is calculated using the Thornthwaite method (Thornthwaite and Mather 1955), modified for daily input data (Willmott 1977). The assumption of a linear relationship between the ratio of actual to potential evaporation and available moisture (Baier and Robertson 1966) is employed to calculate evaporative water loss from the litter layer (Blow 1955; Metz 1958; Helvey 1964). Runoff from the forest surface is computed as a function of precipitation, antecedent precipitation, forest condition, and soil group classification (USDA-SCS 1971). Infiltration (into the mineral soil) is calculated as the difference between the computed litter moisture value and the litter moisture retention capacity for days when the former exceeded the latter. Five types of input parameters are required to operationalize the model: (1) the latitude of the site, (2) throughfall and stemflow equation coefficients for dormant and growing season, (3) the water retention capacity of the forest litter layer, (4) the SCS hydrologic soil group classification, and (5) the SCS forest condition classification.

Daily infiltration into the mineral soil was computed for the period 1951–80 from daily precipitation and temperature data for 52 National Weather Service (NWS) stations in lower Michigan. Water retention capacity of litter from mixed coniferous-deciduous forests in Michigan was determined gravimetrically (Schaetzl and Isard 1990). The retention capacity for deciduous forest litter was assumed to be 50 percent of that for coniferous forests (Molchanov 1960) because the former generally occurs as thinner layers; both estimates of litter water retention are conservative (Mader and Lull 1968). Runoff potential on the sandy forest soils examined herein was low (USDA-SCS 1971, table 7.1, Hydrologic Soil Group A). The condition of the litter layer on the forest floor was considered to be loose or friable.

It should be noted that the computed infiltration values are only approximations for comparative analyses of factors that influence the degree of soil development. The use of empirical formulas for canopy throughfall, snowmelt, evaporation, and runoff is justifiable because data necessary for more rigorous, physically-based analyses are lacking. Similarly, the water-balance methodology has proven useful for many environmental applications. An analysis of the sensitivity of the output from a comparable earlier version of the hydrologic model to changes in input parameters within the reported range of values indicates that infiltration computations for the snowmelt season are very sensitive to variations in the throughfall equation coefficients for solid precipitation, whereas infiltration during the growing season is not sensitive to changes in the litter water-retention capacity (Schaetzl and Isard 1990).

Results and Discussion

Patterns of Spodosol Development in Southern Michigan

Wide expanses of dry, sandy parent materials exist in northern sections of southern Michigan (Fig. 5A) with lesser but significant areas of similar parent materials in the extreme south. Spodosols are not found in the latter region (Fig. 3). This absence clearly cannot be ascribed to a lack of adequate parent materials.

Early general maps of the distribution of Spodosols in lower Michigan (Fig. 3) provide information on the southern limit of these soils but do not address strength of soil development within the Spodosol-mixed forest province or the spatial dominance of Spodosols on the landscape. Detailed soil maps (Fig. 6) indicate that Spodosols are dominant only in the northwestern sections of the lower peninsula and are in agreement with SCS data (Fig. 5A). Strongly-developed Spodosols (Typic Haplorthods), having abundant organic carbon in the B horizon, are even more geographically restricted (Figs. 5B, 6A).

Data from Figures 5 and 6 are used to create a map of the "strength of podzolization" in lower Michigan (Fig. 4). This map depicts a zone of strongest podzolization and Spodosol development (Typic Haplorthods dominant) in extreme northwestern sections of lower Michigan. Landscapes where podzolization is weakly expressed (Entic Haplorthods dominant as they have weakly-developed spodic horizons) extend to the south and east. Still further south and east, a transition zone can be inferred that divides the Spodosol province, where Spodosols are likely to develop on dry, sandy sites, from areas to the south where Spodosols are generally absent on such sites (Fig. 4). The southern limit of the inferred transition coincides well with the floristic tension zone (Fig. 1).

Factors Affecting Strength of Spodosol Development

The data presented above suggest that vegetation and climate play an important role in determining the general distribution of Spodosols in lower Michigan. Because the southern limit of Spodosols corresponds with that of the floristic tension zone (cf. Figs. 1–3, 6), the presence of a coniferous forest appears to be a necessary but not sufficient condition for the development of Spodosols, probably because of additions of acidic litter (Messenger 1966; Mokma and Vance 1989). If degree of soil development was only a function of the proportion of coniferous species in the forest, strongly-developed Spodosols should be present across the entire northern half of the lower peninsula (Fig. 2). Although SCS data on a county-wide basis are incomplete, the northeastern section of the Spodosol province appears to be an area of weaker soil development than areas to the west (Figs. 4–6; Williams 1990).

Variation in air temperature across the Spodosol province of Michigan, whether expressed by growing degree days, heat accumulation, or length of the frost-free period, primarily reflects the latitudinal and "lake effect" trends (cooler summers near Lakes Huron and Michigan; McCann 1979). Maps of average monthly, seasonal and annual air temperature for the period 1940–69 (Michigan Department of Agriculture 1974) fail to correspond well with the soil development trends shown in Figure 4. It appears that the relatively small regional variation in air temperature within the Spo-

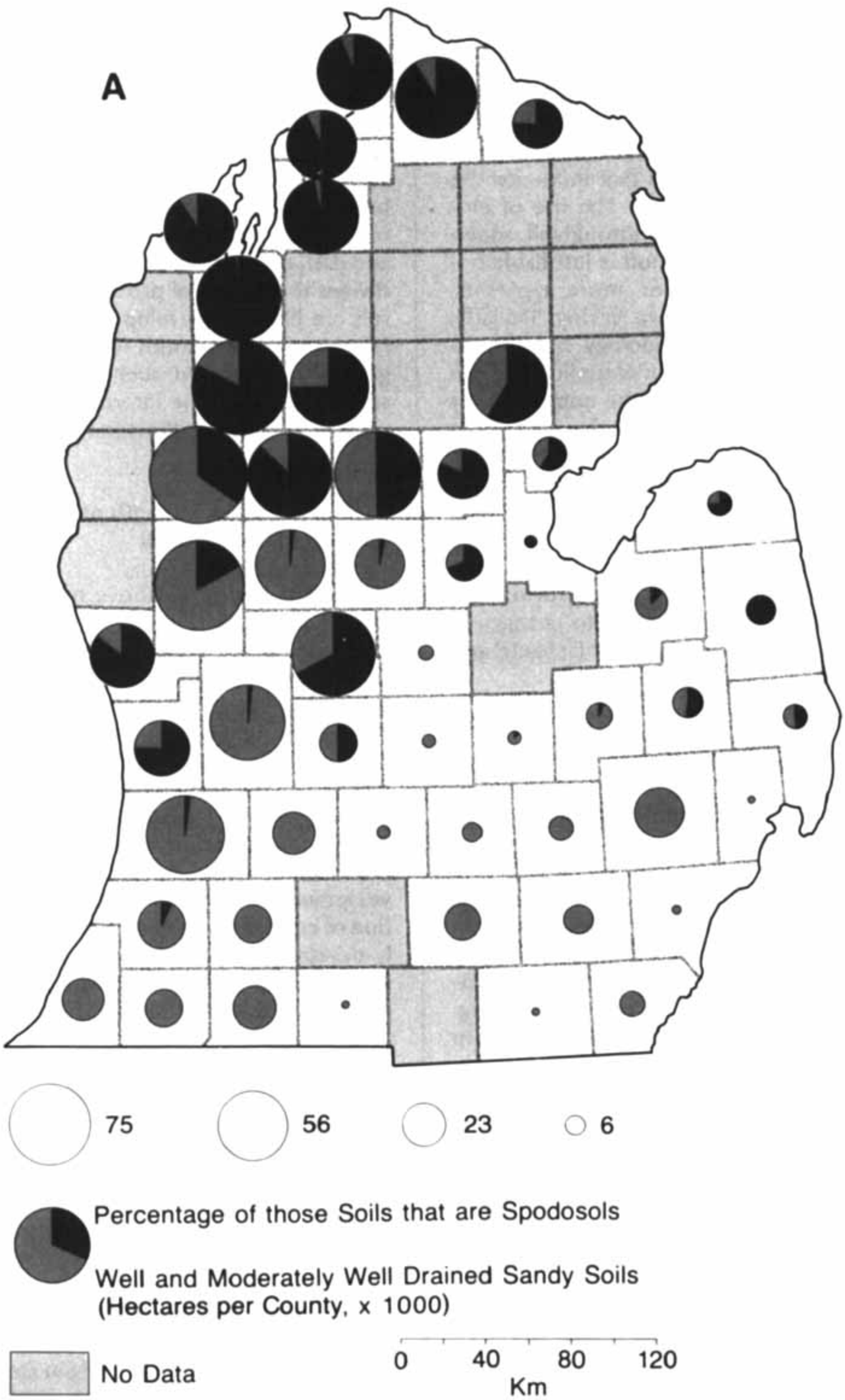
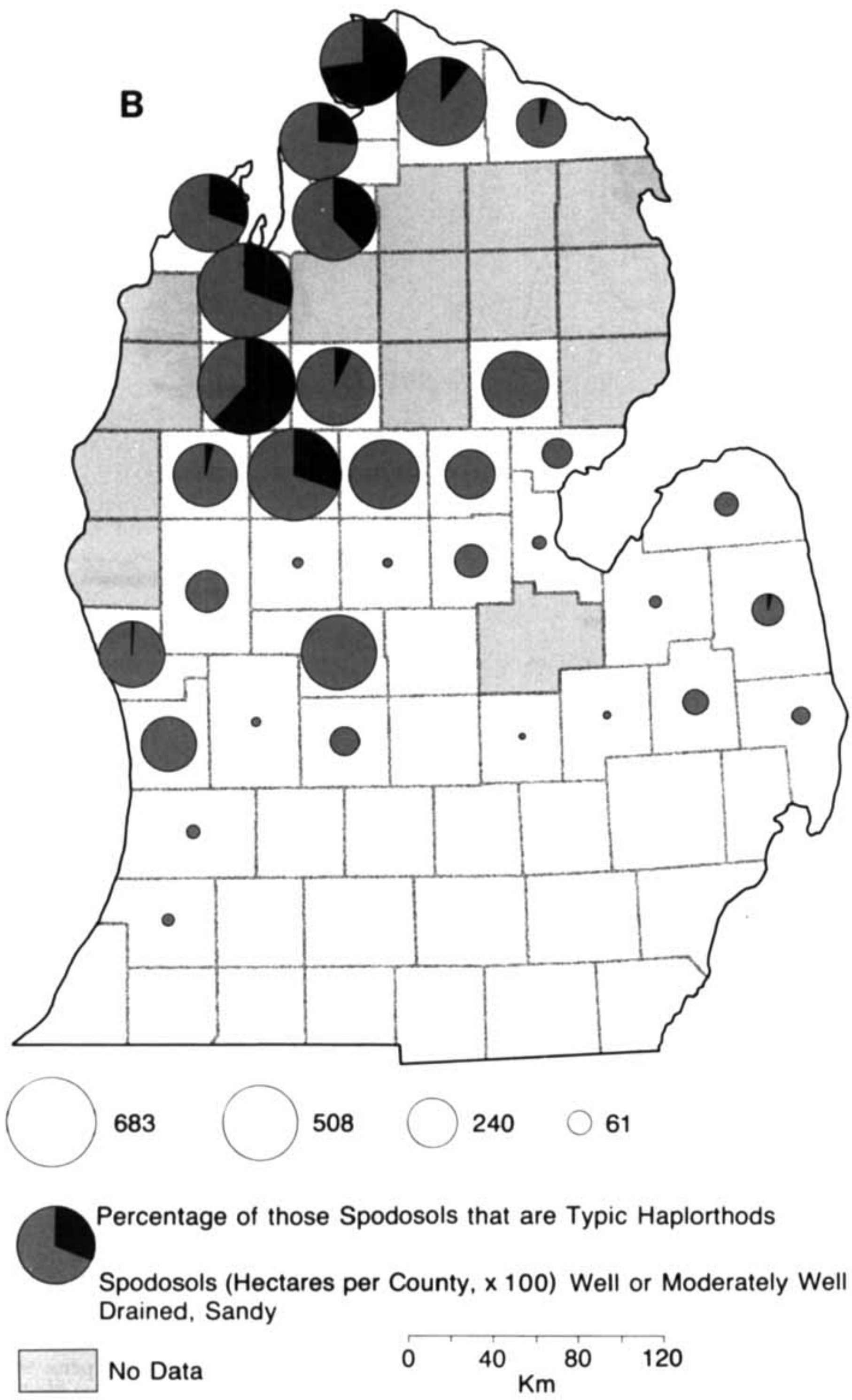


Figure 5. A. The areal extent of well and moderately well-drained (dry), sandy soils per county, lower Michigan. The amount of area darkened in for each graduated circle represents the percentage of the dry, sandy soils that are Spodosols. B. The areal extent of well and moderately well-drained, sandy, Spodosols per county, lower



Michigan. The amount of area darkened in for each graduated circle represents the percentage of the Spodosols that are strongly developed (Typic Haplorthods).

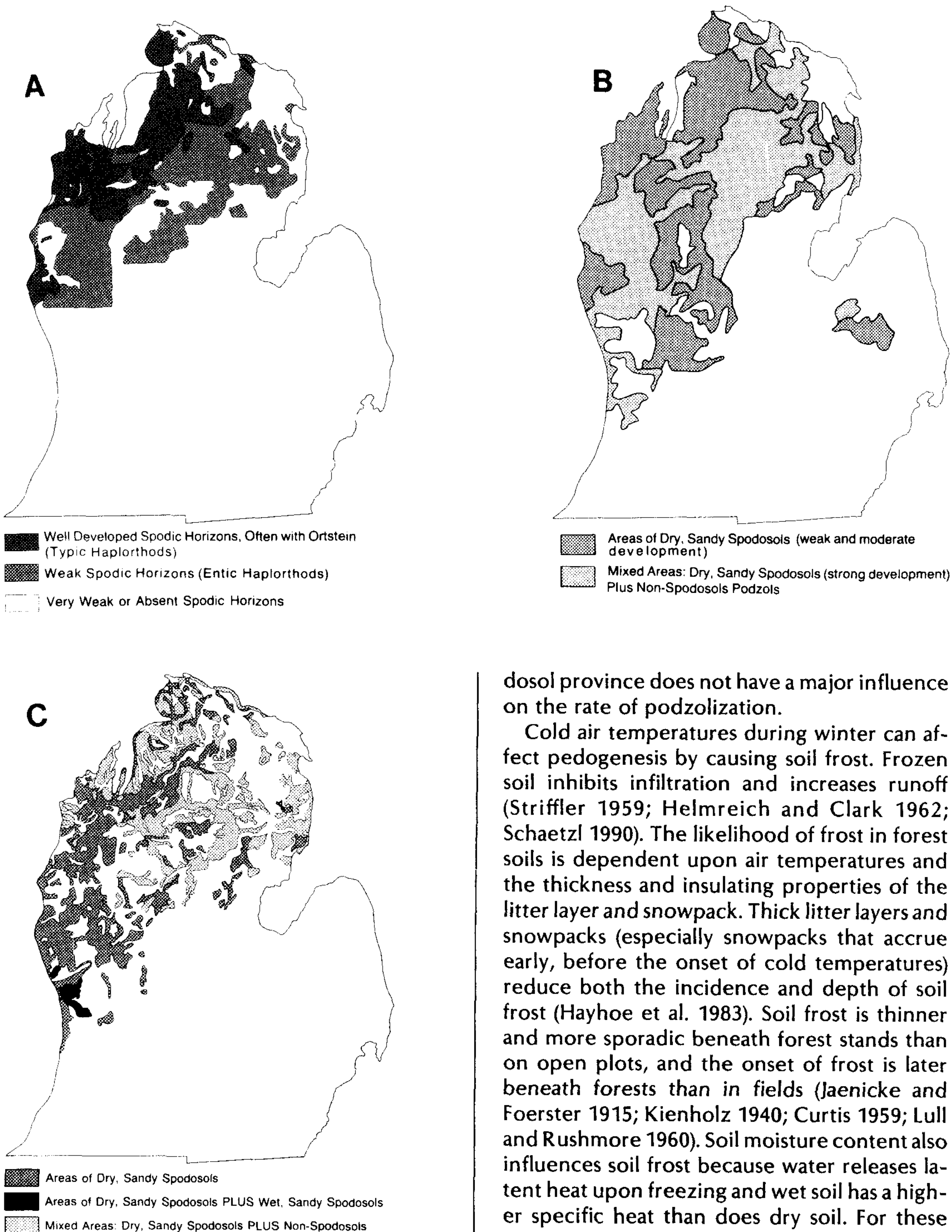


Figure 6. The distribution of Spodosols in lower Michigan. Generalized from maps by (A) Veatch (1937), (B) USDA-SCS (1957), and (C) USDA-SCS (1981).

dosol province does not have a major influence on the rate of podzolization.

Cold air temperatures during winter can affect pedogenesis by causing soil frost. Frozen soil inhibits infiltration and increases runoff (Striffler 1959; Helmreich and Clark 1962; Schaetzl 1990). The likelihood of frost in forest soils is dependent upon air temperatures and the thickness and insulating properties of the litter layer and snowpack. Thick litter layers and snowpacks (especially snowpacks that accrue early, before the onset of cold temperatures) reduce both the incidence and depth of soil frost (Hayhoe et al. 1983). Soil frost is thinner and more sporadic beneath forest stands than on open plots, and the onset of frost is later beneath forests than in fields (Jaenicke and Foerster 1915; Kienholz 1940; Curtis 1959; Lull and Rushmore 1960). Soil moisture content also influences soil frost because water releases latent heat upon freezing and wet soil has a higher specific heat than does dry soil. For these reasons, soils in lower Michigan that are wet and have a thick snowpack prior to the onset of cold temperatures are most likely to remain frost-free throughout winter (Striffler 1959; McKenzie et al. 1960).

Air temperature and snowpack depth (water equivalent as computed by the hydrologic model) were combined to indicate "potential freeze days," that is, those days in which the potential existed for the development or deepening of soil frost. Although the result is not based on the physical processes that cause soil frost (which are driven by temperature gradients in the air, litter layer and soil and are influenced by thermal conductivities and moisture contents of the litter and soil; Hillel 1982), it does provide a proxy measure of potential for soil frost (cf. MacKinney 1929), and the results agree with field observations of frost incidence. Mean number of potential freeze days per year were calculated by summing the average number of days in which the *maximum* daily temperature did not exceed 0°C (32°F) and the snowpack was less than 10 cm (4 in.) thick. A second, similar index was calculated as the number of days per year in which the *mean* daily temperature did not exceed −6.7°C (20°F) and the snowpack was less than 10 cm (4 in.) thick.

Maps of these indices for lower Michigan (Fig. 7) show a minimum of potential freeze days (PFDs) in a zone approximately 15–100 km inland and parallel to Lake Michigan. This linear zone corresponds to a belt of heavy lake-effect snowfall,[2] best expressed approximately 40 km inland from Lake Michigan (Eichenlaub 1970). Snow tends to accumulate early in winter at inland positions in the snow belt (Dewey 1971). In more eastern sections of the Spodosol province, deep snowpacks are generally formed later in the winter than in the snow belt. In extreme southern Michigan, snowpacks are generally thin and discontinuous during the winter (Eichenlaub 1970), and consequently, numerous cold days occur during which the soil has little snow cover for insulation. Thus, the number of PFDs increases to the east and south of the lake-effect snow belt. The correspondence between Figures 4 and 7 supports the suggestion that podzolization is influenced by soil frost. This relationship was alluded to by Messenger (1966), who noted the correspondence between strongly developed Spodosols in Michigan and mean annual snowfalls greater than 152 cm.

The quantity and chemistry of water that infiltrates into the mineral soil is also important to podzolization (Volobuyev 1959; Jauhiainen 1973; Schaetzl and Isard 1990). Only during deep infiltration events, when the soil wetting front penetrates into the B horizon, does substantial profile differentiation and development occur.

Total annual infiltration is greatest in southwestern Michigan (Fig. 8). Parts of the northern sections of the Spodosol province have only 70 percent of the total annual infiltration that is received farther south. Nonetheless, the pattern of infiltration within lower Michigan does

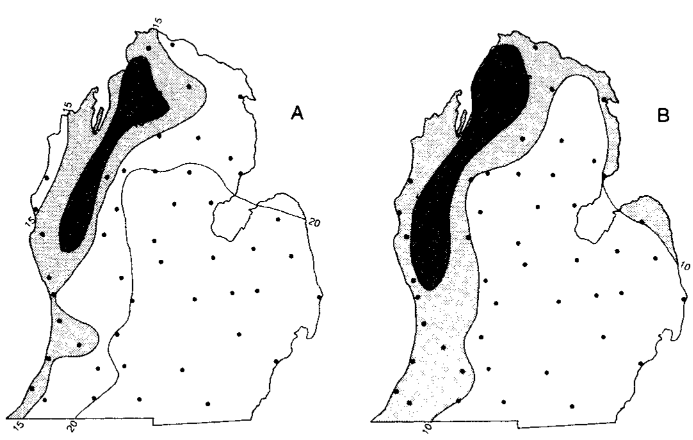


Figure 7. Potential freeze days per year for lower Michigan, as determined from National Weather Service (NWS) data for 52 stations. Period of record: 1951–80. The grid of NWS stations used in this study is represented by a dot pattern on this and subsequent figures. A. Mean number of days per year in which the maximum daily temperature was ≤0°C, AND the snowpack depth was ≤10 cm. B. Mean number of days per year when the mean daily temperature was ≤−6.7°C, AND the snowpack depth was ≤10 cm.

Figure 8. Mean annual infiltration (mm) for lower Michigan, as calculated by the hydrologic model. Based on 1951–80 data for 52 NWS stations.

not correspond to that of Spodosol development (Fig. 4).

Figure 9 shows infiltration totals for three periods of the year: (A) 10 May through 20 October ("leaf-on" period; the growing season), (B) October through December (period of autumn rains and soil water recharge), and (C) March and April (period of snowmelt and spring rains). Summer infiltration (Fig. 9A) is greatest in southwestern sections of the state and decreases to the north and east. This gradient not only corresponds to the summer precipitation patterns in lower Michigan but also reflects the greater thickness of the litter (water storage capacity) in the northern mixed coniferous-deciduous forests than in the *Quercus* forests farther south.

The input of potential organic acids to the pedologic system is facilitated by leaf-fall in autumn. As it provides the vehicle whereby these acids are transported into the soil profile, infiltration during this period may be important to podzolization. Also, autumn is generally a period of soil moisture recharge in lower Michigan (McGuinness 1941) and the amount of soil water present at the onset of cold temperatures can affect the incidence and depth of frost. Using water balance calculations, Messenger (1966) concluded that most sandy soils in northwest lower Michigan reach field capacity in November in most years.

Fall infiltration is greatest south of the floristic tension zone (Fig. 9B). Minimum amounts of infiltration occur in extreme northeastern and northwestern lower Michigan. Thus, at the onset of cold temperatures, soils in these areas are probably drier, and potential leaching of organic acids is less in these areas than at other sites in the Spodosol province.

A comparison of the PFD maps (Fig. 7) with that of fall infiltration patterns (Fig. 9B) reveals that fall infiltration within the Spodosol province is greatest in areas that also have low numbers of potential freeze days. This area corresponds to a belt of lake-effect snows that parallels Lake Michigan. The combination of high autumn infiltration and low PFDs likely results in increased soil leaching and little soil frost in this area (McKenzie et al. 1960). Even in cold winters with thin snowpacks, soil frost may not be deep or spatially continuous under the mixed forests in this zone (Striffler 1959; Trimble et al. 1958). Conversely, northeastern sections of the lower peninsula have more freeze days and less autumn infiltration, increasing the likelihood of soil frost (Figs. 7, 9B). Volobuyev (1959) notes that a fall leaching phase is typical in climates that have led to the development of Spodosols.

The quantity of water available for infiltration as a result of snowmelt and spring (March and April) rains is maximal in the lake-effect snow zone and lower in northeast lower Michigan (Fig. 9C) where winter snowpacks are usually thin or absent. It should be noted that, whereas the hydrologic model calculates runoff for heavy rain events (warm-season runoff is uncommon on sandy soils in Michigan [Hansen 1969]), it cannot account for runoff from frozen soil during snowmelt, which may rarely occur. Notwithstanding the inability of the hydrologic model to account for snowmelt runoff, the correspondence between Figures 9C and 6A, in conjunction with the finding that more Fe and Al cations may be translocated during snowmelt than during the warm season (Schaetzl and Isard 1990), suggests that the flush of water through the soil during the snowmelt period is important to the podzolization process (Volobuyev 1959; Ugolini et al. 1982). McGuinness (1941) has documented deep percolation of snowmelt waters into sandy soils in Michigan.

A subset of NWS stations in lower Michigan with 50 years of continuous, daily air temper-

Figure 9. Seasonal infiltration totals (mm) for lower Michigan, as calculated by the hydrologic model. Based on 1951–80 data for 52 NWS stations. A. 10 May through 20 October, inclusive (growing season). B. October through December, inclusive (autumn period). Isolines having values greater than 100 mm have been omitted for clarity of expression. C. March through April, inclusive (snowmelt period).

ature and precipitation records (1931–80) were used to analyze the frequency of years with low PFDs and high availability of water for infiltration during March and April. The resulting indices were compiled in histogram form for three representative stations in the Spodosol province (Fig. 10). Cadillac and East Jordan are situated in the zone of maximal Spodosol development in northwestern lower Michigan; sandy soils near West Branch generally have weakly-developed spodic horizons (Figs. 3, 4, 9A).

There is a higher frequency of years with a low number of PFDs at Cadillac and East Jordan than at West Branch (Fig. 10). In addition, there is a greater frequency of years with high availability of water for spring infiltration at the stations in the zone of maximal soil development than at West Branch, in the eastern portion of the Spodosol province.

Snowmelt and Podzolization in Southern Michigan

Spodosol development in lower Michigan is best expressed north of a well-established floristic tension zone, in a zone parallel to Lake Michigan, approximately 10–100 km inland (Fig. 4). Of several climate factors examined, we find a close correspondence between the zone of strong podzolization and low numbers of PFDs, coupled with relatively high amounts of water available for autumn and spring infiltration (Figs. 7, 9). These factors combine to allow a large amount of infiltration into potentially unfrozen soil during March and April. Patterns of summer infiltration do not correspond with the variation in strength of Spodosol development, possibly because much of the throughfall and stemflow is taken up by roots in the litter layer and upper horizons, thereby limiting the amount of deep infiltration that can occur. Pronounced leaching at the onset of spring snowmelt, coupled with decreases in soil moisture during early summer is common worldwide in climates dominated by Spodosol soils (Volobuyev 1959). In eastern sections of the Spodosol province, soils are weakly-developed, perhaps corresponding to a higher incidence of frost induced by drier autumns and more PFDs. In addition, thinner snowpacks in northeastern lower Michigan provide for less water available for spring infiltration than in the area of maximum spodic development (Fig. 9C). Even when thick snowpacks develop in the northeastern section of the Spodosol province during late winter, a great percentage of the snowmelt waters may run off because of frozen soil.

This study supports the theory of episodic pedogenesis and leaching for the Spodosol

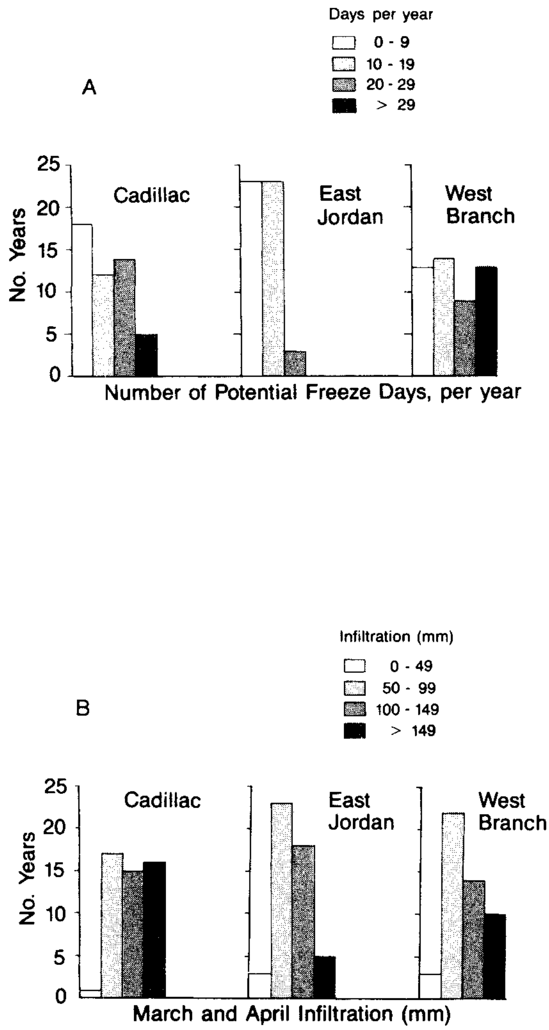


Figure 10. A. Frequency of years (1931–80 data) in which the potential freeze days for Cadillac, East Jordan, and West Branch, Michigan, were 0–9, 10–19, etc. B. Frequency of years (1931–80 data) in which the March and April infiltration for Cadillac, East Jordan, and West Branch, Michigan, was 0–49 mm, 50–99 mm, etc.

province of lower Michigan, previously documented via process studies in Arctic regions (Ugolini et al. 1982; Stoner and Ugolini 1988) and the northern peninsula of Michigan (Schaetzl and Isard 1990). The spatial correspondence between areas of strong spodic development with areas of heightened snowmelt infiltration suggests that snowmelt is important as a driving mechanism of podzolization (Volobuyev 1959; Davies 1971; Moore 1974).

Infiltration events during the warm season are usually interspersed with rain-free days and are often smaller in magnitude than snowmelt infiltration events. The soil quickly dries out between infiltration events, due to high evapotranspirative demand and low water-holding capacities of sandy soils. Water infiltrating into dry soil must first fill void spaces, such that the wetting front may not even reach the B horizon. Little or no horizon formation can occur under this scenario. During snowmelt, however, water infiltrates into previously wetted soil and produces deeper wetting fronts than a similar amount of infiltration into dry soil. Fe and Al chelates are effectively translocated into the B horizon, and profile differentiation is accomplished.

Summary and Conclusions

The southern limit of Spodosols in Michigan corresponds with a floristic tension zone between mixed coniferous-deciduous forest and deciduous forest, supporting the long-observed conclusion that Spodosol development is enhanced under coniferous and mixed forest types. Likewise, parent materials in this region are generally sandy, a factor that also promotes the development of this soil order. A factorial analysis of the effects of spatial variations in vegetation, relief, parent material, and time upon soil development within this region suggests that none of these factors effectively explains soil distribution patterns. Thus a climatic explanation is considered.

Within this assemblage of Spodosol-mixed forest (the "Spodosol province"), the strongest soil development occurs in the northwestern sections, where thick snowpacks occur frequently. We have provided data that point to a correspondence among abundant fall infiltration, deep snowpacks and Spodosol development. The combination of wet soils in autumn followed by deep early-winter snowpacks inhibits soil frost. Further, the lack of soil frost coupled with deep snowpacks allows unimpeded infiltration of abundant amounts of meltwater in spring. We suggest that podzolization is strengthened in such areas because during snowmelt, runoff and evapotranspiration are small quantities, and deep infiltration events can efficiently translocate organometallic complexes into the B horizon. Lack of strong spodic development in northeastern lower Michigan is likely due to lower snowfall amounts and slightly drier autumns, both of which enhance the likelihood of soil freezing and runoff of snowmelt waters.

The results point to the strong linkage between climate, especially cold-season climatic elements, and the podzolization process. Whereas the correspondence between coniferous forest and podzolization has been documented for many areas, comparatively little notice has been paid to climatic effects at strengthening or inhibiting this process in such areas, and future work on this topic may prove to be fruitful. We urge others to examine the effects of climate on soil processes across regions that are relatively homogeneous with respect to soil-forming factors: biota, relief, parent material, and time. Results from such studies may further our understanding of soil processes, soil geography, and perhaps, paleoclimate.

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Notes

1. The Spodosol soil order is approximately equivalent to the taxonomic Great Soil Group "Podzols" (Baldwin et al. 1938), although exceptions do occur (c.f. Mokma 1983). In this paper, we usually refer to the taxonomic order Spodosols, although maps and data from the period prior to 1965 would have been referring to Podzols.
2. Climate, like vegetation, has changed markedly throughout the Holocene in lower Michigan (e.g., Webb and Bryson 1972; Webb et al. 1983). Studies in which soil development is related to climate must incorporate known climatic and vegetational changes into the pedogenic model or make assumptions about the impact of previous climates on present-day soil development and patterns. Because little is known, quantitatively, about Holocene climatic changes in southern Michigan, we cannot employ the first option. We have assumed that although climate has changed and lake levels have fluctuated (Larsen 1987), the position of Lake Michigan has remained essentially constant. Dominant westerly winds sweeping across any of the ancestral water bodies that occupied the Lake Michigan basin would have produced lake-effect snows in essentially the same locations throughout the Holocene. Thus the overriding effects of lake snows and their effects on soil climate may have compensated for temperature and precipitation variability across the region during the Holocene.

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