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REGRESSIVE PEDOGENESIS FOLLOWING A CENTURY OF DEFORESTATION: EVIDENCE FOR DEPODZOLIZATION

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After the logging and fires of the late nineteenth century, the upland stump prairies of Michigan's Upper Peninsula, which had previously supported dense forest, have remained deforested. Surrounding areas in similar geomorphologic settings have returned to forest. We investigated whether soil B horizon properties have degraded in response to the removal of podzolization-promoting vegetation by studying pedons under forest and stump prairie. Active soil processes were examined by analyzing ions sorbed on cation exchange resins and chelating resins that had been buried in the pedons, at three depths, for approximately 1 year.

In both vegetation types, patterns of sorbed Fe and Al indicate that podzolization is on-going, with active translocation of sesquioxides into the B horizon. Larger absolute amounts of sesquioxides were sorbed on resins in forested pedons compared with stump prairie pedons, however, suggesting that podzolization processes are more active in forested than in stump prairie environments.

The chemical and morphological properties of forested and stump prairie pedons were examined by analyzing the organic C and extractable Fe and Al content of horizon-based samples. Strength of podzol development was greater, in general, for forested than for stump prairie soils. The primary chemical difference between the two types was found in organic C content and in properties associated with organic C, including pyrophosphate-extractable Fe and Al. Differences between forested and stump prairie soils were much smaller for inorganic constituents.

Depodzolization (the degradation of existing podzol features) in stump prairie B horizons is most evident in morphological properties associated with organic C, which are dependent on continued input of organometallic complexes. Depodzolization has occurred in the stump prairie soils because the balance between progressive development (podzolization) and regressive development (depodzolization) has been altered under stump prairie vegetation. (Soil Science 1998; 163:482–497)

Key words: Pedogenesis, podzolization, Spodosols, northern Michigan, soil solution, disturbance.

PEDOGENESIS is often perceived as a progressive process by which an isotropic parent material is transformed into a soil with one or more distinct horizons. With time, many soil profiles become more anisotropic (i.e., more horizons) and progressively thicker (Johnson 1985). This perception is often true, but it illustrates only one aspect of pedogenesis. However, it continues to be reinforced by the abundance of chronosequence studies that describe increasing solum thickness, horizon differentiation, and organization with increasing surface age (e.g., Bockheim 1980; Harden 1990; Barrett and Schaetzl 1992; Schaetzl et al. 1994).

One current pedogenic theory holds that soils are the products of two distinct pathways of development, a progressive and a regressive pathway (Johnson and Watson-Stegner 1987; Johnson et al. 1990; Phillips 1993; Johnson and Hole 1994). Progressive or developmental path-

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ways include horizonation processes and those that promote soil deepening and/or thickening. Processes viewed as regressive, or promoting profile haploidization, include surface erosion, nutrient biocycling, and most forms of pedoturbation (Johnson and Watson-Stegner 1987; Johnson et al. 1987). The pedogenic pathways affecting a soil may change with time, either in response to changes in external conditions such as climate or vegetation (Bryan and Albritton 1943; Reheis et al. 1995), or in response to the crossing of internal thresholds (Muhs 1984). Thus many, or even most, soils may be considered polygenetic (Johnson and Hole 1994) because they have changed pedogenic pathways, however defined, at least once. To ascertain accurately the conditions that have led to the current morphology and chemistry of a soil, we must examine its properties in relation to the cumulative processes that have acted over its history (Bryan and Albritton 1943; Chadwick et al. 1995). Some soil features, formed under earlier circumstances, may be relict; they are deteriorating or degrading under current, changed conditions (Phillips 1993). The solid phase properties of soils are useful in this regard because they contain a record of past pedogenesis (Yaalon 1971; Retallack 1990). However, the existence of a pedogenic feature in a soil shows only that the processes that contributed to its formation exist or once existed. By studying *soil solutions,* one can identify those processes still active (Ugolini et al. 1987; Righi et al. 1990) and help to isolate the relict features from those that may be currently forming.

The two methods used most frequently to study ongoing translocation processes involve (i) tension (suction) and zero-tension (passive) lysimeters, both of which capture samples of the soil solution (e.g., Grier 1975; Singer et al. 1978; Barbee and Brown 1986; Ugolini et al. 1988; Schaetzl 1990) and (ii) buried cation exchange and chelating resins, which act as passive traps for ions moving in solution (Righi et al. 1990; Ranger et al. 1991; Ranger and Nys 1994). Buried resins require less ongoing maintenance than lysimeters, facilitating the study of less accessible soils. They also expedite site replication because installation and maintenance are less complex (Ranger et al. 1991).

In this paper we describe some sandy soils in northern Michigan that underwent a dramatic change in vegetation about 100 years ago, suggesting that their morphologies may be relict. We ask whether podzol B horizons *degrade* in response to removal of podzolization-promoting vegetation, as originally postulated by Francis D. Hole in 1975. We hypothesize that the removal of forest vegetation in the 1890s has (i) altered at least one pedogenic pathway, as reflected in the active podzolization-translocation processes and (ii) measurably degraded some morphological and chemical properties. We tested the first hypothesis using the buried resin technique to study the movement of selected cations in soil solutions. The second hypothesis was tested with evidence derived from soil chemical and morphological properties.

PODZOLIZATION

Podzols[a] typically have a surface horizon of accumulated organic matter, a bleached eluvial horizon (in well developed soils, this horizon classifies as albic), and a reddish brown or black illuvial horizon (a podzol B horizon; sometimes classifying as a spodic horizon) (Muir 1961; McKeague et al. 1983; Rourke et al. 1988; Base and Brasher 1990; Courchesne and Hendershot 1997). Podzolization processes include mechanisms for mobilizing aluminum and humus, with or without iron, in the eluvial horizon and immobilizing one or more of them in the illuvial horizon. Traditionally, podzolization has been thought to require chelation of sesquioxides by fulvic or low molecular weight organic acids (DeConinck 1980). Some have postulated, however, that these elements can move independently of organic matter in the form of amorphous aluminosilicate compounds (Farmer et al. 1980; Anderson et al. 1982; Farmer et al. 1985). Recent studies have suggested that both organic and inorganic mechanisms of iron and aluminum translocation may occur, either sequentially or simultaneously (Jakobsen 1991; Barrett 1997).

Fiorenzo Ugolini and colleagues. after examining the soil solutions of podzolic soils, proposed that two separate compartments exist within the pedon with respect to podzolization processes (e.g., Dawson et al. 1978; Dahlgren and Ugolini 1989). Organometallic complexes released in the upper compartment (E and Bhs horizons) are immobilized at the Bhs/Bs horizon boundary by adsorption/precipitation reactions with noncrystalline minerals synthesized in the lower compartment (Bs, BC, and C horizons; Ugolini and

[a] The term podzol is used to refer to soils with characteristic Spodosol or Spodosol-like morphology and chemistry, irrespective of whether they classify as Spodosols (or Podzols). For example, a Spodic Udipsamment that has weak spodic development would be included in this category. Similarly, the term podzol B is used to designate the illuvial horizon of these soils, whether or not it meets spodic horizon criteria as outlined by the Soil Survey Staff (1994).

Sletten 1991). Thus, active podzolization has a signature wherein relatively large quantities of Fe and Al enter the Bhs horizon in solution, but very little Fe or Al leaves.

Rates of podzolization vary considerably from place to place (Schaetzl and Isard 1996). In northern Michigan, soils on surfaces less than 4000 years old show very weak horizonation, whereas soils that classify as Spodosols require about 10,000 years to develop (Franzmeier and Whiteside 1963; Barrett and Schaetzl 1992). Under especially favorable conditions, however, recognizable horizons can develop much more rapidly (Burges and Drover 1953; Paton et al. 1976). Because rates of podzolization vary, their use as a surface exposure dating tool is limited (Arbogast et al. 1997), underscoring the need to establish and understand those environmental factors that lead either to an acceleration or a retardation in the rate of this process.

Certain vegetation types promote podzolization. In Europe, strongly developed podzols have been associated with heath vegetation, presumably because of the strong chelating ability of heath litter (Nielsen et al. 1987). Evergreen trees, particularly eastern hemlock (*Tsuga canadensis*), are often associated with strongly developed podzols (Hole 1975; Messenger 1975). In northern Michigan, however, the most strongly developed podzols are associated with northern hardwood forests, which include components of sugar maple (*Acer saccharum*) and other hardwoods with some intermixed hemlock and white pine (*Pinus strobus;* Mokma and Vance 1989).

Because vegetation cover can change on time scales that are rapid with respect to pedogenesis, the question arises as to whether and how quickly both soil processes and soil morphology respond to major changes in vegetation (e.g., Graham and Wood 1991). Under favorable circumstances, the introduction of a species that strongly promotes podzolization appears able to cause a measurable increase in spodic characteristics within a century (Nornberg 1977; Herbauts and De Buyl 1981; Nornberg et al. 1993). We questioned whether the converse was also true.

DEPODZOLIZATION

If a change in vegetation can increase the rate of podzolization within decades in some soils, can the removal of a strongly podzolizing species also degrade an existing podzol soil? Recent reports from Europe suggest that changes in vegetation can make soils "less acid and tending to depodzolize" (Miles 1985). Nielsen et al. (1987) and Nornberg et al. (1993) reported that soils of a former heath area that had been invaded by oak about 70 years before had lower organic matter content, different B horizon colors, and a slightly decreased B horizon iron and aluminum content when compared with soils which remained under heath vegetation. Contents of phenolic compounds in the soil solution from the O and A horizons were lower under oak than under heath vegetation (Nørnberg et al. 1993), suggesting that depodzolization[b] can be operative long before it becomes manifested in the soil's morphology.

In northern Wisconsin, soils under mature hemlock forest showed stronger podzol development than soils in which the hemlock had been removed 30 to 200 years previously (Hole 1975). The author concluded that removal of hemlock from the forest had allowed the podzol B horizon to diminish, with an estimated half-life of a century. Hole suggested that at any given site, podzol B horizons may have appeared and deteriorated repeatedly as the vegetation at the site experienced natural disturbance and succession processes. Hole's study, however, examined only B horizon organic matter accumulation, so it is unknown whether there was a concomitant decrease in B horizon iron and aluminum content. The question of whether the conclusions from this study in northern Wisconsin are site-specific helped to prompt our work.

STUDY AREA

Our study area is located in Alger County, Michigan, about 7 km south of Lake Superior, centered around a currently deforested area known as the Kingston Plains (Fig. 1). The Kingston Plains comprise a large outwash apron with numerous incised depressions (Blewett and Rieck 1987; Blewett 1994). The earliest vegetation data for the region come from General Land Office survey notes compiled between 1840 and 1851. At that time, the site was forested with a northern hardwoods/white pine forest (Frederick et al. 1976; Barrett 1995). The entire area was logged, primarily for white pine lumber, in the late 19th century. Logging operations were soon followed by widespread wildfires, which affected most of the study area. Forest vegetation returned to only a portion of the study area; large parts remain unforested even today.

Predominant species in currently forested areas include red maple (*Acer rubrum*), white pine, beech (*Fagus grandifolia*), hemlock, and balsam fir

[b] The term depodzolization (Nørnberg et al. 1993) is used for the degradation of an existing podzol, especially its B horizon properties. Processes typical of podzolization are either ceased or reversed during depodzolization.

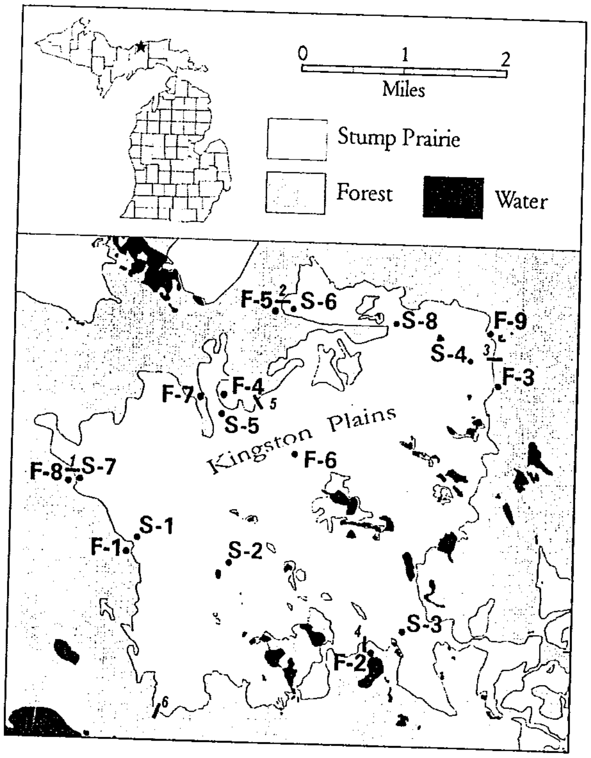

Fig. 1. Map of the study area in Alger County, Michigan. Labeled points are the locations of sampled pedons. Numbered line segments are the locations of sampled transects.

(*Abies balsamea*). Scattered trees in the unforested areas are predominantly white pine, red maple, and black cherry (*Prunus serotina*), but grasses, low-growing shrubs (primarily blueberry [*Vaccinium* sp.]), bracken fern (*Pteridium aquilinum*) and reindeer moss lichens dominate the landscape (Barrett 1995). Numerous stumps from 19th century logging operations remain as a testament to the former forest (Fig. 2). Thus, we refer to this vegetation type as "stump prairie." Aerial photographic evidence indicates that the present pattern of forest and nonforested regions was well established by the 1930s (Barrett 1995).

The soils of the study area are developed on well sorted outwash sands, and the majority are well drained, except in kettle depressions. A thin A horizon occurs typically at the surface of stump prairie soils, whereas in the forest, an Oa horizon is usually located directly above an E horizon. Most soils in the study area have a gray E horizon overlying reddish brown Bs horizons; a dark Bhs horizon is present in some pedons. Bhs and Bs horizons often contain masses or columns of cemented material (orstein), which may be up to 30 cm in diameter and more than a meter thick. Soils across most of the study area have not been intensively mapped, although the predominant soil series mapped on a similar area located within 1 km of the Kingston Plains is Rubicon (Entic Haplorthods), with some Kalkaska units (Typic Haplorthods), also indicated (Carey 1993). The 17 pedons sampled for the present study classify primarily within the Rubicon and Kalkaska series, but a few pedons of lesser developed Deer Park (Spodic Udipsamments) and the more strongly developed Wallace (Typic Haplorthods) were also included for completeness (Barrett 1995). There is no statistically significant difference in parent material (C horizon) texture between sites currently forested and those in stump prairie, nor does the forest/stump prairie vegetation boundary correspond to landform or drainage boundaries (Barrett 1997).

METHODS

Field Methods

Seventeen representative pedons, nine in forest and eight in stump prairie areas, were chosen for study. When possible, a pedon within a forest

Fig. 2. Photograph of typical stump prairie vegetation in the study area as it appeared in 1995.

vegetation stand was paired with one in the nearest stump prairie stand (Fig. 1). Sites with indications of wetness were not included. At each site, a pit was excavated and standard field descriptions were made (Soil Survey Division Staff 1993), and bulk samples (about 0.5 kg) were taken from each genetic horizon for laboratory analysis. The approximate proportion of ortstein (cemented materials; see Mokma et al. 1994) in each subhorizon was estimated by measuring the horizontal extent of cemented material exposed on a 1-m-wide section of the pit face. Ortstein portions of Bs subhorizons were sampled separately when strongly cemented ortstein comprised more than 20% of the subhorizon.

In order to estimate the variability in soil development near the forest/stump prairie boundary, six transects were made perpendicular to the boundary (Fig. 1). Six 1-m^2 quadrats were established along the line, at 30-m intervals, on each side of the boundary. Within each quadrat, nine regularly spaced samples were taken with a 2.5-cm-diameter push-probe to a depth of approximately 50 cm or until hard ortstein obstructed the probe (obstruction of the probe by coarse fragments, rather than ortstein, was not likely in these sandy soils). At each sample point, we recorded whether ortstein was present or absent. The color of the darkest, reddest soil retained in the probe, usually from the upper B horizon, was measured by visually matching the color to the closest Munsell chip.

In Situ Monitoring of Soil Processes

Three pairs of pedons (from the 17) were chosen for an *in situ* study of podzolization processes using permeable bags containing resins (Ranger and Nys 1994): sites S-6 and F-5; S-7 and F-7; S-8 and F-9 (Fig. 1). A Na-saturated cation exchange resin (Amberlite IRN 77; Rohm and Haas Co., Philadelphia, PA) and a Na- and H-saturated chelating resin (Chelex 100; Bio-Rad laboratories, Richmond, CA) were used. Small bags (approximately 5 × 8 cm) were constructed of nylon tricot fabric with mesh small enough to retain the resin. One bag, containing either ≈ 1.2 g chelating resin or ≈ 3.0 g cation exchange resin (dry weight equivalent), was inserted into the undisturbed pedon face at the top of the E, B, and BC horizons. After four replications were performed for each of the six pedons, the pit was carefully refilled. The bags were installed in August and September 1994, and retrieved in late May 1995. (Summers are relatively dry in this region, and little deep infiltration is thought to occur; Schaetzl and Isard 1990, 1996.) After retrieval, the bags were air-dried and the resin reweighed. Cations were desorbed from the resins by shaking for 4 h in 40 mL of $1N$ HCl (for the cation exchange resin) or $1N$ HNO_3 (for the chelating resin). The extracts were analyzed for Ca, Mg, Fe, and Al cations by directly coupled plasma (DCP) spectroscopy.

Laboratory Methods

Laboratory analysis of the air-dried, horizon-based samples (including ortstein as a separate subsample) included particle size distribution by pipette after pretreatment with H_2O_2 to remove organic matter (Soil Survey Laboratory Staff 1992). Extractions for Fe and Al were performed using acid ammonium oxalate (Fe_o, Al_o), sodium pyrophosphate (Fe_p and Al_p), and sodium citrate-dithionite (Fe_d and Al_d) (Soil Survey Laboratory Staff 1992). The three types of extracts were analyzed for Fe and Al by DCP spectroscopy. Organic carbon content was determined using a modified Walkely-Black procedure (Singer and Janitzky 1986).

For calculations requiring a single value per horizon, B subhorizon values were determined by mathematically weighting the ortstein and non-ortstein subsamples according to the field estimate of the ortstein proportion of the subhorizon. For example, for a Bs1 horizon with an estimated 30% ortstein content and 2.9% clay in the matrix and 2.6% clay in the ortstein portion, the weighted Bs1 clay content would be calculated as $[(2.6 \times 30) + (2.9 \times 70)]/100$, or 2.8%. To facilitate comparisons of pedons with different horizon sequences and horizon thicknesses, a weighted B horizon value was calculated by using the mean value for all B subhorizons, weighted for (multiplied by) subhorizon thickness, using the formula: $\Sigma (P \times H)/\Sigma H$, where P = the soil property for a given subhorizon and H = horizon thickness. The statistical test for differences between forest and stump prairie pedons was the Mann-Whitney U test at a significance level of 0.05.

RESULTS AND DISCUSSION

Our results are designed to compare stump prairie soils with nearby forested soils in both their active soil processes and their chemical and morphological properties. To do this comparison, we assume that soils in the forest and stump prairie regions were similar before the advent of 19th century logging and that any present differences post-date the establishment of stump prairie vegetation and are a result of the dramatic vegetation change on this landscape. It should be noted that the soils of the stumped areas and those currently forested may not have been exactly the same (Barrett 1997), and neither was the forest species composition of the two areas the same (Barrett 1995). Nevertheless, because the forest and stump prairie regions are found near each other, in similar positions on similar landforms, and because both areas were forested before logging, we believe that the assumption is reasonable.

The present study is not designed to investigate *why* the post-logging vegetation of the forest and stump prairie area are different. Various hypotheses have been advanced to explain the differences, including the severity of the logging methods and post-logging fires in the stump prairie area, differences in pre-logging forest composition, and pre-logging differences in soil properties. More complete discussion of these hypotheses can be found elsewhere (Barrett 1995, 1997).

The direction and extent to which the assumption about comparable soil development is false will affect conclusions about depodzolization. If, in actuality, the stump prairie soils were *less* developed than the forested soils in 1890, as data about pre-logging vegetation suggest (Barrett 1995), conclusions about the degree of depodzolization will be exaggerated. Therefore, conclusions about depodzolization, especially those derived from solid phase properties, must be approached cautiously.

If depodzolization occurs, the shift in pedogenic pathway (reflected in soil solution chemistry) must precede measurable changes in soil morphology. In this section we first discuss our hypothesis that the establishment of stump prairie vegetation has altered active soil processes. Next, we test the hypothesis that the stump prairie soils show measurable degradation of the morphological and chemical properties associated with podzolization.

Evidence from Active Soil Processes

As evidence of soil processes currently active in the soils, we examined the cations sorbed on buried bags of resin. The sorbed cations are assumed to portray relative movements of cations in the soil solution over the time the resins were in place (Righi et al. 1990).

Of the cations measured in the study, Ca and Mg are related to biological processes in the ecosystem (Ranger and Nys 1994), whereas Al and Fe most closely reflect podzolization processes (Ugolini and Dahlgren 1991). In both forested and stump prairie pedons, 4 to 6 times more Ca than Mg was sorbed on the cation exchange resin (Table 1). These relative amounts are in agreement with proportions of cations measured in a forested ecosystem in New Hampshire (Likens et al. 1977). Similarly, Ca:Mg ratios measured in soils in northern Minnesota (Alban 1982) and France (Ranger and Nys 1994) are approximately 6:1.

Amounts of sorbed Mg and Ca are, in general, relatively high at the top of the E horizon (Figure 3). An exception is that in the stump prairie pedons, Ca values are higher at the top of the B horizon (Fig. 3). The Mg and Ca sorbed at the top of the forest pedons' E horizons exceed amounts sorbed in any horizon of the stump prairie pedons (Fig. 3). This is probably attributable to grater cation recycling by forest vegetation and greater cation release from decomposition in the thick forest litter layer (Ranger and Nys 1994). In both soil types, with one exception, very little Ca or Mg is present in soil solutions reaching the top of the BC horizon (Fig. 3), implying that biocycling is restricted mainly to the solum and that the lower part of the B horizon is dominated by inorganic processes and carbonic acid weathering (Ugolini and Sletten 1991).

Fe and Al sorbed on both resin types indicate ongoing, active sesquioxide translocation. For most pedons under both vegetation types, sorbed Fe and Al on both the cation exchange resin and the chelating resin are at a maximum at the top of the B horizons (Figs. 3 and 4). This depth pattern suggests that amounts of sesquioxides leaving the litter layer are relatively small and that the source of metal cations in the soil solution is mineral weathering or release in the A and E horizons. Soil solutions leaving the B horizons have very low Fe and Al contents, suggesting that most sesquioxides are immobilized within the B horizon (Ugolini et al. 1977.

The patterns of Fe and Al sorbed on the chelating resin are typical of patterns found in lysimeter studies in other podzols (Ugolini et al. 1977, 1987, 1988; David and Driscoll 1984; Schaetzl 1990; Ugolini and Sletten 1991). Typically, lysimeter studies in soils undergoing active podzolization reveal depth trends wherein Fe and Al concentrations in soil solutions are low just beneath the litter layer, highest where the solution enters the Bs horizon, and low again as it leaves the solum. A pattern common to both forested and stump prairie soil is that amounts of sorbed Al are generally higher than sorbed Fe for both the cation exchange resin and the chelating

TABLE 1

Mean amounts (and standard deviation) of cations sorbed on cation exchange and chelating resins in forest and stump prairie pedons

	Forest pedons*	Stump prairie pedons*
	---------- mg kg^{-1} dry resin	----------
Cation exchange resins (all horizons)		
Mg	62.7 (67.8)	30.5 (17.9)
Ca	226.2 (363.3)	87.4 (68.4)
Fe	30.1 (39.0)	18.7 (9.1)
Al	93.9 (132.6)	37.3 (33.1)
Chelating resins (all horizons)		
Fe	117.3 (184.9)	64.0 (61.6)
Al	473.4 (551.3)	282.7 (265.3)
Cation exchange resin (top of B horizon only)		
Mg	65.5 (46.1)	36.9 (16.2)
Ca	155.3 (132.3)	142.3 (84.1)
Fe	60.8 (59.7)	27.6 (9.6)
Al	201.4 (198.0)	59.6 (38.5)
Chelating resin (top of B horizon only,		
Fe	255.6 (285.5)	130.9 (52.6)
Al	959.0 (768.4)	550.7 (311.2)

*For all rows, column means are not significantly different at $p = 0.05$ by the Mann-Whitney *U* test.

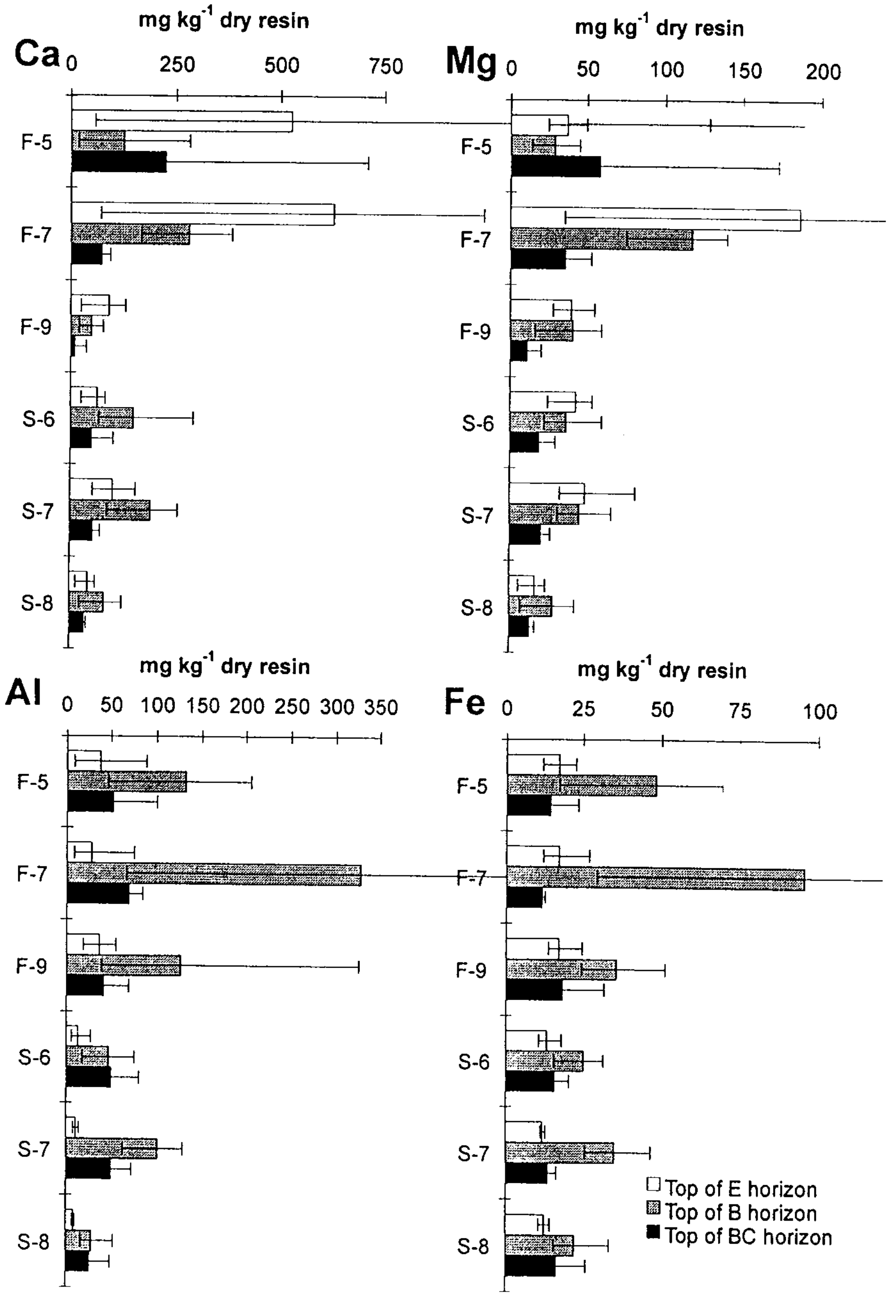

Fig. 3. Amounts of cations sorbed on the cation exchange resins buried in forest (F-5, F-7, and F-9) and stump prairie (S-6, S-7, and S-8) pedons. Bars indicate mean values; error bars indicate minimum and maximum values within a pedon.

resin (Figs. 3 and 4). Furthermore, most of the Fe and Al in the soil solution of both soil types appears to be in organically complexed forms because the amounts sorbed on the chelating resin are much higher than amounts sorbed on the cation exchange resin (Figs. 3 and 4).

From the within-pedon pattern of Fe and Al sorption, podzolization seems to be active in both stump prairie and forest soils. Although not statistically significant, mean amounts of sorbed Fe and Al seem to be slightly greater in the forest pedons than in the stump prairie pedons in all horizons

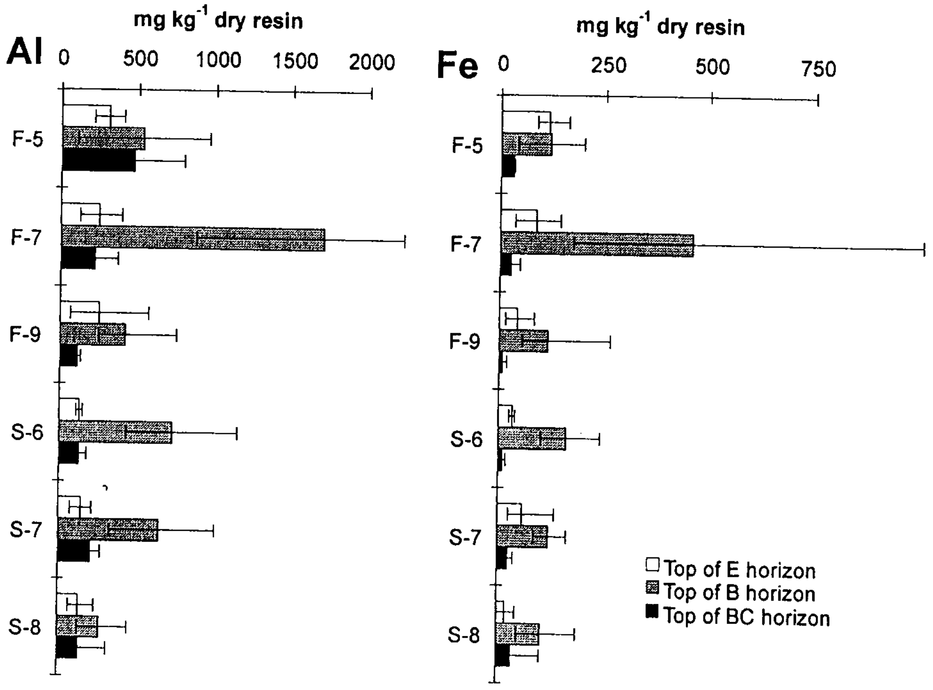

Fig. 4. Amounts of cations sorbed on the chelating resins buried in forest (F-5, F-7, and F-9) and stump prairie (S-6, S-7, and S-8) pedons. Bars indicate mean values; error bars indicate minimum and maximum values within a pedon.

(Table 1). However, variability is very high both within and between pedons. The variability could be the result of preferential or "funnel flow" of water in these sandy soils (Kung 1990; Dekker and Ritsema 1996; Ju et al. 1997). The generally larger absolute amounts of sesquioxides sorbed on the resins of the forested pedons suggest, however, that podzolization processes are more active in forested than in stump prairie soils. Nevertheless, the signature of active podzolization is clear in the stump prairie soils, especially in the pattern of Al sorbed by the chelating resin (Fig. 4). Thus the *in situ* data do not support our hypothesis that the stump prairie soils have undergone a change in pedogenesis. Rather, they suggest only that the *intensity* of podzolization processes has been diminished under the stump prairie.

Evidence from Solid Phase Soil Properties

We examined the morphological and chemical properties of the stump prairie and forest soils to test the hypothesis of whether measurable degradation of static soil properties had occurred.

Morphological Properties

Morphological properties, especially B horizon color and degree of cementation, differ between the two soil types. In six transects across the forest/stump prairie boundary, the B horizons of forested soils have (i) redder Munsell hues, (ii) lower color values and chromas (Table 2), and (iii) more ortstein. Redder hues and darker color values in the B horizon are associated with increased development (Schaetzl and Mokma 1988; Mokma 1993; Courchesne and Hendershot 1997) and are reflective of contrasting B horizon chemical properties. In Michigan, podzol B horizon hues become redder and their values and chromas decrease with increasing amorphous organometallic complexes (Mokma 1993) and with increasing soil age (Barrett and Schaetzl 1993). In Ontario, redder hues and lower color values are correlated with Fe accumulation, whereas lower chromas are associated with organic C accumulation (Evans and Cameron 1985). Likewise, larger amounts of ortstein are also associated with more strongly developed podzols (Wang et al. 1978; Pagé and Guillet 1991; Barrett and Schaetzl 1992, 1993; Freeland and Evans 1993). Thus, even though forested soils may have been better developed before logging, the morphological data provide no evidence that this trend has been reversed.

TABLE 2

Average color of darkest, reddest B horizon observed in probe samples ($N = 54$ for each transect). Color was measured by matching the sample visually to the nearest Munsell chip

	Munsell hue (YR)	Munsell value	Munsell chroma
All forest	6.6	3.2	3.7
Transect 1	6.9	3.4	3.9
Transect 2	6.3	3.0	3.3
Transect 3	6.8	3.2	3.6
Transect 4	6.8	3.3	4.1
Transect 5	7.0	3.5	4.6
Transect 6	5.7	3.0	2.7
All stump prairie	7.1	3.4	4.4
Transect 1	6.9	3.3	3.9
Transect 2	7.1	3.3	4.0
Transect 3	6.9	3.5	4.2
Transect 4	7.5	3.7	5.2
Transect 5	7.4	3.6	4.9
Transect 6	6.8	3.3	4.1

Chemical properties

Weighted B horizon organic C content and most forms of extractable Fe and Al are higher in forested than in stump prairie pedons (Figures 5 and 6). Nevertheless, the contrast between the two soil types is not equally strong for all sesquioxide forms.

Pedogenic Fe has customarily been partitioned into total pedogenic Fe (Fe_d), crystalline Fe oxides such as goethite, lepidochrocite, and hematite (Fe_d-Fe_o), inorganic amorphous or poorly crystalline Fe (Fe_o-Fe_p), and organically-bound Fe (Fe_p; McKeague et al. 1971; Baumler and Zech 1994). The exact nature of the Fe extracted by pyrophosphate has been questioned, but much of the Fe extracted from podzol B horizons using pyrophosphate is probably associated with organic matter (Schuppli et al. 1983). The interpretation of Al forms is not quite analogous. Al_d is usually considered to represent a combination of exchangeable and organically bound Al, and also Al of lattice-substituted Fe oxides (McKeague and Day 1966), whereas Al_o represents exchangeable and organically bound Al as well as Al from silicates (Parfitt and Childs 1988). Thus Al_o may exceed Al_d content in the same horizon, as it does here (Table 3); McKeague et al. 1971). Al_p is used here to estimate Al in organic complexes, although it may also include some Al hydroxide phases (McKeague and Schuppli 1982; Kaiser and Zech 1996).

The primary chemical differences between the forest and stump prairie soils are related to organic C and properties associated with organic C (Figs. 5 and 6). For example, the differences in B horizon Fe and Al contents of the two soil types are most apparent in organically bound Fe and Al (Fe_p and Al_p). The total free sesquioxide forms (Fe_d and Al_d) show a smaller (not statistically significant) difference, and inorganic amorphous forms of Al (Al_o-Al_p) are actually slightly higher in the stump prairie soils (Fig. 5). That the differences are most apparent in organic C and organically bound sesquioxide forms may reflect the contrasting rates and forms of organic matter input on the two landscapes. The organically bound forms of Fe and Al may be particularly sensitive to a lack of replenishment by organometallic complexes in the litter because they decay over time and require input of fresh organic C to maintain a constant level in the soil.

Organic matter content is a soil property that "turns over" rapidly and, therefore, responds relatively rapidly to environmental changes (Olson 1958; Birkeland 1984; Schlesinger 1985; James

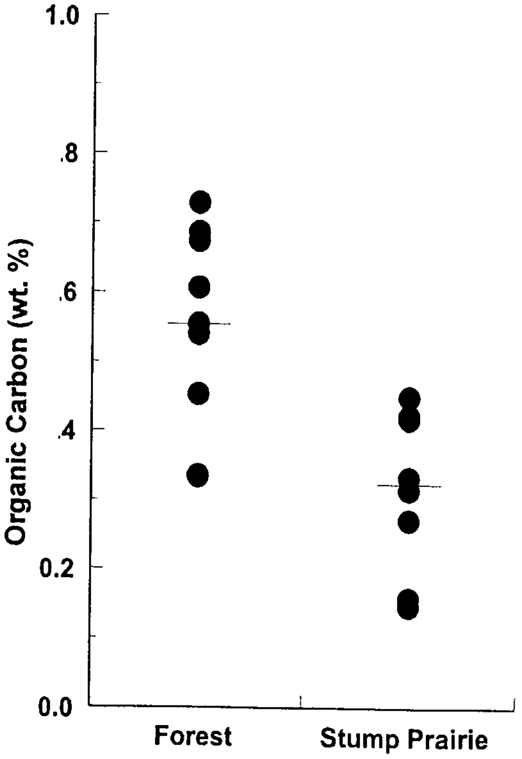

Fig. 5. Weighted B horizon organic carbon content in 17 sampled forest and stump prairie pedons. Horizontal bar indicates median value.

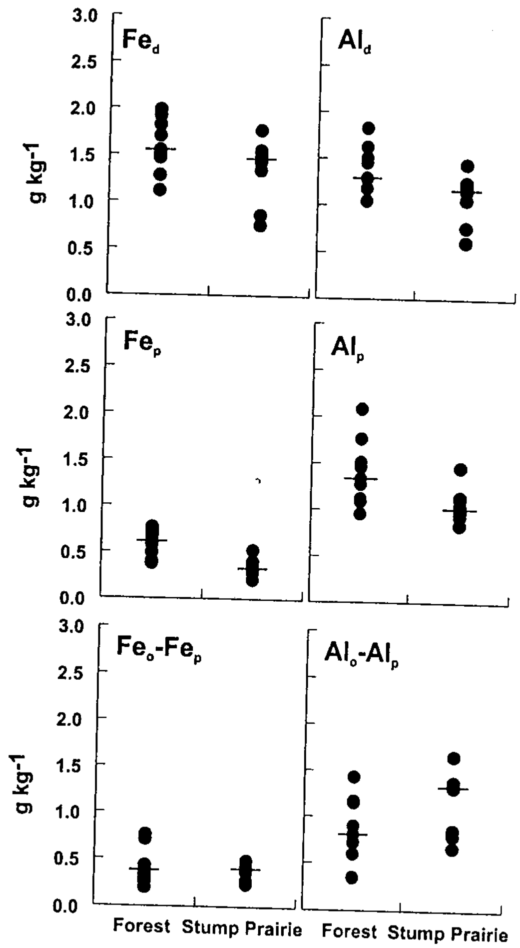

Fig. 6. Weighted B horizon content of extractable Fe and Al in 17 sampled forest and stump prairie pedons. Horizontal bar indicates median value.

1988; Schaetzl 1994). The turnover rates of the organic matter in some podzol B horizons, as shown by the radiocarbon mean residence time (MRT), are equally rapid (Gilet-Blein et al. 1980; Geyh et al. 1983). Podzol B horizon material has been reported to have MRT ages of <700 years (e.g., Dubois et al. 1990; Pagé and Guillet 1991; Schaetzl 1992), but some turnover rates are much slower (MRT ages > 3000 yrs; Pagé and Guillet 1991). Thus, organic matter contents in podzols could be expected to respond rapidly to a decrease in input of organometallic compounds resulting from vegetation change although not all of the organic C in these soils is likely to be lost within a few hundred years. Ladyman and Harkness (1980) showed that the upper B horizon of a pedon undergoing depodzolization after a transition from heath to birch vegetation contained younger carbon after 40 years of tree growth, probably because of increased microbial activity and an acceleration in the rate of organic decomposition.

If organic C content is more sensitive to vegetation changes than other B horizon properties, depodzolization in its early stages should be most evident in organic C and related properties. Previous evidence of depodzolization has been based primarily on decreases in B horizon organic C content in the soils that had undergone a change in vegetation (Hole 1975; Nørnberg et al. 1993). The lower organic C and organically bound sesquioxide contents of the stump prairie pedons could, therefore, be caused by degradation of B horizon organic compounds in the absence of a forest that would normally contribute large amounts of organic matter to the pedologic system.

Fe and Al contents

For inorganic constituents, the differences between forest and stump prairie soils are minimal. Total B horizon Fe content (Fe_d) is apparently slightly lower in the stump prairie soils, but the differences for this and for total Al (Al_o) are not statistically significant (Table 3). Crystalline (Fe_d-Fe_o) and inorganic amorphous Fe (Fe_o-Fe_p) and inorganic amorphous Al (Al_o-Al_p) are slightly higher in the stump prairie than in forest soils (Table 3). Because inorganic Fe and Al contents in the stump prairie have not decreased measurably, the decrease in total B horizon sesquioxide content must be attributed primarily to a decrease in organically complexed forms. As organic complexing agents in the B horizon decompose, inorganic amorphous Fe and Al may

TABLE 3

Weighted B horizon means of selected soil properties for forest and stump prairie soils

Soil property (g kg^{-1})	Forest	Stump prairie
Organic C**	5.5	3.1
Fe_d	1.6	1.3
Fe_o**	1.0	0.7
Fe_p**	0.6	0.3
Fe_d-Fe_o	0.58	0.62
Fe_o-Fe_p	0.42	0.38
Al_d*	1.4	1.1
Al_o	2.3	2.3
Al_p*	1.4	1.1
Al_o-Al_p	0.9	1.2

*, **Means are significantly different at $p < 0.05$ and $p < 0.01$, respectively, by the Mann-Whitney *U* test.

form stable inorganic compounds, possibly accounting for the increase in stump prairie Al_o-Al_p. The overall decrease in total B horizon sesquioxides in the stump prairie soils suggests, however, that some of the Fe and Al originally present in organically complexed forms is being lost from the B horizons, albeit slowly. Under changed vegetation cover, the data suggest that previously stable B horizon sesquioxides are eventually remobilized and removed from the profile. Thus, the evidence from soil chemical and morphological properties appears to support the hypothesis that measurable degradation of stump prairie B horizons has occurred in about a century with respect to organic C and organically bound sesquioxides.

Comparison of Soil Solution and Solid Phase Data

Contrasting evidence regarding depodzolization can be derived from the two parts of our study. The data from the *in situ* part of this investigation, which focus on Fe and Al translocations, provide evidence for slowed podzolization in the stump prairie areas but do not point to a change in pedogenic pathway *per se*. If lower B horizon Fe and Al contents in stump prairie soils have resulted from continued losses of previously illuviated material, resin-sorbed Fe and Al should be higher at the top of the BC than at the top of the B horizon because the soil solution leaving the B horizon would be enriched in Fe and Al. Amounts of Al sorbed on the cation exchange resin at the top of the BC horizon in pedons S-6 and S-8 are approximately the same as those sorbed at the top of the B horizon, suggesting that B horizon Al contents are changing very little or not at all in these pedons (Fig. 3). These pedons are exceptional, however, as the pattern for Fe sorbed on the cation exchange resin and for both Fe and Al sorbed on the chelating resin (Figs. 3 and 4) indicates ongoing podzolization in all the studied pedons, i.e., continuing increases in B horizon total sesquioxide contents.

Thus the *in situ* data do not support our original hypothesis that most differences in soil morphology and chemistry are the result of depodzolization of the stump prairie soils, at least with respect to sesquioxide translocations. Depodzolization may be occurring, however, with respect to organic C and organic C-dependent properties (e.g., B horizon color) because the resins do not monitor translocations of organic C separately. Data on the chemistry and morphology of forest and stump prairie soils suggest that depodzolization processes, if they are occurring, involve organic C and organically bound sesquioxides to a greater extent than inorganic forms. If these organic complexes are decomposed in the B horizon at a rate faster than they are replaced, a decrease in total B horizon organic C and organically bound sesquioxides in the horizon may still take place, and depodzolization may occur.

From these data we infer that the three major illuvial components of podzol B horizons (organic C, organically bound sesquioxides, and inorganic sesquioxide forms) respond independently to environmental changes. All three may be both added and removed continually; in a pedon undergoing active podzolization, the removal processes are relatively slow, whereas, in a pedon undergoing depodzolization, removals exceed additions. Organic C content of B horizons begins to decrease when a change in vegetation type results in decreased inputs, and it will thus be among the first measurable changes in soil properties after a change in pedogenic pathway. Subsequently, the organically bound sesquioxides decrease, and some are converted into inorganic forms as the organometallic complexes decompose. Inorganic sesquioxides in the B horizon respond more slowly to a change in vegetation type, such that a decrease in organic sesquioxides is not readily identifiable after a century of depodzolization. Furthermore, our *in situ* data showed only scant evidence of remobilization and removal of inorganic Fe and Al.

In the study area, the depodzolization processes do not work as rapidly as previously thought (Hole 1975). B horizon organic C content decreased in measurable quantities over a century, but the sesquioxide content, especially the inorganic forms, decreased much more slowly, if at all. In addition, our assumption of pre-logging similarity of the two soil types probably exaggerates the apparent rate of depodzolization determined from static soil properties because, based on evidence of vegetation type in the forest and stump prairie areas (Barrett 1997), the currently forested soils were probably slightly more developed before logging took place.

In the study area soils, the balance between progressive development (podzolization) and regressive development (depodzolization) is profoundly affected by the vegetation type. Although in this case the deforestation was anthropogenic, natural disturbances and vegetation succession may also influence the pathway of soil development. Overall rates of podzolization, a composite result of the balance between podzolization and depodzolization processes active since initiation of pedogenesis, must be influenced by the frequency of disturbances and the course of succession in a landscape, possibly leading to weakly developed soils under high frequency disturbance regimes and more strongly developed podzols where disturbance is less frequent (Whitney 1986; Mokma and Vance 1989).

CONCLUSIONS

Some aspects of depodzolization have occurred in the logged-over and essentially treeless Kingston Plains. Data from an *in situ* study of active soil processes suggest that podzolization remains active in both forest and stump prairie soils, though it has been slowed in the latter. A detailed examination of the sesquioxides extracted from B horizon solid phases suggests that the contrast in chemical properties between the forested and stumped areas is greatest in organically bound Fe and Al forms. In fact, inorganic sesquioxide content appears to be slightly higher in the stump prairie pedons.

We conclude, therefore, that the morphological evidence of depodzolization is measurable first in organic C and organically bound sesquioxide forms because decomposition of B horizon organic C and organometallic complexes exceeds additions after a decrease in organic acid input caused by deforestation. Evidence for depodzolization does not appear in the *in situ* study because the resin data do not measure translocation and decomposition of organic C. Both progressive (podzolization) and regressive (depodzolization) processes occur in dynamic balance in any given pedon, affecting individual soil constituents at different rates and resulting in a complex, polygenetic history of soil development here and, presumably, elsewhere.

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