This is to certify that the

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Soils, Forest Vegetation, Logging, and Fire

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Major professor

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A STUMP PRAIRIE LANDSCAPE IN NORTHERN MICHIGAN: SOILS, FOREST VEGETATION, LOGGING, AND FIRE

By

Linda R. Barrett

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ABSTRACT

A STUMP PRAIRIE LANDSCAPE IN NORTHERN MICHIGAN: SOILS, FOREST VEGETATION, LOGGING, AND FIRE

By

Linda R. Barrett

Parts of a sandy plain located in northern Michigan today are "stump prairie," devoid of trees, although prior to the logging and fires of the late 19th century they supported dense forest. Nearby, otherwise similar sites have regenerated to forest. The aims of this study were to determine how site and human disturbance patterns are related to patterns of long-standing changes in this ecosystem and to examine the possible impact of these forest regeneration patterns on active soil processes.

Evidence from the General Land Office survey notes suggests that original forest composition has a strong relationship to forest regeneration patterns, possibly due to the manner in which early logging was accomplished. White pine (*Pinus strobus*) was especially prevalent in the pre-logging forest of current stump prairie areas, but sugar maple (*Acer saccharum*) was nearly lacking there. Land ownership and tax records suggest that stump prairie sites were acquired and logged at least as early as adjacent forested sites. Tree rings and recent stumps provide evidence that in currently forested areas loggers left more trees to provide shade and seed sources for forest recovery.

Soil parent material texture is not significantly different between the forest and stump prairie sites. Spodic horizon development, as shown by degree of ortstein cementation and Fe, Al, and organic matter contents, is slightly stronger where forest regeneration has occurred than in areas that have remained stump prairie. Most of the extractable Fe and Al is present in organically-bound forms, but inorganic forms become more important in the lower B horizon. Ortstein content represents the primary difference between the soils in forested and stump prairie areas.

In order to study current soil development processes, bags of cation exchange and chelating resins were buried in forested and unforested sites. Although variability within and between pedons was very high, slightly greater amounts of Fe and Al were sorbed in B horizons of soils of forested than of unforested sites, suggesting that podzolization processes are more active in the forest than in the stump prairie. These data highlight the importance of forest vegetation in maintaining the spodic (Bs) horizon.

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INTRODUCTION AND STATEMENT OF PROBLEM

Logging and uncontrolled wildfires largely destroyed the forests of northern Michigan in the latter half of the last century (Twining 1983; Benson 1989; Williams 1989). Most of these lands soon regenerated into second-growth forests of successional hardwoods and pines. In a few scattered locations, however, trees and forest vegetation have still not returned following the logging and associated fires. One such area, an outwash plain located in the Upper Peninsula just south of the Lake Superior shoreline, is known as the Kingston Plains. At one time, this area supported one of the best pine and mixed pine/hardwood forests of the peninsula (Frederick et al. 1976), but today the sparse vegetation consists of reindeer moss, grasses, bracken ferns, and low-growing blueberry bushes, with a few scattered, stunted trees growing beside the huge pine stumps ("stump prairie"). The treeless area covers about 2500 ha; it is surrounded by seemingly thriving second-growth forest in similar positions on similar landforms; some of these are today being logged a second time.

The objective of this dissertation is to elucidate the factors, both physical and anthropogenic, that contributed to the existing spatial pattern of regenerated forest vs. "stump prairie" in the Kingston Plains area. The study focuses on the relationship between soil properties and vegetation regeneration patterns, but also examines spatial relationships between vegetation regeneration and 1) pre-existing vegetation patterns; 2) logging and land management practices; and 3) logging-era fires. A secondary purpose of the research is to explore the relationship between forest vegetation and soil development (podzolization) processes in the sand soils of northern Michigan, and whether, in fact, the long-term elimination of the forest has altered the pathways of soil development, or even caused soil degradation. Thus the study emphasizes the importance of physical processes *and* human actions in understanding long-standing environmental degradation associated with economic development.

Structure of the dissertation

Both the Methods chapter and the Results and Discussion chapter of this dissertation are structured around three possible factors that could be related to spatial pattern of forest regeneration in the Kingston Plains: (1) pre-disturbance[1] forest patterns; (2) substrate and soil properties; and (3) logging era fires and logging practices. A section of both chapters is devoted to each of the three factors. Preceding these three sections, both chapters also contain a section devoted to the current forest/stump prairie patterns.

[1] The term "pre-disturbance" is used in this dissertation to refer to the forest patterns that existed prior to the logging and associated fires that occurred at the end of the nineteenth century.

LITERATURE REVIEW

Stump Prairies

The term "stump prairie" is used in this dissertation to denote a landscape found on formerly forested land of northern Michigan that now has few trees and abundant old stumps. Also the term refers to a plant community dominated by grasses, bracken ferns, and low growing shrubs. Some scattered trees may be present, usually white pine (*Pinus strobus* L.), white birch (*Betula papyrifera* Marshall), black cherry (*Prunus serotina* Ehrhart), aspen (*Populus* spp.), or juneberry (*Amelanchier* spp.), but a distinctive feature is the abundance of large, old stumps (now often more than a century old), which attest to the former forests of these sites. The term itself is used colloquially among land managers and residents where the stump prairies are common. It has not been formalized in the scientific literature, although its informal use has been reported (Vogl 1964; Curtis 1971). Rohe (1971, p. 49) used it to describe an area in northeastern Wisconsin where repeated fires had left a degraded soil supporting only short grasses and some shrubs. The term has been in use at least since the late nineteenth century, when Roth (1898, p. 13) described "large tracts of bare wastes, 'stump prairies,' where the ground is sparsely covered with weeds and grass, sweet fern, and a few scattering runty [sic] bushes of scrub oak, aspen, and white birch" remaining on cut-over pine lands in northern Wisconsin.

The vegetation of the northern Michigan stump prairie is similar to that described in northern Wisconsin as "bracken-grassland" (Vogl 1964; Curtis 1971). Bracken-grassland communities are dominated by bracken ferns and various grass and forb species; shrubs such as sweet fern and blueberry are also common (Curtis 1971, pp. 315-316). Vogl (1964) reported the presence of stumps on all but one of his bracken-grassland study sites. Despite the fact that these sites had been formerly forested and originated from disturbance, they did not appear to be succeeding back to a forest community (Curtis 1971, p. 314). A similar community, the blue grass association, was described as being common on former (pine) forested land in northern Michigan, although it was being rapidly encroached upon by forest (Gleason 1918).

Possible origins

Little work has been done on the origins of the stump prairies and related unforested vegetation types of northern Michigan and Wisconsin (Vogl 1964a; Vogl 1970; Curtis 1971). A number of theories regarding their origin(s) have been suggested:

(1) Pre-existing vegetation patterns. Some of these areas lack stumps today and may not have supported trees, or only scattered trees, before logging (Vogl 1964a; Curtis 1971). Open vegetation[2] types similar to that existing on the Kingston Plains were not unknown in the pre-logging Great Lakes forests, especially on sandy substrates (Vogl 1964b; Vogl 1970; Curtis 1971; Whitney 1986). These "barrens" contained scattered jack pine clumps and large, open-grown red pine (*Pinus resinosa* Aiton) trees, and were maintained by frequent fires (Vogl 1970; Whitney 1986). Many of the areas which supported only scattered trees in pre-logging times have, however, developed into thick jack pine forests following the suppression of fires beginning in the early part of this century (Vogl 1964b; Curtis 1971; Bourdo 1983); in some areas controlled burns have been used to restore the original savanna vegetation (Vogl 1964b). The "bracken-grasslands" of northeastern Wisconsin, however, occur today on a variety of pre-logging site types, ranging from open forests of red pine and scattered white pine to more mesic stands of sugar maple and associated species, or even boreal forest (Vogl 1964a).

[2] The term "open vegetation" is used in this dissertation to refer to vegetation communities in which the forest canopy is not closed, i.e., savanna or grassland vegetation types.

(2) Logging era fires and logging practices. Fire is often cited as a principal cause of open vegetation types and recurrent fire is thought to be necessary for their maintenance (Vogl 1964a, b; Curtis 1971). Stump prairie sites may have undergone particularly *intense* fires, consuming all or most of the soil organic matter (Curtis 1971; Frederick et al. 1976), or particularly *frequent* fires, killing tree seedlings and eventually eliminating seed sources (Curtis 1971; Bourdo 1983). Vogl (1970) reported that fire, while essential to the establishment of northern Wisconsin pine barrens, is less important than previously thought. He believed that the critical factor in determining their location was the presence of sandy plains with low fertility that promote droughts and fires of the proper intensities. Curtis (1971, p. 317) suggested that some of the bracken-grasslands may have originated following logging and fire, but that fire is not necessary for their continued maintenance.

(3) Competition and allelopathy. Antibiotic production by grassland flora and competition between grasses, bracken ferns, and tree seedlings might contribute to the maintenance of open areas once they become established (Vogl 1964a; Curtis 1971). Reindeer moss lichens are also suspected of allelopathic effects on tree seedlings (Brown and Mikola 1974; Fisher 1979; Bruhn et al. 1987). Competition and allelopathy, however, are unlikely to serve as an explanation for the *initial* appearance of open vegetation areas.

(4) Microclimate. Frequent or prolonged frost activity, or "frost pockets," might also inhibit tree reproduction in low-lying or depressional sites, which are common on the pitted outwash plains where barrens vegetation exists today (Vogl 1964a; Curtis 1971). Microclimate, however, cannot explain the occurrence of open vegetation areas on the relatively flat upland expanses of the majority of the Kingston Plains and other sites (Vogl 1964a), nor the existence of trees in some nearby depressions.

(5) Soil properties. Many authors have suggested that the logging and fires inflicted on these sites have left the soil too degraded to support contemporary forest

vegetation (e.g., Roth 1908; Rohe 1971; Curtis 1971). Vogl (1964a) thought that many bracken-grassland sites might have developed "hardpans" while under forest vegetation which, after elimination of all vegetation in logging and fires, resulted in a harsh environment fluctuating seasonally from wet to dry, favoring sedges over tree species. Veatch et al. (1929), in their soil map of Alger County, distinguished between the soil of the deforested areas and that where forest exists today, indicating that they believed that the soil reflected, and may have caused, the vegetation differences.

Role of human disturbance vs. environmental factors

Since before the turn of the century, researchers concerned about the degradation of Michigan's forest ecosystems (that is, the change from forest to non-forested shrub- and grass-dominated ecosystems) have tended to place primary emphasis on the role of the logging companies that cut the trees and policies that failed to protect them from, or even encouraged, widespread fires (Beal 1888; Roth 1906; Buttrick 1921; Curtis 1971). Certainly these human activities, as major disturbances to the ecosystem, precipitated the ensuing forest degradation. Ecosystems are not alike, however, in their ability to withstand disturbances; the concepts of ecosystem resilience and stability have been formulated to explain the behavior of ecological systems in response to disturbance (Holling 1973; Barrow 1991). In "natural" systems, both disturbance and site factors work together to produce the resulting vegetation patterns (Whitney 1986). For example, the role of "natural" disturbances in ecosystem maintenance has been much investigated (e.g., Maissurow 1941; Vogl 1970; Heinselman 1973; Swain 1978), as has the influence of substrate on forest vegetation patterns (e.g., Livingston 1905; Veatch 1928; Wilde 1933; Brubaker 1975; Whitney 1986; Barrett et al. 1995). When environmental degradation is associated with anthropogenic disturbances, however, the tendency has been to ignore nature's role in the human/environmental interaction equation and place all blame on the human side of the equation (Quinn 1991).

This study is conducted on the premise that in order to understand environmental degradation precipitated by human activity, an examination of the interaction between the site, the ecosystem, and the activity itself is required. "Environmental susceptibility" has been defined as a condition whereby the environment of a particular location, because of that location's natural features, is especially vulnerable to injury from specific human activity (Quinn 1991). Environmental susceptibility in this sense has been demonstrated in the severe environmental degradation associated with the copper mining and smelting activity of the late 19th century in Tennesee's Copper Basin (Quinn 1991).

Human activity, including logging, removal of the trees, and the subsequent slash fires, undoubtedly played a role in the change from magnificent pine forest (Frederick et al. 1976) to stump prairie on the Kingston Plains. Nevertheless, similar logging and fires occurred over most of northern Michigan, including large areas of impoverished sandy soils, and most of these areas today support thriving successional forests of aspen, birch, pine, and maple. Clearly, some characteristic of the Kingston Plains site itself (and others like it), something in the manner in which the disturbance occurred and/or the interaction between the site and the disturbance, is responsible for the stark lack of forest so evident today. This study examines both site and disturbance factors in order to determine why this particular place at this particular time experienced such dramatic environmental degradation. Knowledge about the Kingston Plains site can then be applied to other regions in order to help managers and planners predict more accurately which activities might lead to drastic, long-lasting consequences, and which will have relatively minor effects. Such information is becoming increasingly important as population growth puts escalating pressure on our natural resources and forest reserves. It can be used to point out priority areas where disturbance of any kind is likely to lead to severe environmental degradation from which recovery cannot be expected for decades.

Pine forests, fire, and succession in northern Michigan

White pine, and to a lesser extent red pine, was an important component of northern Michigan's presettlement[3] forests. Because white pine is only moderately tolerant of shade and usually requires exposed mineral soil for successful establishment (Graham 1941), its widespread presence in the presettlement forest has been interesting to ecologists. A variety of factors has been invoked to explain the origin and maintenance of pine forests in northern Michigan. Clearly, either the unique nature of the xeric, sandy soils or widespread repeated disturbances (fires) arrested the succession of the pine forests to the more tolerant northern hardwoods types (Whitney 1986).

Early studies often emphasized the role of soils and substrate in determining presettlement forest type (e.g., Livingston 1905; Veatch 1928; Wilde 1933; Brubaker 1975). The relationship between such physical site characteristics as soil texture, drainage, and landform type, and presettlement forest composition has been well established in studies using the notes of the General Land Office surveyors to investigate presettlement forest composition (Whitney 1986; Leitner et al. 1991; Barrett et al. 1995). It is also possible that more subtle site characteristics, such as sand texture, B horizon development, or the frequency of finer-textured subsoil bands, may also influence forest composition (Palik and Pregitzer 1992).

More recently, many have emphasized the role that disturbances, especially fire, have played in the development of the white pine forests (e.g., Maissurow 1941; Heinselman 1973; Little 1974; Clark 1989; Frelich and Lorimer 1991). Periodic fires eliminate the competing shade-tolerant hardwood species and provide a mineral seedbed conducive to pine seedling establishment. Fire frequency, as determined from the General Land Office surveyors' notes, has been related to presettlement forest composition in

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[3] The term "presettlement" is used in this dissertation to refer to the period before major European settlement of Michigan; i.e., prior to around 1850 in the Upper Peninsula.

Michigan. On dry sites in Michigan, presettlement pine forests experienced light surface fires at intervals of 20 - 40 years, followed by higher intensity fires which killed the mature pines perhaps every 100 - 200 years (Heinselman 1981). Areas in northern Lower Michigan experiencing the most frequent fires were forested with jack pine (*Pinus banksiana* Lambert) or mixed pine forests, while sites experiencing infrequent fires were under hardwood forests (Whitney 1986; Mokma and Vance 1989).

Even before the time of European settlement, anthropogenic fires may have influenced forest vegetation patterns in the Lake States. In northeastern Wisconsin, savanna vegetation in presettlement times appears to have been closely associated with Indian sites, and likely resulted from Indian-caused fires (Dorney and Dorney 1989). Pine forest maintenance in parts of Michigan's Upper Peninsula was also probably due to Indian-caused fires (Loope 1991). In the northeastern United States, however, little evidence for purposeful burning by Indians has been found (Russell 1983).

Other explanations for the origin and maintenance of the pine forests have also been advanced. For example, the period during which most of the presettlement pine forests were being regenerated was warmer and dryer than that prevailing in the mid-19th century, and may also have had a different fire regime (Clark 1989). Thus, climate may have played a part in establishing a forest that remained on as a relict as the climate became cooler and drier. Historical circumstances also influence forest composition and successional pathways (Palik and Pregitzer 1992).

Most likely, the origin of Michigan's pine forest can be ascribed to the interaction of a combination of factors, including fire frequency, climate, soils, human actions, and historical accident. The dry, sandy soils favor the initial establishment of pine trees, which in turn contribute to the frequent return of fires, further perpetuating the presence of the fire-resistant pines (Whitney 1986). Climate and historical circumstances, including human actions, further influence the frequency of fire return and thus may also play a role in determining forest composition (Palik and Pregitzer 1992). A sudden, drastic change in certain of these factors, such as happened at the time of nineteenth century logging, may upset the balance of the interactions, leading to transformations of forest composition that are dramatic and lasting by creating a new set of equilibrium conditions (Whitney 1987).

Fire regimes, forest types, and soil development

On the sandy stubstrates of northern Michigan, presettlement fire frequency may have influenced the degree of soil development by controlling forest composition, which in turn determines the amounts of organic acids and chelating substances moving through the solum, i.e., podzolization processes (Mokma and Vance 1989). Mokma and Vance (1989) found a relationship between B horizon development and forest type in the northern Lower Peninsula. Weakly developed B horizons are found under jack pine forests which burned frequently. Recurring fire in jack pine forests (Brubaker 1975; Simard and Blank 1982; Cayford and McRae 1983) results in the burning of the litter layer and the leaching of fewer organic compounds through the soil, which in turn leads to slowed development of the spodic (Bs) horizon. Moderately developed B horizons are associated with red and white pine forests, which burn less frequently than jack pine forests (Van Wagner 1970; Bourdo 1983; Whitney 1986). The lower burn frequency creates more available organic compounds, leading to soils with darker Bs horizons and more iron, aluminum, and organic carbon accumulation. Under northern hardwoods vegetation, which burns infrequently (Whitney 1986), the strongest soil development is found, with dark Bhs horizons and the highest organic carbon, iron, and aluminum accumulations. In this manner soils on surfaces of the same age and texture may develop to contrasting degrees due to the establishment of contrasting vegetational communities. It may also be that once the differences in soil development are established they are perpetuated because the white pine and northern hardwood species compete better on the more strongly developed Spodosols, while jack pine and red pine compete better on the weakly developed soils (Mokma and Vance 1989).

Many of the relationships between forest species and soil development are maintained today in the successional forests that followed logging (Mokma and Vance 1989). In some parts of Pictured Rocks National Lakeshore, however, former red and white pine stands are now dominated by jack pine (Loope 1991). It is not clear whether a change in the forest type due to logging will, over time, influence soil development by changing the litter type and fire susceptibility of the site, or whether a change in forest type alone is sufficient to cause a degradation of an already strongly developed spodic horizon.

Active soil processes and soil degradation

The close relationship between forest vegetation and podzolization processes in northern Michigan suggests the question of whether soils, especially spodic horizons, degrade and become weaker following the destruction of forest vegetation. The spodic horizon is extremely important to forest yields on the sandy soils of northern Michigan because it increases water-holding capacity and nutrient availability. The presence and strength of a spodic horizon can be used to predict site yields for many forest types (Shetron 1972).

Recent advances in pedogenic theory (Johnson and Watson-Stegner 1987; Phillips 1993a;b) suggest that soils develop along distinct pathways and that these pathways can be drastically altered by intrinsically-acquired or extrinsically imposed thresholds (Muhs 1984). In the case of the Kingston Plains, the extrinsic threshold has clearly been deforestation and fire. I have investigated the possibility that deforestation has noticeably changed the pathways of these soils from one of podzolization (c.f. Schaetzl and Isard 1991) to one dominated by low nutrient cycling, organic matter oxidation, and predominantly bicarbonate ion weathering (as opposed to organic/fulvic acid weathering).

Soil development processes and weathering are controlled primarily by the amount and type of proton donors or acids present in the soil solution (Ugolini and Sletten 1991). Podzolization is characterized by soil solutions dominated by soluble organic acids in the O, E, and Bhs horizons, while in the lower solum carbonic acid becomes the major proton donor at slightly higher pH values (Ugolini et al. 1977, 1988, 1991). By studying soil solution composition, it is possible to determine whether a soil horizon is currently undergoing the development processes suggested by its morphology, or whether it reflects former conditions no longer present at the site (Ugolini et al. 1988; Ranger et al. 1991).

The type of proton donor present in the soil solution is thought to be determined in large part by the vegetation of the site (Ugolini and Sletten 1991). A change of forest type from deciduous to spruce-dominated has been shown to have affected both the soil solution and soil properties after a period of only 60 yrs (Ranger and Nys 1994). In Britain, a change from heather to grasses and bracken has been associated with a "depodzolization" of the underlying soil (Miles 1985), and also, possibly, a disintegrating iron pan (Mitchell 1973).

No studies investigating the effect of forest composition changes on podzolization processes in the northern Great Lakes region have been published, but a few papers have reported that forest composition does affect spodic horizon morphology. Hole (1975) observed trends suggesting that spodic horizons in northern Wisconsin gradually fade upon the removal of hemlock stands. He estimated the "half-life" of a spodic horizon to be about 100 years after the removal of the trees. Similarly, Milfred et al. (1967; cited in Buol et al. 1980) noted much lower B horizon organic matter content in bracken grassland soils with charred tree stumps than in the adjacent unharvested hemlock stands. The possibility that spodic horizon expression may have changed since logging is especially crucial to this study because at issue is whether soil patterns influenced tree regeneration or whether tree regeneration patterns influenced soil development. Finally, since soil development, especially in sandy soils, does affect the potential yield of a site (Shetron 1972; Host et al. 1987), if the vegetation changes have caused a change in soil development pathways, they may, by extension, have had "permanent" detrimental effects on the ecosystem, and, ironically, the soil itself.

Nineteenth century logging in the Upper Peninsula

Logging practices

During the nineteenth century, white pine was the primary target of the U.S. lumber industry (Whitney 1987; Williams 1989, p. 198). For this reason, the white pine forests of Michigan were highly attractive to the lumbering industry. The center of the pine industry moved from the eastern pine forests of New England into Michigan and the Lake States beginning in the mid-nineteenth century (Williams 1989, p. 193). Within Michigan, navigable rivers, combined with the extensive pine forests of the northern Lower Peninsula, comprised the basis of a flourishing pine industry for about 40 years, from 1855 to 1895, and about 10 years longer in the Upper Peninsula (Sparhawk and Brush 1929).

In the early lumbering years, the pine resources of Michigan were believed to be so extensive that they would never be exhausted (Sawyer 1919). As early as 1885, however, depletion of accessible pine in the Lower Peninsula began to be noticed (Sparhawk and Brush 1929). In response, the efforts of the lumber industry began to turn towards the more inaccessible portions of the region, including the Upper Peninsula and parts of northern Wisconsin and Minnesota (Rector 1953, p. 59).

Advances in lumbering and transportation technology aided in the exploitation of these areas. As pine stands located near enough to navigable rivers for efficient river transportation of the logs became increasingly scarce, railroad logging gained in importance. Construction of logging railroads became common during the 1880s, so that by 1887 there were 89 logging railroads in Michigan (Williams 1989, p. 212). Railroad transportation of logs was especially vital in Upper Peninsula lumbering, because large areas of the forests there were not penetrated by navigable rivers. These areas of forest were generally the last to be logged (Rector 1953, p. 49).

Increasing mechanization was also introduced in the logging process itself (Rector 1953, p. 59). As accessible lumber became scarce, owners of timber began to consolidate their holdings and cooperate, with the objective of clear-cutting all the pine and then abandoning the area. Sometimes tracks would be picked up and re-laid through the forest as often as yearly in order to quickly clear out the last substantial tree (Williams 1989, p. 230). Regions logged in this manner were efficiently stripped of all pine lumber within a short period of time, leaving few or no large, standing pine trees.

Pine logging in the Lake States was essentially finished due to lack of pine by 1900 (Williams 1989, p. 228). Only after that time did the lumbering of hemlock and hardwood species begin to gain in importance (Sparhawk and Brush 1929). As the pine forests of the Lake States became depleted, many lumbering companies turned their attention to other parts of the country, especially the Pacific Northwest (Williams 1989, p. 229).

Logging-related fires

In nineteenth century Michigan, fire followed logging, often as multiple fires in quick succession. The loggers removed the parts of the tree useful for lumber, leaving the tops and branches behind as slash. Large amounts of dry slash provided ample fuel for any fire that was started. Lightning started some fires, but often the most destructive forest fires were the result of brush burning to clear the land, sparks from locomotives, or vandals, or berry pickers (Kittredge and Chittenden 1929; Whitney 1987). In a dry year, smoke from the constantly burning fires in the Lake States could become so thick that it even became a hazard to navigation on Lake Michigan (Fries 1951, p. 246).

By the turn of the century, the destructive nature of repeated fires in the cut-over lands had begun to be recognized. Sparhawk and Brush (1929) reported that "practically every acre of northern Michigan [had] been burned over repeatedly during the last 60 years," and that more than half of the sand plains had been burned at least four times since they had been cut over. A movement to educate the public about the the destruction that fire caused and to begin to protect against forest fires began around this time (e.g., Sherrard 1903).

Around the turn of the century, some authorities began to associate fire with the regenerative failure of former pine lands (Whitney 1987). They noted that vast areas of northern Lower Michigan that had previously been covered by pine trees had no trees left at all (Livingston 1905). Repeated fires were reported to reduce the cover on these lands to a few plants which resist burning, such as bracken, blueberries, and grasses because the trees were not able to survive the fires (Sherrard 1903). Filibert Roth (1898, p. 13) blamed the frequent fires in the pine areas of northern Wisconsin for their transformation to "wasteland." The fire was thought to destroy the O horizon of the sandy soils, and then recur due to the sparse, weedy vegetation growing in the immediate aftermath, which further reduced the soil's fertility (Roth 1898, p. 48). He also pointed out (p. 51) that it was the lack of burning which allowed the hardwood forests on the more mesic sites to regenerate quickly after pine had been removed from them.

It is likely that the fire that followed the logging, and not the logging itself, caused the greater damage to Michigan's former pine forests (Whitney 1987). The combination of logging followed by fire altered the disturbance regime and changed the competetive balance between the forest species. Even though white and red pine depend to an extent on natural disturbance for their maintenance, the change to a much more intense and frequent disturbance regime quickly killed both the young seedlings and those mature trees left for seed, and favored the reproduction of other species, including aspen and oak (Whitney 1987).

Fire following logging has been shown to alter the species composition of forests in northern Michigan (Whitney 1987). In a stump prairie, however, the forest has simply failed to regenerate. The origins and maintenance of a stump prairie landscape have been little discussed in the literature. Soil and substrate patterns, pre-existing forest patterns, and destruction caused by logging and fire have been suggested as possible factors in stump prairie formation. In this dissertation, I will investigate the relationship between these three factors and the patterns of forest regeneration in a stump prairie region.

STUDY AREA

General

The study area is located in the northeastern portion of Alger County, Michigan, bordering on Lake Superior, and centered around the main stump prairie region (Figure 1). The eastern portion of Pictured Rocks National Lakeshore (PRNL) and its buffer zone adjoining the Lake Superior shore immediately north of the study area. The study area itself lies mostly within Grand Sable State Forest, with only a small portion under private ownership. Grand Marais, the nearest settlement, is approximately 20 km to the northeast. A larger study area consisting of the surrounding six survey townships in Alger and Schoolcraft counties has been used for those parts of the dissertation in which a broader geographical perspective was desirable, e.g., the section dealing with presettlement forest vegetation patterns (p. 54; Figure 2).

The name "Kingston Plains" has long been associated with the stump prairie portion of the study area, although its use presents some problems because it has sometimes been applied much more broadly to the extensive outwash deposits extending from the study area east into Luce county (e.g., Bergquist 1936; Futyma 1981). In this dissertation I use the term in its narrowest sense, to indicate only the stump prairie regions located to the southeast of Kingston Lake in T 48 N, R 15 W.

Geomorphology

The topography of the study area is generally level with numerous incised depressions, in places forming chains of kettle lakes. Prominent escarpments trend east to west just north of the Kingston Plains stump prairie, separating it from Kingston Lake to the north. The most recent investigation of the geomorphology of the study area

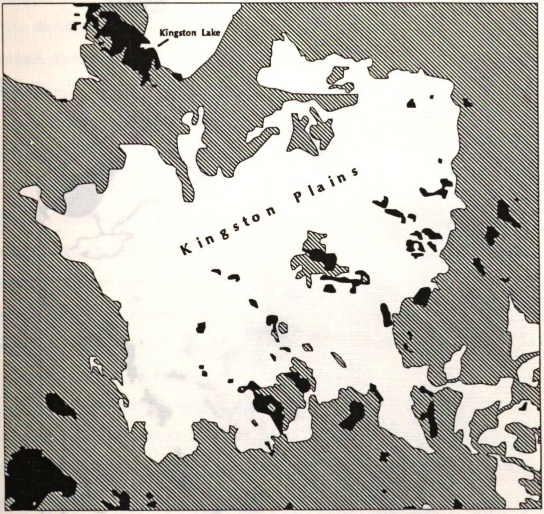

Figure 1. Map of the study area, Alger County, Michigan. Hatching represents forested areas; unhatched polygons are current stump prairie. Black areas represent water bodies. Scale 1:62,500.

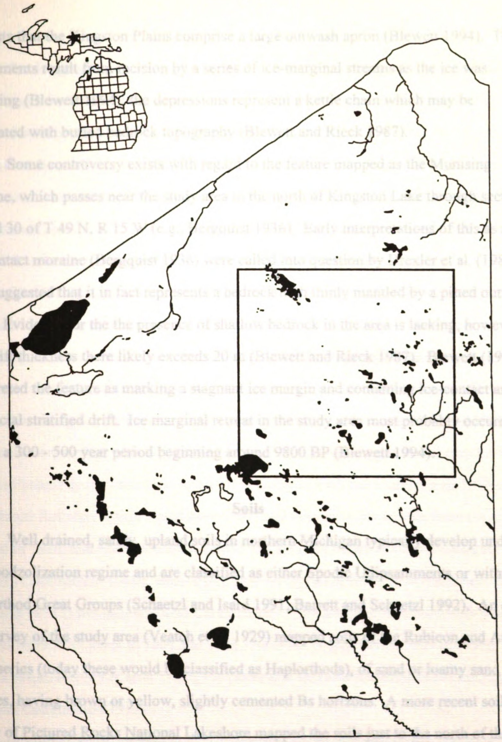

Figure 2. Map of the six township study area, Alger and Schoolcraft Counties, Michigan. Inset square denotes area of field study area shown in Figure 1. Black areas represent water bodies. Scale 1:154,000.

suggests that the Kingston Plains comprise a large outwash apron (Blewett 1994). The escarpments result from incision by a series of ice-marginal streams as the ice was retreating (Blewett 1994); the depressions represent a kettle chain which may be associated with buried bedrock topography (Blewett and Rieck 1987).

Some controversy exists with regard to the feature mapped as the Munising moraine, which passes near the study area to the north of Kingston Lake through sections 29 and 30 of T 49 N, R 15 W (e.g., Bergquist 1936). Early interpretations of this as an ice-contact moraine (Bergquist 1936) were called into question by Drexler et al. (1983), who suggested that it in fact represents a bedrock high thinly mantled by a pitted outwash plain. Evidence for the the presence of shallow bedrock in the area is lacking, however, and drift thickness there likely exceeds 20 m (Blewett and Rieck 1987). Blewett (1994) interpreted the feature as marking a stagnant ice margin and containing ice-contact and proglacial stratified drift. Ice marginal retreat in the study area most probably occurred within a 300 - 500 year period beginning around 9800 BP (Blewett 1994).

Soils

Well drained, sandy, upland soils in northern Michigan typically develop under an acid, podzolization regime and are classified as either Spodic Udipsamments or within Haplorthod Great Groups (Schaetzl and Isard 1991; Barrett and Schaetzl 1992). An old soil survey of the study area (Veatch et al. 1929) mapped soils of the Rubicon and Au Train series (today these would be classified as Haplorthods), of sand or loamy sand textures, having brown or yellow, slightly cemented Bs horizons. A more recent soil survey of Pictured Rocks National Lakeshore mapped the soils just to the north of the study area as Rubicon, Kalkaska, and Deerton soils (Entic and Typic Haplorthods; Carey 1993).

Vegetation and lumbering

Pre-logging vegetation in the study area consisted of dense forests of white pine and northern hardwoods, with many large trees 300 - 400 years old (Frederick et al. 1976). As such, this forest was representative of that found on the better developed sandy soils of northern Michigan (Graham 1941; Bourdo 1983). Although white pine was very common in these forests, it is not self-perpetuating in upland positions (Graham 1941; Brown and Curtis 1952). More detail about the pre-logging vegetation of the area will be provided in the section beginning on p. 54.

The first recorded lumbering operation near the Kingston Plains occurred at Sullivan's Landing on the shore of Lake Superior in 1882, and operated for three years, extracting 50 million board feet of pine (Carter 1967). These logs were stacked on the beach and rafted to Ontario or the town of Alpena on Lake Huron for milling (Carter 1967). The Kingston Plains area itself was probably logged between 1885 and 1890 (Frederick et al. 1976), although dates of railway operations suggest that it may have occurred primarily between 1890 and 1895 (Michigan Railroad Commission 1919). The Manistique Railway, which would have been used to remove the lumber from the area, opened in 1886, and was extended to Grand Marais from Seney in 1893 (Michigan Railroad Commission 1919). Most extensions along this railroad were made between 1889 and 1893 (Michigan Railroad Commission 1919), and abandonments took place in 1895 to 1899, with some in 1903 and 1906. After the largest lumber mill in Grand Marais closed in 1909 (Carter 1967), the entire line was abandoned in 1910 (Michigan Railroad Commission 1919).

A crown fire is reported to have come through the area as logging was in progress, following which logging was accelerated to salvage the burned timber. This fire, in turn, was followed by several slash fires. The last major fire occurred around 1910 (Frederick et al. 1976).

METHODS

Current forest patterns

Stand composition

Seventeen stands of apparently homogeneous vegetational composition and post-disturbance history as determined from historical aerial photography were chosen for analysis of tree species composition (Figure 3). Most stands were located near each other and paired, i.e., a stump prairie and a forested stand. Stands were numbered in the order of sampling; stump prairie stands were designated with "SAV" (for "savanna") and forested stands with "FOR". Site FOR-7 was included as an alternative pair to site SAV-7 for the purposes of resin bag placement (discussed below). Areas with atypical topography or poorly drained soils were avoided, as were regions where trees (usually red or jack pine) had been planted, whether or not the planted trees had survived.

Stand composition was measured using the point-centered quarter method for trees with a diameter at breast height (DBH) > 5.0 cm (Cottam and Curtis 1956). Adequacy of sample size was determined using a species-area curve (Phillips 1959; Bonham 1989). When > 5 m, distances from the point to the tree were measured using an optical range finder. Otherwise, a tape was used. Overstory tree species were characterized for mean diameter, basal area, relative frequency, relative density, relative dominance, and importance value (Cottam and Curtis 1956; Grieg-Smith 1983). In stump prairie stands, no tree was recorded for quadrants in which distance to the nearest tree was > 30 m, the limit of the optical range finder. For such quadrants, 30 m was substituted for calculations requiring a distance measurement, and "missing" was used instead of a species name in relative frequency and relative density calculations.

Figure 3. Location of sampled stands in the study area. See Figure 1 for reference.

In many parts of the study area a secondary means of reconstructing the pre-disturbance forest exists due to the excellent preservation of logging era stumps. For this reconstruction, it must be assumed that all stumps still remain, and that none have rotted and disappeared. Many stumps remain in good condition, but some have decomposed and fallen apart. Wood samples from one well-preserved stump and four decomposing stumps from various parts of the stump prairie were sent for species identification at the Forest Products Laboratory (Madison, WI) to assess whether stump preservation may be related to tree species. The position and size of stumps in all stands for which stumps were still evident was used to calculate the assumed density and basal areas of trees in the pre-disturbance stands, using the point-quarter method (Cottam and Curtis 1956). Distance from the sample point was measured using a range finder (for distance > 5 m). Otherwise, a tape was used. In areas that are currently forested, locating the stumps in the field became difficult if no stumps were encountered within a few m of the sample point. Measurement of distances greater than about 20 m in the forest was also difficult due to obstructions in the line of sight. Therefore, occasionally a stump could not be located in a quadrant. In calculating density for these quadrants, 20 m was substituted as the point-to-stump distance. The diameter at breast height (DBH) for the stumps was estimated to the nearest 10 cm based on the diameter of the top of the stump (if it was < 1.4 m high) and the height and preservation of the stump. The diameter values obtained must be viewed as minimum values, since some stumps, especially of smaller trees, may have decayed and because bark and outer wood layers were gone.

Age determination of selected large trees was made in order to establish whether the older trees in the stand had germinated before or after nineteenth century logging operations. Increment cores were taken and ring counts made in the laboratory. Ring counts of stumps from large trees felled in recent logging operations were also taken in the field where possible.

Land cover/stand boundaries

A study of change in vegetation patterns over time, with special attention being given to the stability of the forest/stump prairie boundary, was conducted using historical aerial photography. Photographs used for this study include 1939 black and white panchromatic with a nominal scale of 1:24,000, and 1954 and 1986 black and white infrared with a nominal scale of 1:15,840. Change over time between sets of photographs was determined by comparing representative areas of the boundary at two different dates at the same scale using a Zoom Transfer Scope. Further examination of the photographs under magnification was also accomplished using a Delft scanning stereoscope.

Factor 1: Pre-disturbance forest patterns

The primary data source used for the determination of pre-disturbance of Alger County forest patterns is the records of the General Land Office (GLO) survey. In the course of establishing section and township boundaries, GLO surveyors noted the location, diameter, and species of two "witness" trees at each section corner and halfway along each one-mile long section line (quarter section corner). Also recorded were the location, diameter, and species of trees located directly on section lines ("line trees"). Usually four line trees were noted for each mile of section line (White 1984, p. 370). Although surveyor bias in tree selection is a concern for those using these data in vegetation reconstruction (Bourdo 1956), GLO witness tree data have often been successfully used to reconstruct the presettlement forest conditions (e.g., Elliot 1953; Potzger et al. 1956; Kapp 1978; Delcourt and Delcourt 1977; Leitner et al. 1991).

GLO survey records (notes) for six townships (T47N, R15W; T47N, R16W; T48N, R15W; T48N, R16W; T49N, R15W; and T49N, R16W) were obtained from the archives of the state of Michigan. The surveys of exterior township lines for these townships were conducted in 1840 and 1841, whereas the subdivision of the townships into sections was accomplished in 1850 and 1851. All surveyor notations were coded in a computer spreadsheet and transferred to the GIS package Arc/Info for analysis. Surveyor notations coded into the spreadsheet included the common species name, diameter at breast height (DBH, in inches), and direction and distance (in links) from a section corner for each tree. Also included in the spreadsheet were comments about landscape features (e.g., "Enter swamp") and the surveyor line summary for each section line, in which the surveyor described timber and soil conditions for the entire mile-long line. Two types of data were then able to be included in the GIS database: (1) point locations of trees and with the accompanying descriptive information (hereafter called "witness trees"), and (2) survey line locations with the accompanying surveyor's line summary.

At the end of each mile of section line surveyed, the surveyor was instructed to provide a description of conditions common along that section line. Included in this description was typically an assessment of the topography (e.g., "gently rolling"), the soil quality (e.g., "2^{d} rate sandy"), and the tree species common along the section line, listed in order of decreasing prevalence (White 1984). Sometimes understory species were also listed, as were other notable features of the land, especially the presence of swamps, rock outcrops, burns, or windfalls. Timber species found in swamps were often listed separately from those in upland portions of the line. These notations were entered into the database in a separate, miscellaneous "comments" field.

Because the surveyors recorded tree species using the common name of the time, there are some nomenclatural problems in the data set. Species names used by the surveyors and their current common and scientific names are given in Table 1. Occasionally, confusion resulted because the surveyors did not all use the common names the same way. For example, most surveyors consistently distinguished between white birch and yellow birch, but at least one surveyor often used the term "birch" without modification. Where "birch" alone was encountered, it was assumed that the surveyor was referring to yellow birch.

Table 1. Common and scientific names associated with surveyors' notations of tree species.

Surveyors' notation	Common name[1]	Scientific name[1]
Alder	Alder	*Alnus* spp.
Aspen	Aspen	*Populus* spp.
B Ash	Black ash	*Fraxinus nigra* Marsh.
B Oak	Black oak	*Quercus velutina* Lamarck
Beech	American beech	*Fagus grandifolia* Ehrhart
Cedar	Northern white cedar	*Thuja occidentalis* L.
Cherry, B Cherry	Black cherry	*Prunus serotina* Ehrh.
Elm	American elm	*Ulmus americana* L.
Fir	Balsam fir	*Abies balsamea* (L.) Mill.
Hemlock	Eastern hemlock	*Tsuga canadensis* (L.) Carr.
Maple	Red maple	*Acer rubrum* L.
S Pine	Jack pine	*Pinus banksiana* Lamb.
Spruce	Spruce	*Picea* spp.
Sugar	Sugar maple	*Acer saccharum* Marsh.
Tamarack	Tamarack	*Larix laricina* (Du Roi) K. Koch
W Birch	White birch	*Betula papyrifera* Marsh.
W Pine	Eastern white pine	*Pinus strobus* L.
Y Birch, Birch	Yellow birch	*Betula alleghaniensis* Britton.
Y Pine	Red pine	*Pinus resinosa* Ait.

[1]Best estimate.

Current landcover data (for comparison with the pre-disturbance data) were derived from the Michigan Department of Natural Resources' Landuse/Landcover maps of Alger and Schoolcraft counties (Michigan Department of Natural Resources, Lansing, MI). The 1:24,000 maps were made from 1978 aerial photography and were obtained in digital format. Landuse/landcover classes were simplified by grouping into four broad categories: (1) upland forest; (2) stump prairie and upland pines; (3) swamp and lowland forest; and (4) other (Figure 4). Upland areas with pine forest were grouped with stump prairie because much former stump prairie land had been planted to red pine or other pine species. The "other" category included beaches, dunes, water features, riverbanks, and non-vegetated or cultural features.

A line-in-polygon overlay of the surveyor line summaries map and the simplified landcover map was then performed. The mile-long section lines often spanned more than one landcover category. Therefore, to avoid using the same surveyor comments multiple times, I analyzed the data using only those lines which had a length greater than 2700 feet (830 m; or > 1/2 mile) within one polygon after the overlay. I also eliminated from the analysis those lines for which the surveyor listed fewer than three tree species in the summary, since these cases were essentially those for which the surveyor had failed to provide a line summary (Figure 5).

A point-in-polygon overlay of the witness tree coverage and the simplified landcover map was also performed. Witness tree data were used to calculate frequency, basal area, relative density, and relative dominance of the presettlement forest as grouped by current landcover type (Cottam and Curtis 1956; Delcourt and Delcourt 1974; AuClair 1976; Fralish et al. 1991). A modified importance value was calculated as the average of relative density and relative dominance. Relative frequency was omitted from the usual calculation of importance value because it could not be calculated due to the sampling design used in the GLO notes: only two trees recorded per corner, with single trees at intermediate points. Data were analyzed in the units used by the surveyors (inches and

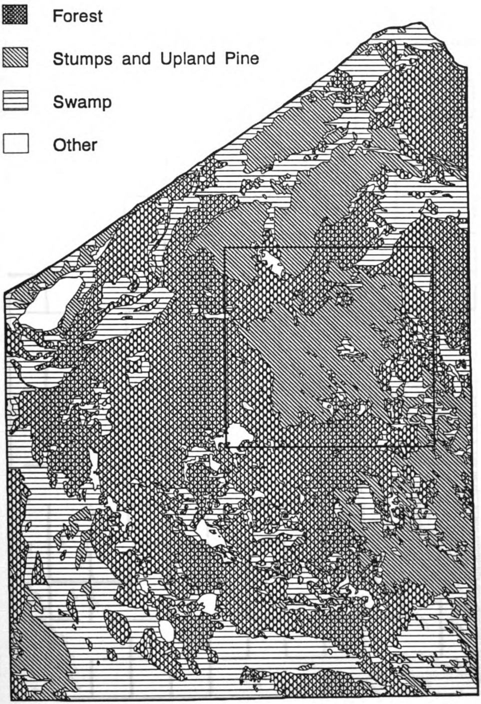

Figure 4. Map of simplified current landcover classes for six townships in Alger County, Michigan as of 1981. Inset square denotes area of field study area.

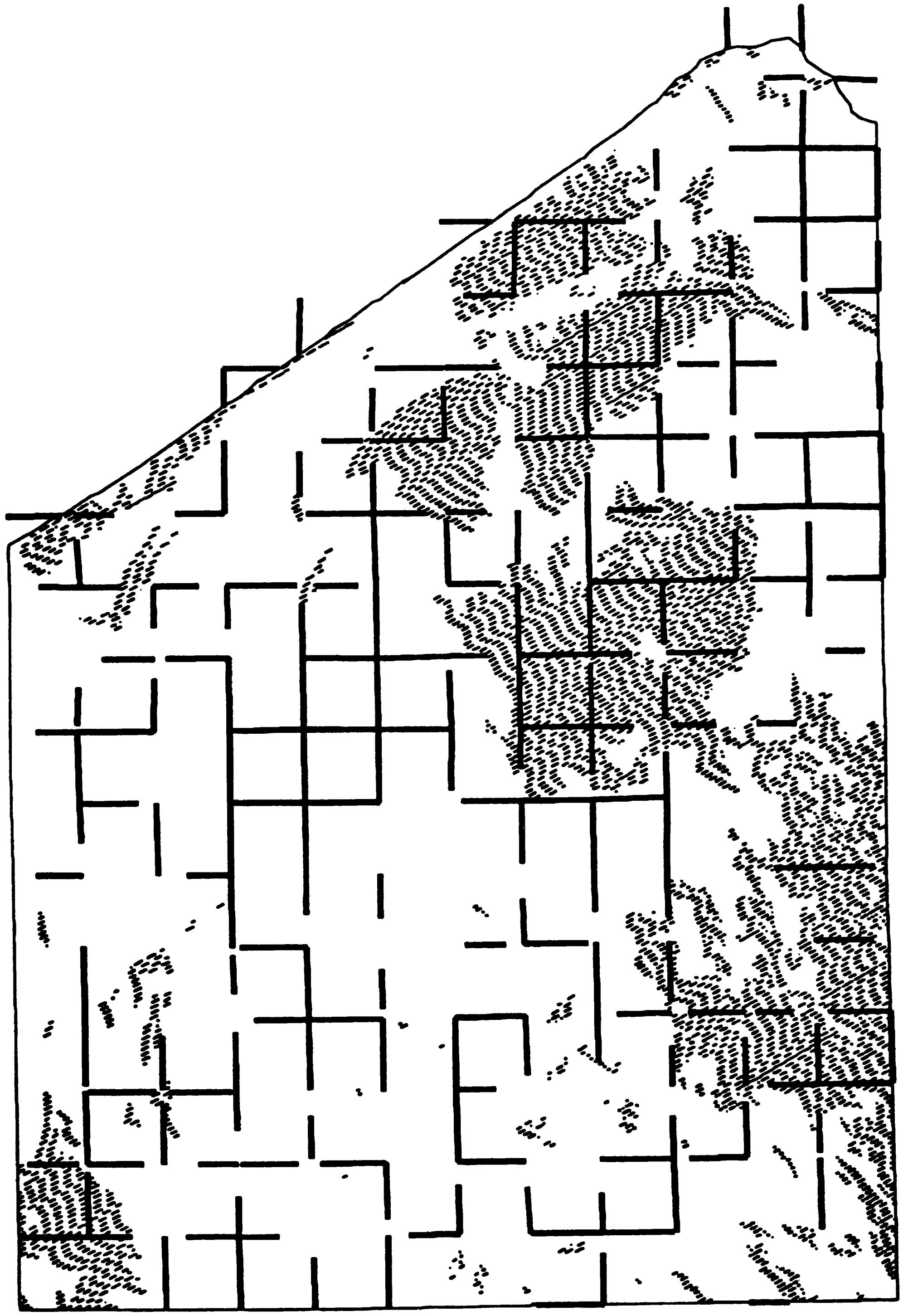

Figure 5. Map of section lines with at least three timber species listed by the surveyor and with a length of > 2700 ft. (830 m; > 1/2 mile) after the line-in-polygon overlay. Hatching represents current (1981) stump prairie areas.

links), but results were converted to cm and reported as such to facilitate comparison with data from the sampled modern forest and stump prairie stands.

Individual species relationships with current landcover classes were examined using contingency table analysis (Whitney 1986; Barrett et al. 1995). A 2×4 contingency table was constructed for each species-landcover variable combination, where 4 was the number of classes for the landcover variable. Species that occured in the database fewer than 50 times were eliminated prior to this analysis to avoid errors due to small sample size. The signed standardized residuals from the contingency table analysis indicate the direction and strength of association of the species and the current landcover class; the G^2 statistic (G in Whitney 1986) was used to test the statistical significance of the association between a species and landcover class (Whitney 1986; 1990; Barrett et al. 1995).

Factor 2: Substrate and soil properties

Field methods

Within each of the 17 sampled vegetation stands (9 forest and 8 stump prairie), a representative pedon was chosen for sampling. A pit, approximately 1.5 m × 0.7 m and deep enough to expose the C horizon, was dug. Standard field descriptions were made (Soil Survey Staff 1981) and bulk samples (about 0.5 kg) were taken by genetic horizon for laboratory analysis. The approximate proportion of ortstein 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 B subhorizons were sampled separately when strongly cemented ortstein comprised a significant proportion (> 20%) of the subhorizon. Deep sampling (> 2m) by bucket auger was performed to check for the existence of fine-textured lamellae (Schaetzl 1992) below the base of the pit, which have been shown to affect forest growth (Miles and Franzmeier 1981; Host et al. 1988).

As a further means of measuring soil development near the stump prairie/savanna boundary, six transects perpendicular to the trend of the boundary were made (Figure 6). Beginning at the approximate location of the boundary, six 1 m^2 quadrats were established at 30 m intervals on each side of the boundary. Within each quadrat, nine regularly spaced samples were taken with a push-probe to a depth of approximately 50 cm or until ortstein obstructed the probe. At each sample point, I recorded whether ortstein was present or absent, and also the Munsell color of the darkest, reddest soil retained in the probe, usually from the upper B horizon.

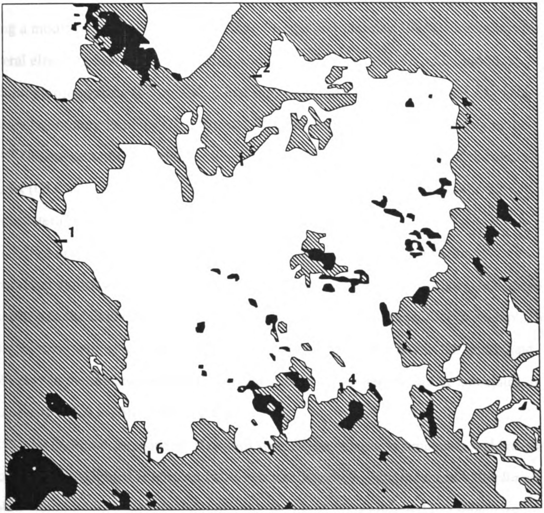

Figure 6. Location of soil color and ortstein content transects within the study area.

Laboratory methods

Laboratory analysis of the horizon-based samples (including ortstein as a separate subsample) included pH (2:1 in water and KCl) and particle size distribution by pipette (Soil Survey Laboratory Staff 1992). Organic carbon (OC) content was determined using a modified Walkely-Black procedure (Singer and Janitzky 1986). Extractions for several elements were performed using acid ammonium oxalate (Fe_o, Al_o, and Si_o), sodium pyrophosphate (Fe_p and Al_p), and sodium citrate-dithionite (Fe_d and Al_d; Soil Survey Laboratory Staff 1992). Extracts were analyzed by DCP spectroscopy in the MSU Department of Crop and Soil Sciences laboratory. Optical density of the oxalate extract (ODOE) at 430 nm was determined on a Bausch and Lomb Spectronic 20 colorimeter (Daly 1982).

For depth plots and calculations requiring a single value per horizon, B subhorizon values were calculated by weighting the ortstein and non-ortstein subsamples according to the field estimate of 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 comparison 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 (not including the BC horizon), weighted for (multiplied by) subhorizon thickness using the following formula: $\Sigma (P * H) / \Sigma H$, where P = the soil property for a given subhorizon and H = horizon thickness in cm. Weighted solum values were calculated analogously to the weighted B horizon values, but including all mineral subhorizons above the upper C horizon.[4]

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[4]Solum weighted values include BC horizon values because (1) for most pedons, the difference between B horizon weighted values and solum weighted values would simply be the E horizon in the solum

In situ *monitoring of soil processes*

Three pairs of pedons from the 17 pedons described and sampled above were chosen for an *in situ* study of podzolization processes using buried resin bags (Righi et al. 1990; Ranger et al. 1991; Ranger and Nys 1994): sites SAV-6 and FOR-5; SAV-7 and FOR-7; SAV-8 and FOR-9[5] (Figure 3). Site FOR-7 was substituted as a partner for site SAV-7 after its original pair, site FOR-8, was discovered to have atypically cemented B subhorizons and a coarser sand and gravel immediately below the solum. A Na-saturated cation exchange resin (Amberlite IRN 77; Rohm and Haas Co., Philadelphia) and a Na- and H- saturated chelating resin (Chelex 100; Bio-Rad Laboratories, Richmond, CA) were used; comparison of the relative amounts of Fe and Al adsorbed on each resin gives information on the speciation of Fe and Al in the soil solution for the period of burial. Small bags (approximately 5 × 8 cm) containing 5 g (moist) of a resin were constructed of nylon tricot fabric with mesh small enough to retain the resin. One bag of each resin type was inserted into the soil from the face of the soil pit at the top of the E, in the uppermost B, and in the BC horizons. Four replicate sets of these bags were installed in each of the six pedons. Each pit was then refilled. Bags were buried in August and September, 1994, and retrieved in late May, 1995. Following retrieval, bags were air-dried, and the resin removed and weighed. Cations were desorbed from the resins (about 1.2 g of dry chelating resin and about 3.0 g of dry cation exchange resin each[6]) by shaking for 4 h in 40 ml of 1 *N* HCl for the cation exchange resin and 1 *N* HNO_3 for the

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weighted value if the BC horizon were not also included; and (2) the BC horizon, though transitional to the C horizon, is more like the B horizon than the C horizon in these soils and should be considered part of the solum. In some pedons, ortstein columns continued into the BC horizon.

[5]Site numbers indicate the order in which *vegetation* sampling was completed; paired pedons for soil resin bag samples do not necessarily share the same number.

[6]Differences in dry weight of chelating and cation exchange resins are due to differences in the original moisture content of the resins. The entire amount of resin was used in the analysis.

chelating resin. The extracts were analyzed by DCP spectroscopy in the MSU Department of Crop and Soil Sciences laboratory.

Factor 3: Logging era fires and logging practices

Historical records relating to land ownership, property tax assessment, and tax payment during the logging era were examined for evidence of whether logging practices in the stump prairie areas were different from those in the forested areas in either character or timing. Records were obtained from the archives of the State of Michigan and included: tax/assessment rolls of Alger County for the years 1885-1887, 1890, 1895, and 1899; abstracts of sales of state tax land for the years 1888 and 1892-1894; and the land tract book which records the initial transfer of property in Michigan from public to private hands. From these sources, data for T 48 N, R 15 W, which approximately coincides with the field study area, were input into the GIS for mapping. Mapped data include: the name of the original purchaser of the land; the date of the original acquisition; the name of the owner for the years 1890 and 1895; and the per-acre assessed value for the years 1890 and 1895.

RESULTS AND DISCUSSION

Current forest patterns

Stand composition

The forests surrounding the Kingston Plains continue to be used as a source of timber. Most forests have been logged at least once since the turn of the century, and many show signs of having been logged more than once. Decomposing hemlock stumps present in many of the forested stands point to selective extraction of the larger hemlock trees 30 to 40 years ago. Current logging operations are removing mostly hardwoods such as red maple, beech, and white birch, as well as the larger white pine trees.

Modern logging has also taken place in parts of the stump prairie itself, as evidenced by the presence of relatively undecomposed white pine stumps and branches alongside the more weathered, nineteenth century stumps. Many parts of the stump prairie have been artificially planted to red pine and jack pine, especially in the western portion of the study area. (These areas were avoided in sampling.) Observations in and around the plantations suggest that natural red pine and jack pine recruitment is not common. White pine seedlings predominate, even in the plantations. Prescribed burning for management of sharptail grouse has been practiced in the northeastern corner of the Kingston Plains (parts of section 10, T 48 N, R 15 W). Site SAV-4 is located within this controlled burn area.

In forested stands today, red maple is the most important species, followed by white pine and beech (Table 2). Hemlock and balsam fir are also common. The species composition is quite consistent from one stand to another (Table 3), with the exception of stand FOR-6, which has an unusually high importance value for white pine, and a low

Table 2. Diameter at breast height (DBH) and importance values by tree species for forest and stump prairie areas.

Species	N	Mean DBH	Max DBH	Total DBH	Total basal area	Rel. Dens.	Rel. Freq.	Rel. Dom.	Imp. Val.
		cm			cm^2	%			
Forest									
Red Maple	148	19.1	48.5	2829.4	53916.5	40.2	35.3	39.7	38.4
White Pine	66	17.8	68.2	1173.9	24198.3	18.2	15.9	17.8	17.3
Beech	56	18.7	60.0	1044.5	25660.6	15.2	17.4	18.9	17.2
Hemlock	32	19.1	65.2	612.4	14941.0	8.7	10.1	11.0	9.9
Balsam Fir	44	9.2	28.0	404.6	3606.3	12.0	13.0	2.7	9.2
White Birch	7	40.6	60.0	284.4	9887.1	1.9	3.4	7.3	4.2
Red Pine	10	19.7	36.7	196.5	3513.1	2.7	3.4	2.6	2.9
Pin Cherry[1]	2	6.1	6.1	12.1	57.5	0.5	0.5	0.0	0.4
Juneberry	1	10.2	10.2	10.2	81.7	0.3	0.5	0.1	0.3
Aspen sp.	1	8.2	8.2	8.2	52.8	0.3	0.5	0.0	0.3
White Spruce[1]	1	5.6	5.6	5.6	24.6	0.3	0.5	0.0	0.3
Total:	368	17.9	68.2	6581.8	135939.5				
Stump Prairie									
White Pine	151	18.5	103	2793.2	70714.4	34.6	29.9	79.0	47.8
Missing[2]	170	0	0	0	0	39.0	29.9	0.0	23.0
Red Maple	32	15.9	36.5	509.3	7128.6	7.3	10.7	8.0	8.7
Black Cherry	23	8.0	13.5	183.6	1263.3	5.3	8.4	1.4	5.0
Jack Pine	14	15.8	20.5	220.7	2968.4	3.2	5.1	3.3	3.9
Juneberry	17	6.3	8.6	107.6	554.3	3.9	6.1	0.6	3.5
Black Spruce[1]	11	10.0	19.7	110.5	1021.9	2.5	3.7	1.1	2.5
Red Pine	5	29.3	35.1	146.4	3455.6	1.2	1.9	3.9	2.3
White Spruce[1]	4	21.7	35.0	86.6	1864.1	0.9	1.4	2.1	1.5
Aspen sp.	7	7.1	7.7	50.0	281.2	1.6	2.3	0.3	1.4
Balsam Fir	1	6.2	6.2	6.2	30.2	0.2	0.5	0.0	0.2
Black Oak[1]	1	18.3	18.3	18.3	263.0	0.2	0.0	0.3	0.2
Total:	436	15.9	103.0	4232.4	89545.1				

[1] Pin cherry: *Prunus pensylvanica* L.; Black spruce: *Picea mariana* (Miller) BSP; White spruce: *Picea glauca* (Moench) A. Voss; Black oak: *Quercus velutina* Lamarck.

[2] Denotes a quadrant in which no tree was located within 30 m of the sample point.

Table 3. Importance values of tree species for the nine sampled forest stands[1].

	FOR-1	FOR-2	FOR-3	FOR-4	FOR-5	FOR-6	FOR-7	FOR-8	FOR-9	All forest stands
Aspen	0	0	0	0	0	2.3	0	0	0	0.3
Balsam Fir	25.0	4.6	9.1	4.2	17.2	0	8.7	18.8	3.9	9.2
Beech	12.2	33.4	23.6	27.7	5.1	0	14.7	13.8	21.6	17.2
Hemlock	10.1	2.3	16.3	18.5	8.0	0	20.3	0	12.4	9.9
Juneberry	0	0	0	0	0	0	0	0	2.0	0.3
Pin Cherry	0	0	0	0	3.4	0	0	0	0	0.4
Red Maple	25.3	**47.8**	**48.6**	**28.5**	**58.7**	3.7	37.5	**64.8**	31.3	**38.4**
Red Pine	0	0	0	0	0	26.7	0	0	0	2.9
White Birch	0	6.5	0	4.7	0	4.0	16.4	0	0	4.2
White Pine	**27.4**[2]	5.5	2.3	16.5	7.6	**63.2**	2.4	2.6	**28.8**	17.3
White Spruce	0	0	0.1	0	0	0	0	0	0	0

[1]Trees found on the stump prairie but absent at forest sample sites include: black cherry, black spruce, jack pine, and black oak.

[2]The tree species with the highest importance value in each stand is highlighted in boldface type.

value for red maple (Table 3). It is also the only forested stand in which red pine is present. These anomalies may be because FOR-6 occupies the site of a former stump prairie where the trees have recovered enough to allow the canopy to begin to close, as discussed below, and therefore retains the species composition of its stump prairie origins.

In stump prairie stands, the living trees are strongly dominated by white pine (Table 2). The lack of trees is shown by the fact that the most common point-quarter observation on the stump prairie (N=170) is the absense of a tree within 30 m of the sampled point (Table 4). Red maple and black cherry are also common in the stump prairie stands. Except for these most common stump prairie species, however, the species composition from one stump prairie stand to another varies markedly (Table 4). For instance, juneberry has a high importance value (27.9) in stand SAV-2, but is either absent or has very low values elsewhere. Similarly, black cherry is remarkably important (22.6) in stand SAV-8 (Table 4). This variability in species composition suggests that the chance circumstances of seed or sprout availability has been a prominent factor in determining the recovery and composition of the stump prairie areas. Black cherry seeds commonly fall to the ground in the immediate vicinity of the parent tree, except for those few spread by birds or omnivorous mammals (commonly bears on the Kingston Plains) in their droppings (Marquis 1990). Black cherry also readily resprouts from its stumps (Marquis 1990). Juneberry trees also have large fruit which may be spread by birds (Barnes and Wagner 1981)

As expected, absolute density of the trees is much greater (nearly 10×) in the forested stands than in the stump prairie stands (Table 5). Stand FOR-6 is the single exception to this. Stands SAV-1 and SAV-6 have the highest absolute densities among the stump prairie stands (Table 5). These two stands are similar to FOR-6 in that the trees in these regions have become quite large. In all three stands, white pine has very

Table 4. Importance values of tree species for the eight sampled stump prairie stands[1].

	SAV-1	SAV-2	SAV-3	SAV-4	SAV-5	SAV-6	SAV-7	SAV-8	All stump prairie stands
Missing[2]	0	**37.2**	36.8	**63.8**	33.3	9.6	4.6	12.7	23.0
Aspen	3.2	0	0	0	0	0	0	8.1	1.4
Balsam Fir	0	0	0	0	0	0	1.6	0	0.2
Black Cherry	5.0	10.9	5.0	0	0	2.3	1.6	22.6	5.0
Black Spruce	9.9	0	0	0	4.9	0	3.4	0	2.5
Jack Pine	13.3	0	0	0	0	0	12.8	0	3.9
Juneberry	0	27.9	0	0	5.5	0	1.6	1.8	3.5
Red Maple	0	20	0	36.2	20.6	0	14.1	**32.2**	8.7
Red Pine	8.5	0	5.9	0	0	2.8	0	5.3	2.3
White Pine	**60.1**[3]	3.9	**52.3**	0	**35.8**	**85.2**	**53.1**	15.4	**47.8**
White Spruce	0	0	0	0	0	0	6.3	1.9	1.5
Black Oak	0	0	0	0	0	0	1.0	0	0.2

[1]Trees found commonly in the forest but absent at stump prairie sample sites include: beech, hemlock, pin cherry, and white birch.

[2] Denotes a quadrant in which no tree was located within 30 m of the sample point.

[3]The tree species with the highest importance value in each stand is highlighted in boldface type.

Table 5. Absolute density of trees in the 17 sampled stands.

Stand-ID	Absolute Density trees ha^{-1}
FOR-1	4258
FOR-2	2299
FOR-3	3247
FOR-4	3045
FOR-5	3361
FOR-6	843
FOR-7	2783
FOR-8	2465
FOR-9	3512
Forest mean:	2816
SAV-1	657
SAV-2	26
SAV-3	25
SAV-4	13
SAV-5	90
SAV-6	1284
SAV-7	73
SAV-8	97
Stump prairie mean:	295

high importance values (FOR-6, 63.2; SAV-1, 60.1; SAV-6, 85.2), red pine is present, and red maple is rare or absent (Tables 3 and 4).

Land cover/stand boundaries

Following the logging of the nineteenth century, vegetation patterns in the Kingston Plains area have not been static. The purpose of this section is to consider the changes in forest patterns evident in historical aerial photography, with particular reference to the boundary between stump prairie and forest. This discussion will focus on data compiled from the 1939 and 1986 photographs, although photographs from 1954 were also included in the analysis. Three questions will be addressed: (1) Has the *nature* of the forest/stump prairie boundaries changed over time? (2) Has the boundary *moved* over time? and (3) Has the *character* of the stump prairie itself changed?

Nature of the boundary. In the study area, the transition between open stump prairie and closed-canopy forest usually occurs within the space of a few meters, with little apparent intermediate landcover between them. Truly discrete boundaries, however, were more widespread in 1939 than in 1986. In 1986, in some places a more gradual transition from stump prairie through scattered trees to closed-canopy forest existed, especially along the western, northwestern, and southwestern edges of the study area stump prairie (Figures 7 and 8). The eastern boundary tended to remain more discrete (Figure 9), possibly because a controlled burn was conducted in 1983 in the northeastern corner of the stump prairie.

Location of the boundary. The overall pattern of stump prairie and forest in the study area remained stable over the nearly 50 year time span from 1939 to 1986. Nevertheless, a close examination of the photography reveals significant[7] movements of

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[7] The intent of this section is to provide a qualitative description of changes in boundary location over time. No quantitative measurements of boundary movements were made, due to the inaccessibility of the necessary aerial photography at the time revisions to this dissertation were accomplished.

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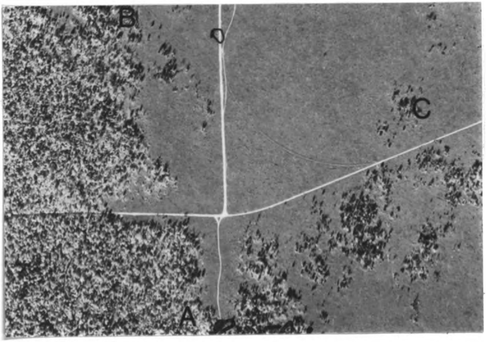

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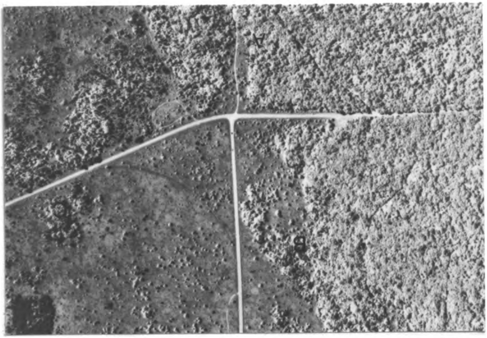

Figure 7. Aerial photographs of the study area, sections 29 and 30 of T 48 N, R 15 W. 1) 1939; 2) 1986.

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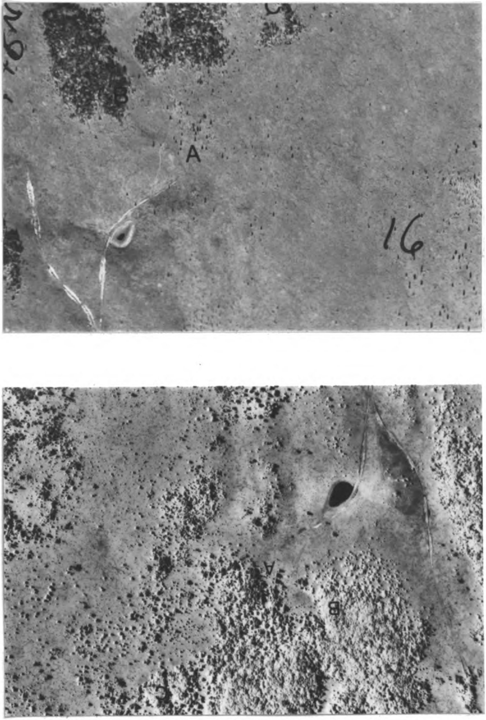

Figure 8. Aerial photographs of the study area, sections 8, 9, 16, and 17 of T 48 N, R 15 W. 1) 1939; 2) 1986.

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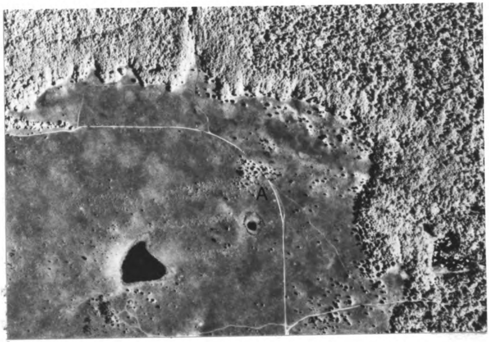

Figure 9. Aerial photographs of the study area, sections 10 and 11 of T 48 N, R 15 W. 1) 1939; 2) 1986.

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the boundary in many locations, usually with the forest gradually encroaching upon the stump prairie area. For example, in the southwestern corner of the study area the forest had noticeably moved into former stump prairie regions between 1939 and 1986 (Figure 7). This is especially obvious around the small "peninsula" of stump prairie that extends south of the main road intersection (Figure 7, location A). In 1939 this peninsula was quite wide, but by 1986 the forest had nearly engulfed the road. Similar shifting of the boundary is apparent throughout the region visible in Figure 7.

Farther to the north in the study area, an even more dramatic advance of the forest boundary can be seen (Figure 8). In the 1986 photo, the forest had expanded to include a few evergreen trees that in 1939 were isolated, far from the forest itself (Figure 8, location A). The 1939 forest boundary is still apparent in the 1986 photo as a change of texture in the forest. Examined with a stereoscope, the 1986 photos reveal that the trees in the original 1939 forest area are taller and closer together than in the newly expanded portion.

Smaller clumps of trees that had been isolated from the main forest in 1939 also grew in size such that by 1986 they had often become joined, or nearly joined, with the main forest itself. Figure 7 shows such an isolated forest "island" in 1939 (location B). In the 1986 photo the area between it and the main forest had nearly filled in. Similarly, isolated trees on the stump prairie in the 1939 photos often had become the center of clumps of trees by 1986. For example, in 1939 a small group of individual evergreen trees (probably pines) was located just north of the road (Figure 7, location C). In the 1986 photo these trees had become the nucleus for a much larger clump of mixed-species, closed-canopy forest. The formerly scattered trees apparently provided an environment favorable for the establishment of both evergreens and hardwoods, as well as a source of seeds and sprouts.

Although evidence for the expansion of the forest boundary between 1939 and 1986 is widespread and no example of boundary retreat could be found, the amount of change varies from location to location. In the northeastern corner of the Kingston Plains the forest boundary had moved only slightly (Figure 9). In this region the stump prairie has been managed for sharptail grouse, including a controlled burn in the early 1980s. Even here, however, the forest boundary has measurably advanced into the stump prairie. Perhaps the most stable boundary in the study area can be found at its southeastern corner (Figure 10, location A). Very little movement of the main boundary between the two dates can be detected in this view. The clumps of trees along the old railroad grade in the north part of the photo had also expanded only slightly. Under the stereoscope, however, the trees between the lake and the wetland to its northeast (Figure 10, location B) are seen to be small and fairly open in the 1939 photo. Much thicker foliage and a closed canopy can be seen in the 1986 photos of the same area, even though the location of boundary itself has not changed significantly.

Around some of the kettle depressions on the Kingston Plains the stump prairie/forest boundary has apparently been affected by the topography. Trees usually establish more slowly within the depressions than the surrounding higher area. Between 1939 and 1986, however, in some places the forest boundary had advanced farther into such depressions. The depression shown in Figure 11 is deep with relatively steep walls; an old railroad grade follows the bottom of the depression. On the west side of the depression (Figure 11, location A), which is the steeper of the two sides, the trees had advanced slightly into the depression by 1986. On the east side, however, the forest boundary had advanced much farther (Figure 11, location B). Very few trees can be found near the bottom of such depressions, even though stumps are common, indicating that they were once forested.

Character of the stump prairie vegetation. Comparison of the 1939 and 1986 aerial photography also reveals that the character of the vegetation on the stump prairie has changed. In 1939, the stump prairie in most places was nearly devoid of trees, and only very scattered evergreen trees can be found at all (Figure 12). Under close

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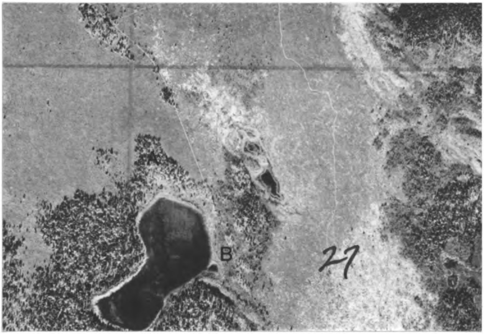

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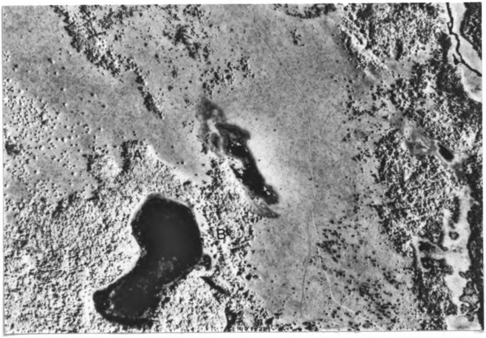

Figure 10. Aerial photographs of the study area, sections 27 and 28 of T 48 N, R 15 W.
1) 1939; 2) 1986.

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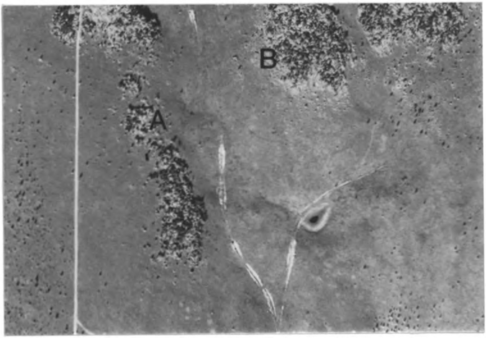

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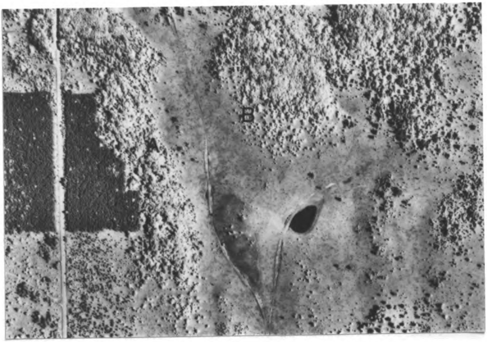

Figure 11. Aerial photographs of the study area, sections 8 and 17 of T 48 N, R 15 W. 1) 1939; 2) 1986.

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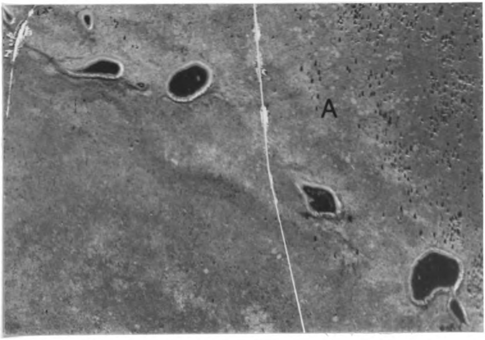

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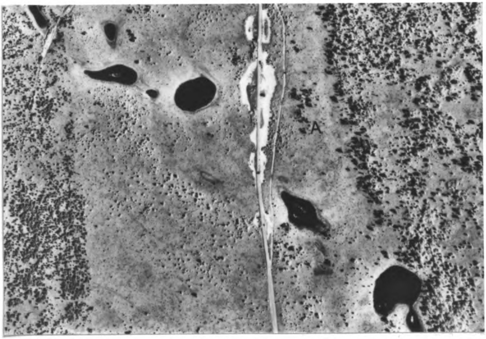

Figure 12. Aerial photographs of the study area, sections 20 and 21 of T 48 N, R 15 W. 1) 1939; 2) 1986.

stereoscopic examination, occasional snags are visible in the stump prairie, but usually the only features are small, dark dots interpreted as stumps. By 1986, however, most parts of the stump prairie contained at least some scattered trees. Many of the trees visible in the 1986 photographs are hardwoods, not evergreens. In places where scattered evergreen trees had been visible in 1939 (Figure 12, location A), the stump prairie had by 1986 become an open-canopy forest. Even where trees had been eliminated by controlled burning some trees are present in 1986 that had not been there in 1939 (Figure 9, location A). The density of trees seen in 1986 photos on the stump prairie varies from place to place. Fewer trees are apparent in the eastern portion of the plains (Figure 10), in depressions (Figure 11), and in the controlled burn area (Figure 9) than in the western portions of the study area (Figures 7 and 12).

Examination of the aerial photography in 1939, 1954, and 1986 reveals that the stump prairie has changed naturally over the 50 year timespan. The forest boundary is gradually encroaching upon the stump prairie, and the stump prairie itself is gaining more and more trees. This suggests that the ecosystem is rebounding from the disturbance of logging, though slowly. Except for where management practices such as controlled burns or new disturbance prevent it, with the passage of another 50 - 100 years, the Kingston Plains will probably become a forest once again.

Factor 1: Pre-disturbance forest patterns

Surveyor line summaries

The surveyor line summaries were subjective on the part of the surveyor, but they do provide a secondary means of assessing forest conditions at the time of the survey, and have been used to support information determined from witness tree distributions (Bourdo 1956; Frederick et al. 1976). Surveyor line summaries have been used most often in determining disturbance frequency in the presettlement forests, based on the notations of fires and windfalls (e.g., Canham and Loucks 1984; Whitney 1986).

The frequency of citation in line summaries of individual tree species for each current landcover category indicates a spatial correspondence between current landcover classes and the surveyors' subjective assessment of the forest (Table 6). In upland forest areas, sugar maple was most commonly cited first, with beech and hemlock also often cited first (Table 6, Figure 13). Yellow birch was more often placed in the second or third position, as were beech and hemlock. Balsam fir and red maple were common associates, listed often in third or fourth position.

For most lines in current stump prairies, the surveyors overwhelmingly recorded white pine as the predominant species (Table 6, Figure 14). Hemlock and red pine were often cited as second in prevalence, while beech and red maple were usually listed third or fourth (Table 6).

Surveyor line summaries in swamp areas are more difficult to interpret, in part because the surveyors listed timber on upland parts of a line separately from timber in parts of the line that were swamp. Swamp species were in these cases included in a separate field in the database, which was not included in this analysis. Thus some of the timber listed for these section lines may actually correspond to the timber in adjacent

Table 6. Citation frequency of the tree species in surveyors' line descriptions for three current landcover classifications.

Species	1st		2nd		3rd		4th	
	N[1]	Percent	N[1]	Percent	N[1]	Percent	N[1]	Percent
Upland forest								
Sugar Maple	35	28.5	15	12.2	10	8.1	3	2.4
Beech	22	17.9	32	26.0	20	16.3	17	13.8
Hemlock	21	17.1	18	14.6	14	11.4	15	12.2
White Pine	17	13.8	8	6.5	3	2.4	16	13.0
Yellow Birch	13	10.6	24	19.5	29	23.6	28	22.8
Red Maple	8	6.5	13	10.6	22	17.9	14	11.4
Balsam Fir	6	4.9	11	8.9	21	17.1	24	19.5
White Cedar	1	0.8	2	1.6	1	0.8	2	1.6
Spruce	0	0.0	0	0.0	2	1.6	1	0.8
Black Cherry	0	0.0	0	0.0	1	0.8	0	0.0
Tamarack	0	0.0	0	0.0	0	0.0	2	1.6
Stump Prairie								
White Pine	41	77.4	2	3.8	3	5.7	3	5.7
Hemlock	6	11.3	19	35.8	8	15.1	6	11.3
Red Pine	1	1.9	12	22.6	2	3.8	1	1.9
Red Maple	1	1.9	4	7.5	12	22.6	7	13.2
Tamarack	1	1.9	1	1.9	0	0.0	1	1.9
Jack Pine	1	1.9	0	0.0	2	3.8	0	0.0
White Cedar	1	1.9	0	0.0	0	0.0	0	0.0
Sugar Maple	1	1.9	0	0.0	0	0.0	0	0.0
Beech	0	0.0	5	9.4	13	24.5	9	17.0
Yellow Birch	0	0.0	4	7.5	2	3.8	10	18.9
Balsam Fir	0	0.0	3	5.7	6	11.3	7	13.2
Spruce	0	0.0	3	5.7	4	7.5	6	11.3
Alder	0	0.0	0	0.0	1	1.9	1	1.9
American Elm	0	0.0	0	0.0	0	0.0	1	1.9
Swamp								
Hemlock	10	22.2	3	6.7	5	11.1	3	6.7
White Pine	9	20.0	2	4.4	2	4.4	5	11.1
White Cedar	7	15.6	1	2.2	2	4.4	1	2.2
Spruce	5	11.1	10	22.2	5	11.1	3	6.7
Tamarack	4	8.9	7	15.6	5	11.1	0	0.0
Beech	4	8.9	2	4.4	2	4.4	7	15.6
Red Maple	3	6.7	2	4.4	3	6.7	6	13.3
Balsam Fir	2	4.4	1	2.2	6	13.3	4	8.9
Sugar Maple	1	2.2	3	6.7	2	4.4	2	4.4
Yellow Birch	0	0.0	11	24.4	6	13.3	1	2.2
Red Pine	0	0.0	3	6.7	0	0.0	1	2.2
White Birch	0	0.0	0	0.0	1	2.2	1	2.2
Alder	0	0.0	0	0.0	0	0.0	2	4.4
Black Ash	0	0.0	0	0.0	0	0.0	1	2.2

Position in abundance lists (column groups 1st–4th).

[1]Number of section lines occurring in landcover classification where species was listed by surveyor in given position.

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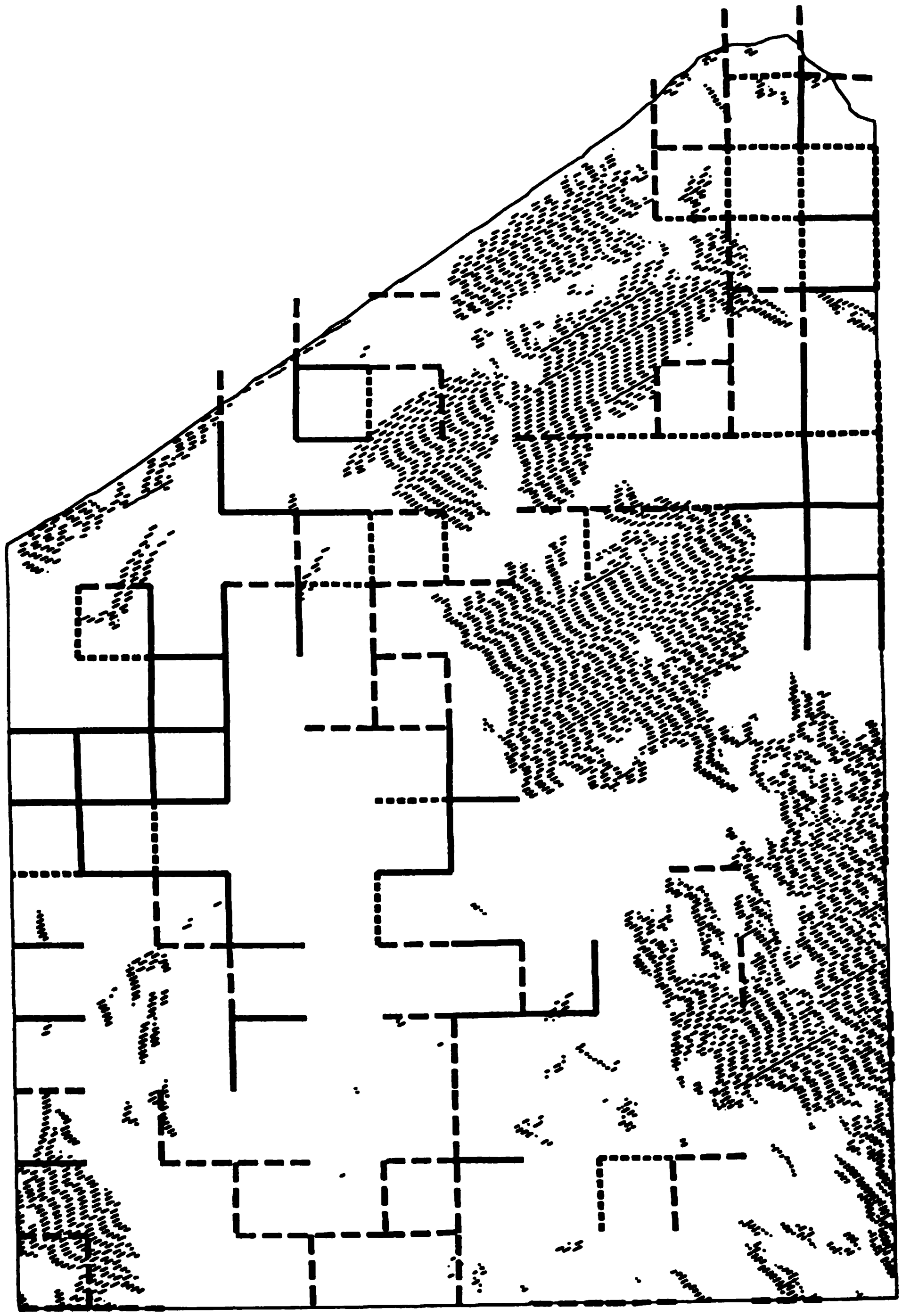

Figure 13. Survey lines for which the surveyor listed sugar maple (solid lines), beech (short dashes), or hemlock (long dashes) as the most abundant timber type. Hatching represents present stump prairie areas.

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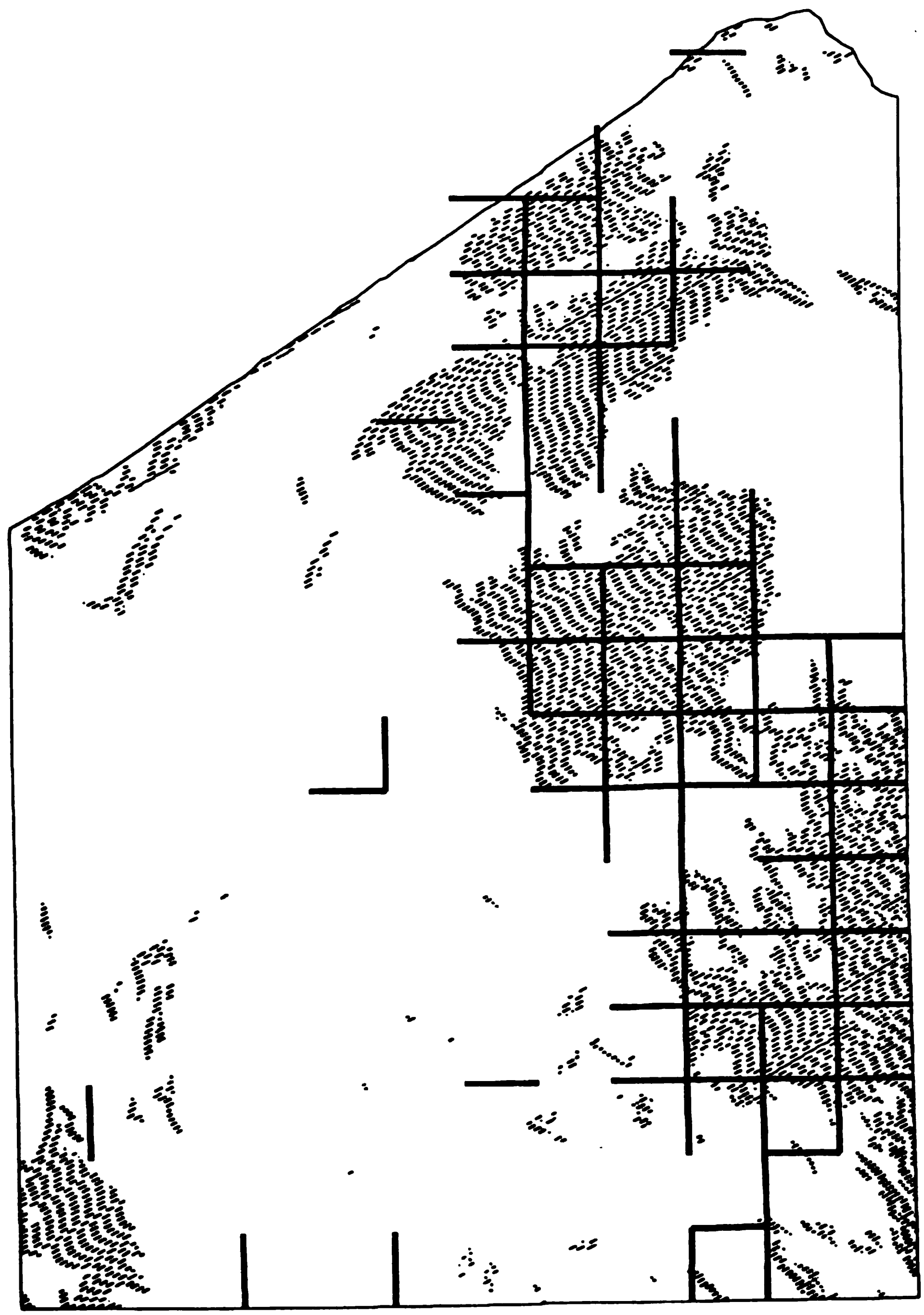

Figure 14. Survey lines for which the surveyor listed white pine as the most abundant timber type. Hatching represents present stump prairie areas.

upland areas. Nevertheless, hemlock, white pine, and cedar were the species most often cited first in these lines (Table 6). Spruce, yellow birch, and tamarack were often listed second.

Surveyors also described the soil texture along each section line, probably based primarily upon observations of the vegetation. The soils along almost every section line in the study area were designated "sandy," sometimes with the addition of "gravelly" or "stony". The soils for only five lines in the study area were described as "sandy loam". The surveyors also ranked soil quality. Only the terms second rate, poor second rate, or third rate were used to describe the soils in the study area. Those lines where third rate soil was noted have a good spatial correspondence with areas that today are stump prairie (Figure 15), and lines where second rate soil was noted correspond well with certain areas of current upland forest (Figure 16).

Judging from the surveyor line summaries, the spatial pattern created by the forest communities of the pre-disturbance forest was apparent to the surveyors. A reasonably experienced person asked to map forest types in the pre-disturbance forest, based on species composition alone, might have drawn boundaries remarkably similar to those defined today by the stump prairie/forest boundary, despite the lack of an obvious geomorphic/topographic contrast. In fact, the plat map drawn by the deputy surveyor of T 48 N, R 15 W in 1851 illustrates this. The portion of the county to the southwest of the Kingston Plains is shown as having "Surface Level 2d rate soil sandy Timber Sugar Maple, &c", but the Kingston Plains area is labelled as "Surface gently rolling 3d rate soil sandy Timber W Pine, Hemlock, Maple, Birch, &c." The placement of the wording suggests that the boundary between the two areas is approximately coincident with the current forest/stump prairie boundary.

The line descriptions indicate that the surveyors recognized a distinction between the forest vegetation present at that time in regions with contrasting vegetation types today. In particular, white pine was present in areas that today are upland forest and

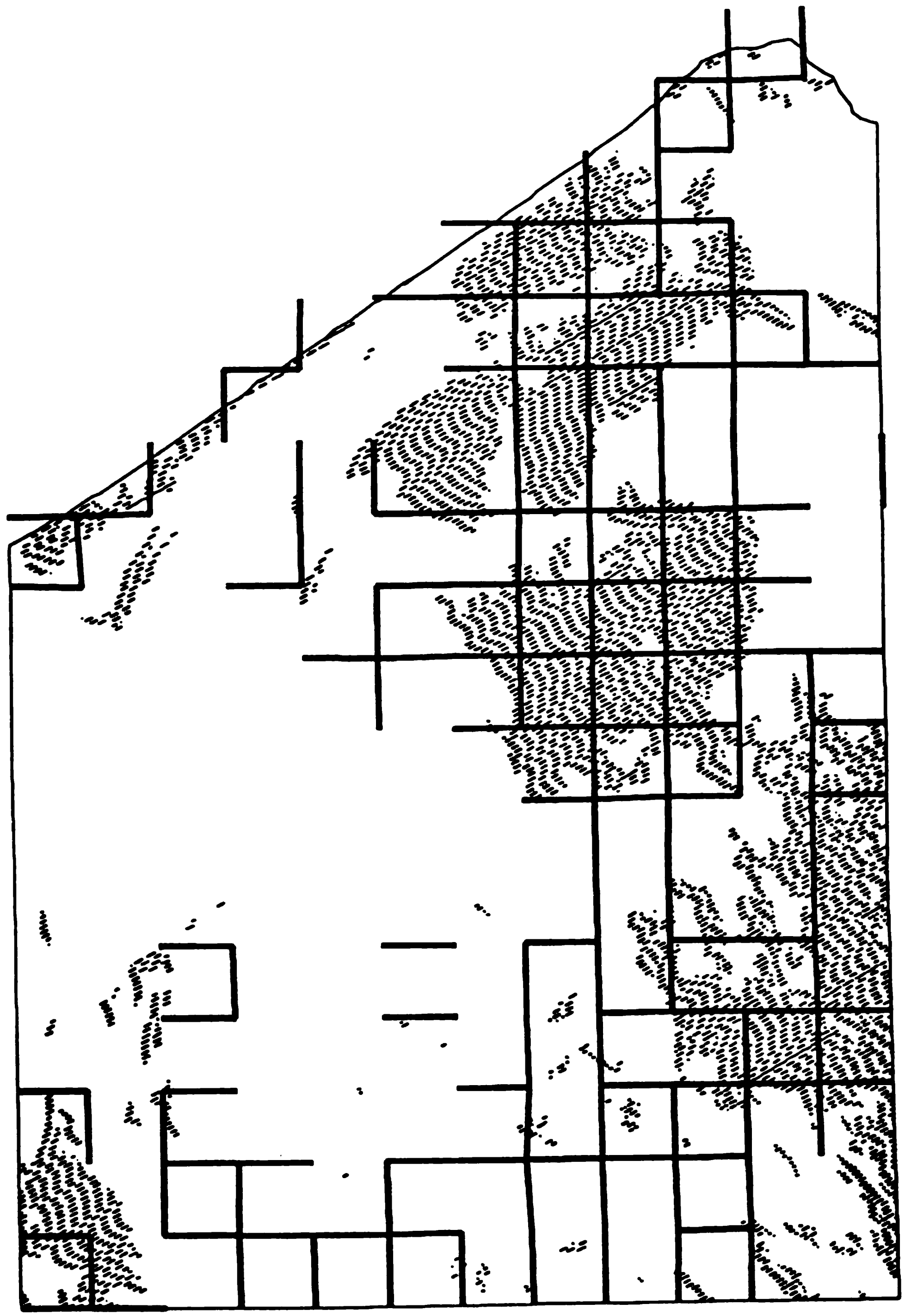

Figure 15. Survey lines for which surveyor described the soil as "3^{d} rate". Hatching represents present stump prairie areas.

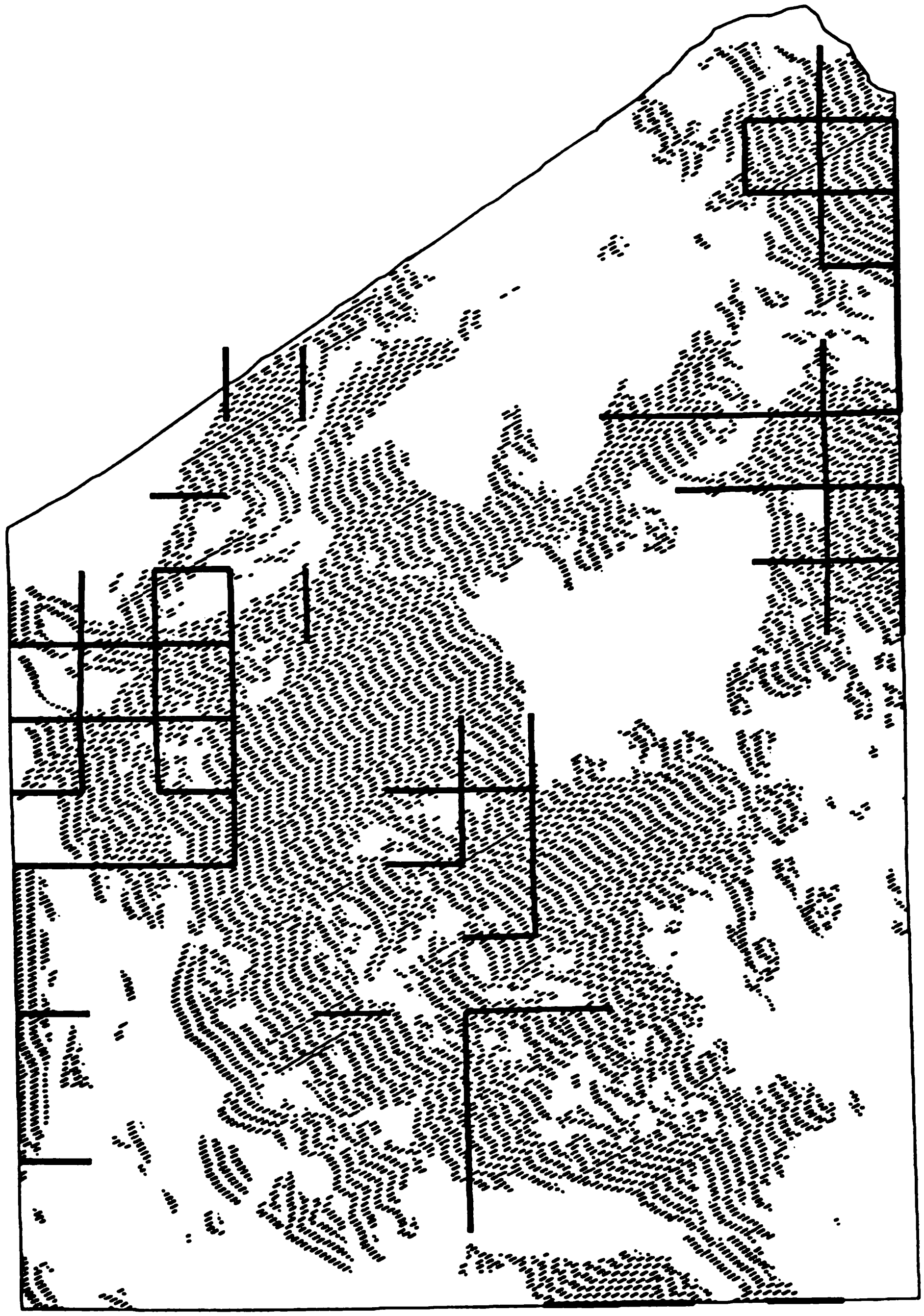

Figure 16. Survey lines for which the surveyor described the soil as “2^d rate”. Hatching represents present upland forest areas.

swamp, but it was often the most prevalent species in areas that today are stump prairie. Similarly, sugar maple, beech, and yellow birch were characteristically abundant in current upland forest regions, but between the three were only once listed first by the surveyors in places that have since become stump prairies.

Witness tree locations

The species, diameters, and locations of the witness trees recorded by the surveyors also indicate a differentiation in pre-disturbance forest composition among the current landcover types. Areas that today are upland forest contained significantly more sugar maple, beech, and yellow birch trees than would have been expected from a random distribution (see "Residual Score" columns in Table 7). Sugar maple was a particularly distinctive component of this forest, as it was confined almost wholly to these sites (Table 7; Figure 17A). Yellow birch was occasionally encountered within areas that today are stump prairie (Table 7), but most often was located at the edges of these polygons (Figure 17B). Beech trees, while present in the stump prairie areas, had a positive association only with the upland forest polygons (Table 7; Figure 17C).

Sugar maple has been shown in many regions to occur only under particular edaphic conditions. In the presettlement forests of Baraga County, Michigan, sugar maple exhibited soil and site specificity, occurring primarily on mesic sites (Barrett et al. 1995; Schaetzl and Brown n.d.). In the forests of northern Michigan today, sugar maple also occurs only on better sites, and is absent on xeric sites (Shetron 1972). It was also remarkably absent from ice-contact hills or outwash plains in northwestern Lower Michigan (Host and Pregitzer 1992), the most xeric landforms. Thus, the absence of sugar maple from the stump prairie sites may indicate that the stump prairie is more edaphically xeric than upland forest areas.

In the current stump prairie polygons, only the two pine species had strongly positive residual scores (Table 7). White pine, the most commonly recorded pine species, was found throughout the study area, but was most frequent in stump prairie areas (Figure 18A). Red pine was less common than white pine, and was seldom noted outside stump prairie sites. In fact, red pine witness trees were nearly confined to one group of stump prairie polygons near the Lake Superior coastline (Figure 18B). Jack pine was noted infrequently by the surveyors, and only in stump prairie areas (Figure 18C).

Table 7. Frequencies and standardized residuals expressing the degree of association between species and current landcover classification.

	Upland forest		Stump prairie		Swamp		Other		
		Residual		Residual		Residual		Residual	
Species	N	score	N	score	N	score	N	score	G^2
Beech	305	55.7	65	-5.2	28	-52.9	0	-11.1	174.9
Cedar	23	-43.6	26	-2.8	112	115.6	5	0.0	156.0
Fir	76	1.5	30	0.1	22	-4.0	4	0.0	6.3*
Hemlock	171	1.5	65	-0.1	66	-2.1	9	0.0	4.3*
Red Maple	99	6.5	35	0.1	17	-12.3	2	-1.2	24.5
Spruce	35	-44.3	53	1.8	105	54.5	11	5.0	117.0
Sugar Maple	202	71.6	1	-46.6	21	-22.7	0	-6.2	202.7
Tamarack	11	-65.2	16	-12.0	134	188.7	10	5.8	266.5
White Pine	107	-29.0	164	97.1	62	-9.1	24	20.0	160.4
Yellow Birch	158	31.0	22	-11.0	23	-15.8	0	-5.6	77.2
Red Pine	1	-24.1	38	63.4	12	-0.1	1	-0.1	84.8

* $P > 0.05$. All other G^2 values are highly significant at $p < 0.0001$.

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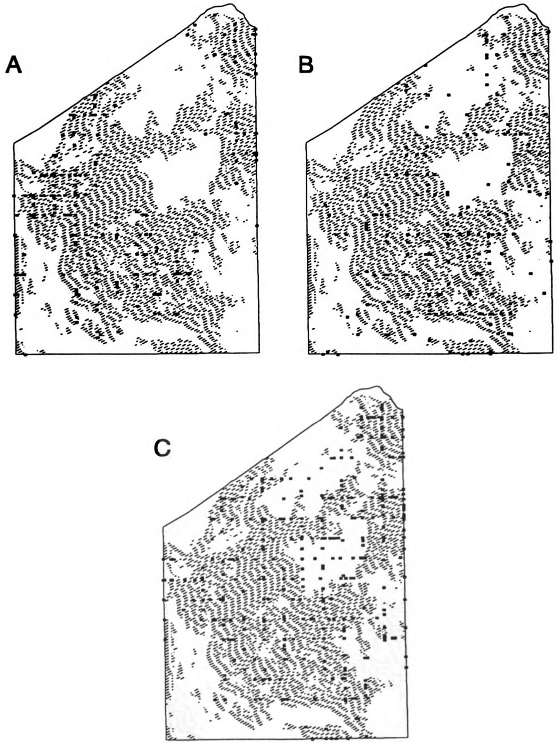

Figure 17. Distribution of witness trees by species. Hatching represents present upland forest areas. A) Sugar maple witness trees. B) Yellow birch witness trees. C) Beech witness trees.

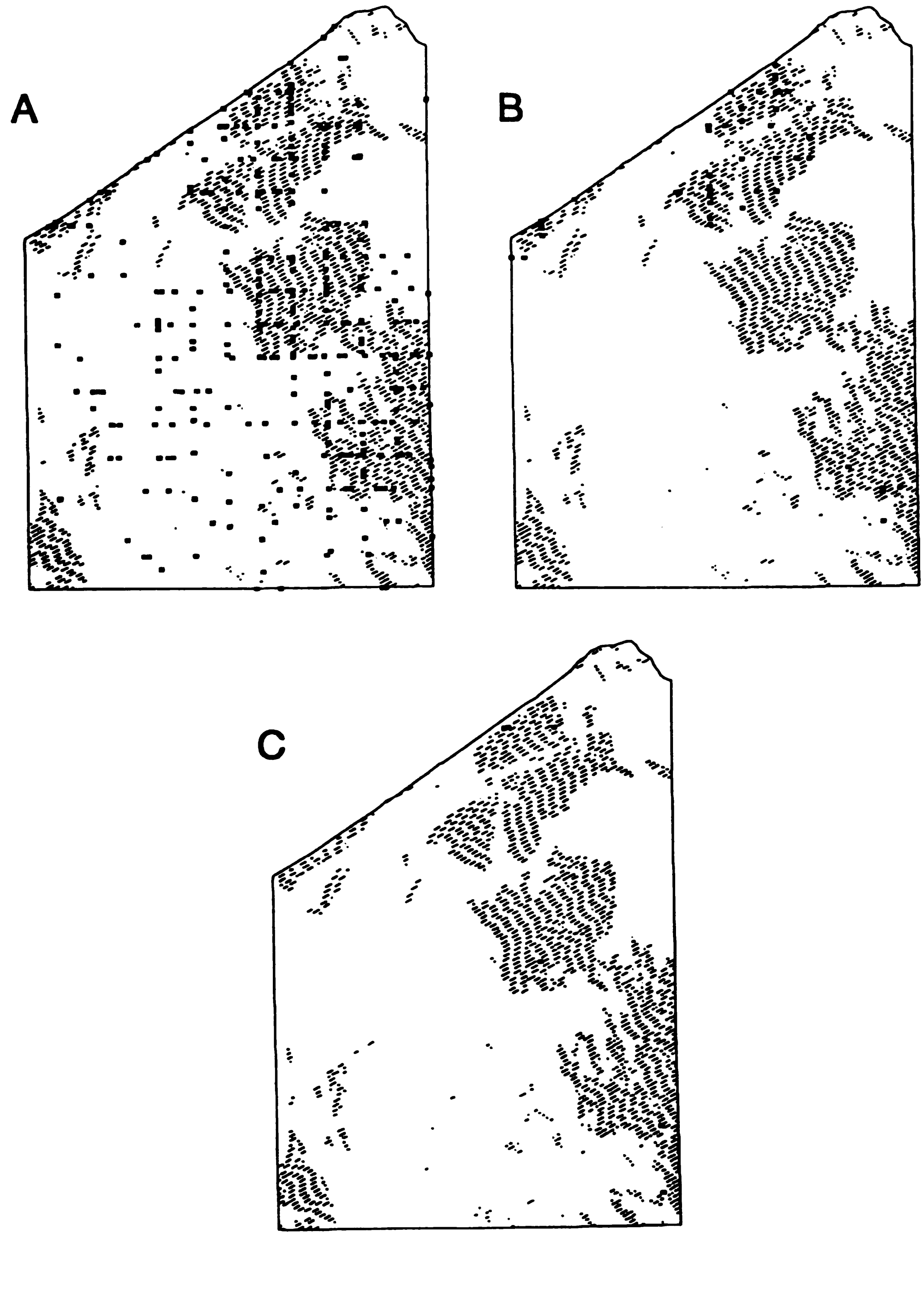

Figure 18. Distribution of witness trees by species. Hatching represents present stump prairie areas. A) White pine witness trees. B) Red pine witness trees. C) Jack pine witness trees.

White pine is known to grow well on a wide variety of sites (Barnes and Wagner 1981; Schaetzl and Brown n.d.), but is found most often on the more xeric sandy soils, especially better-developed Spodosols (Mokma and Vance 1989). In other parts of northern Michigan, for example, pine species were predominant on drought-prone, coarse-textured soils, sites with a tendency towards natural flammability (Whitney 1987; Barrett et al. 1995; Schaetzl and Brown n.d.). In the presettlement forests of northern Michigan white pine has been noted as an occasional associate in a wide variety of community types (Hushen et al. 1966; Frederick et al. 1976; Whitney 1987; Barrett et al. 1995). Thus, the predominance of white pine on stump prairie sites could indicate that these are xeric sites, even though scattered individuals of white pine also occurred in both the upland forest and swamp forest regions.

Tamarack, cedar, and spruce were the species most often recorded by the surveyors in swamp areas (Table 7). The strong association of these species with swamp areas can be discerned from the species distribution maps (Figure 19), especially cedar and tamarack. Spruce witness trees were less confined to swamp areas (Figure 19C), probably because the surveyors did not distinguish between black spruce and white spruce, which have different site preferences (Barnes and Wagner 1981). Spruce trees occurring within stump prairie and upland forest may have been white spruce, while those in swamp polygons were probably black spruce. Tamarack, cedar, and spruce trees were also common in swamp sites in the presettlement forests of Baraga County, in the western Upper Peninsula (Barrett et al. 1995).

Two evergreen species, balsam fir and hemlock, did not show a statistically significant relationship with the current landcover classes (Table 7), and in fact were scattered throughout the study area (Figure 20). The total number of hemlock witness trees recorded was quite large; it was found on all four site types. Similarly, in presettlement forests of Baraga County (Barrett et al. 1995; Schaetzl and Brown n.d.), as well as in surrounding portions of Pictured Rocks National Lakeshore (Frederick et al.

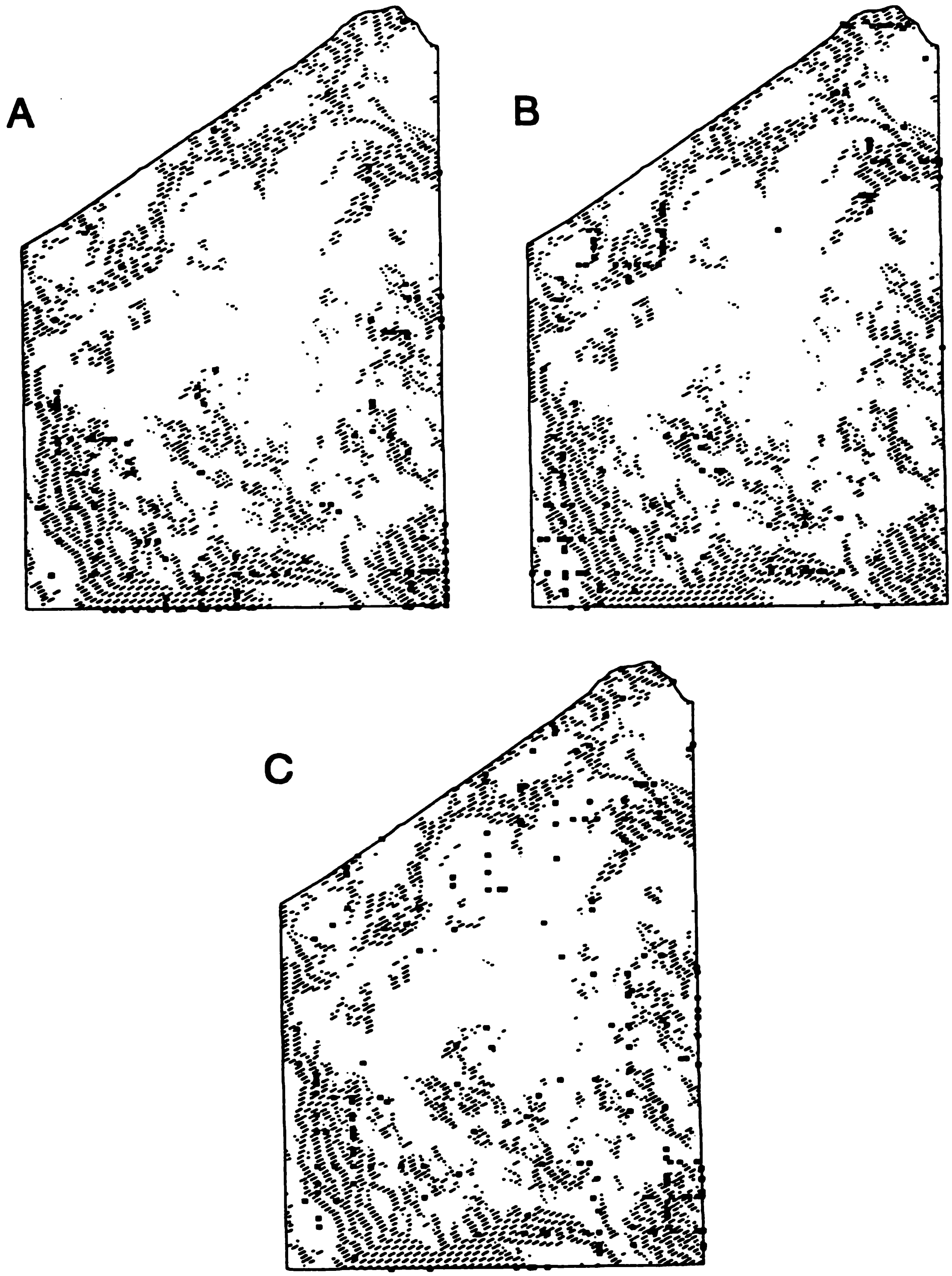

Figure 19. Distribution of witness trees by species. Hatching represents present swamp areas. A) Tamarack witness trees. B) White cedar witness trees. C) Spruce witness trees.

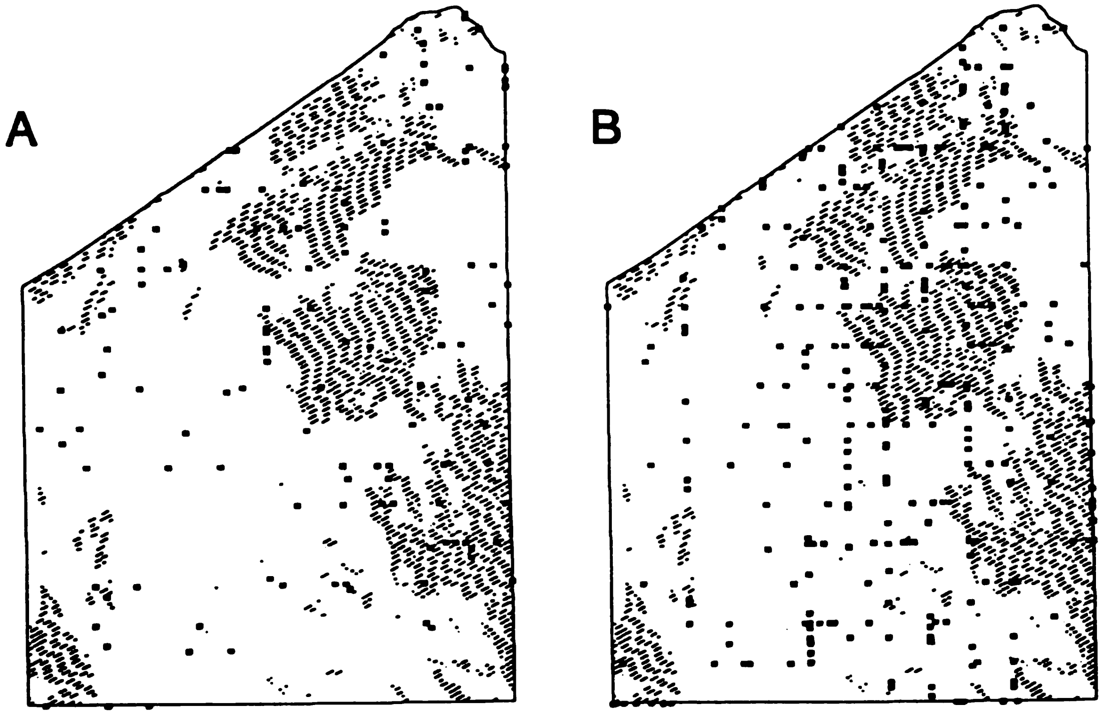

Figure 20. Distribution of witness trees by species. Hatching represents present stump prairie areas. A) Balsam fir witness trees. B) Hemlock witness trees.

1976), hemlock occurred across a wide variety of soil texture and drainage conditions. Fir was less commonly recorded than hemlock in the study area (Table 7). Today it occurs in Michigan on a variety of site types ranging from swamps to well-drained uplands (Barnes and Wagner 1981).

Red maple was also recorded on all site types, although it was most strongly positively associated with the upland forest polygons (Table 7; Figure 21). Red maple thrives on a wide range of soil type and textures (Walters and Yawney 1990). In presettlement Michigan forests, red maple has been noted for exhibiting wide site tolerances (Hushen et al. 1966), although in Baraga County it was rarely recorded by the surveyors (Barrett et al. 1995). It is a common species today in the study area both as a member of the forest canopy and as isolated individuals on the stump prairie (Table 2).

Fig

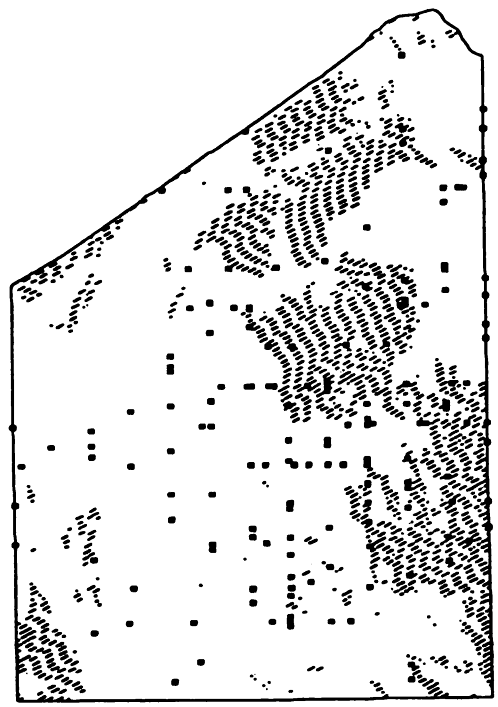

Figure 21. Distribution of red maple witness trees. Hatching represents present stump prairie areas.

Witness tree diameters

When the diameters of the witness trees and the species distributions are taken into account, the distinctions among the forest communities on the four landcover types become more muted (Table 8). In all four landcover classes, white pine has the highest modified importance value, mostly due to its large basal area. To a lesser extent, hemlock also shows a high modified importance value in all landcover classes due to its larger basal area.

Notable differences among the forests of the landcover types are, however, still evident. The importance of white pine in the stump prairie areas (48.6) is proportionally much greater than its importance in either the upland forest (20.0) or swamp areas (20.6; Table 8). The distinction between the upland forest and stump prairie areas is most evident when one examines the data for yellow birch and sugar maple. Both species have high importance values in upland forest polygons (yellow birch, 15.1; sugar maple, 14.3) due to high relative density and relative dominance. Similarly, both have quite low importance values in stump prairie areas (yellow birch, 3.6; sugar maple, 0.2) (Table 8).

The size class distributions of the white pine tree diameters (Figures 22A and B) illustrate the extraordinarily large diameters of the white pine trees, especially those located within upland forest polygons. The broad size distribution of the white pines in the upland forest areas suggests that the trees were of uneven ages, and did not reproduce solely in response to widespread disturbance. The white pine trees in the stump prairie areas also show an uneven age distribution, with the exception possibly of a large cohort in the 25 - 30 inch diameter class.

Beech trees in the upland forest areas have an inverted "J" size class distribution, typical of a reproducing shade-tolerant tree (Quinby 1991) (Figure 23). In the areas that are today stump prairie, the beech trees were especially small, with no tree recorded with

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Table 8. Relative density, relative dominance, and modified importance values of witness trees grouped by current landuse classification.

Species	N	Mean DBH	Max DBH	Total DBH	Total basal area	Rel. Density	Rel. Dominance	Mod. Import. Value
		------------	cm	------------	m^2	--------------	%	--------------
Upland forest:								
White pine	107	65.0	152.4	6946.9	44.91	8.9	31.0	20.0
Beech	305	25.9	63.5	7894.3	18.19	25.5	12.5	19.0
Hemlock	171	39.6	203.2	6766.6	26.57	14.3	18.3	16.3
Yellow birch	158	39.6	203.2	6263.6	24.61	13.2	17.0	15.1
Sugar maple	202	28.7	200.7	5773.4	17.07	16.9	11.8	14.3
Red maple	99	26.2	45.7	2588.3	5.90	8.3	4.1	6.2
Balsam fir	76	22.6	35.6	1714.5	3.24	6.3	2.2	4.3
Spruce	35	24.6	38.1	861.1	1.77	2.9	1.2	2.1
White Cedar	23	27.4	50.8	629.9	1.47	1.9	1.0	1.5
Tamarack	11	25.4	45.7	279.4	0.62	0.9	0.4	0.7
American elm	2	40.6	40.6	81.3	0.26	0.2	0.2	0.2
White birch	2	38.1	45.7	76.2	0.24	0.2	0.2	0.2
Black Cherry	2	16.5	17.8	33.0	0.04	0.2	0.0	0.1
Mountain ash	2	12.7	12.7	25.4	0.03	0.2	0.0	0.1
Red pine	1	25.4	25.4	25.4	0.05	0.1	0.0	0.1
Aspen	1	20.3	20.3	20.3	0.03	0.1	0.0	0.1
Total:	1197	33.3	203.2					
Stump prairie:								
White pine	164	53.3	106.7	8757.9	44.20	31.2	62.4	46.8
Hemlock	65	35.1	91.4	2280.9	7.48	12.4	10.6	11.5
Beech	65	24.1	35.6	1562.1	3.09	12.4	4.4	8.4
Red pine	38	43.2	86.4	1643.4	6.33	7.2	8.9	8.1
Spruce	53	21.3	33.0	1125.2	2.01	10.1	2.8	6.5
Red maple	35	23.1	30.5	807.7	1.56	6.7	2.2	4.4
Yellow birch	22	34.0	61.0	749.3	2.19	4.2	3.1	3.6
White Cedar	26	26.2	45.7	678.2	1.56	5.0	2.2	3.6
Balsam fir	30	19.1	27.9	574.0	0.91	5.7	1.3	3.5
Tamarack	16	23.1	40.6	368.3	0.75	3.0	1.1	2.1
Jack pine	7	26.4	35.6	185.4	0.45	1.3	0.6	1.0
White birch	3	25.4	35.6	76.2	0.16	0.6	0.2	0.4
Sugar maple	1	38.1	38.1	38.1	0.11	0.2	0.2	0.2
Total:	525	35.8	106.7					

Table 8. (Cont.)

Species	N	Mean DBH	Max DBH	Total DBH	Total basal area	Rel. Density	Rel. Dominance	Mod. Import. Value
		------------cm------------			m^2	--------------%--------------		
Swamp:								
White pine	62	47.8	127.0	2954.0	13.78	10.1	31.2	20.6
White Cedar	112	25.1	63.5	2804.2	6.23	18.3	14.1	16.2
Tamarack	134	18.5	40.6	2491.7	4.32	21.9	9.8	15.8
Hemlock	66	35.6	76.2	2347.0	7.45	10.8	16.9	13.8
Spruce	105	19.8	40.6	2080.3	3.60	17.1	8.1	12.6
Yellow birch	23	31.2	55.9	716.3	1.93	3.8	4.4	4.1
Beech	28	24.4	40.6	685.8	1.43	4.6	3.2	3.9
Sugar maple	21	30.5	50.8	640.1	1.77	3.4	4.0	3.7
Red pine	12	36.3	66.0	434.3	1.44	2.0	3.3	2.6
Balsam fir	22	19.1	30.5	419.1	0.68	3.6	1.5	2.6
Red maple	17	25.1	40.6	426.7	0.92	2.8	2.1	2.4
Black ash	4	26.2	30.5	104.1	0.22	0.7	0.5	0.6
Aspen	2	26.7	30.5	53.3	0.11	0.3	0.3	0.3
White birch	2	20.3	30.5	40.6	0.08	0.3	0.2	0.3
Black Cherry	1	40.6	40.6	40.6	0.13	0.2	0.3	0.2
Birch	1	35.6	35.6	35.6	0.10	0.2	0.2	0.2
Jack pine	1	15.2	15.2	15.2	0.02	0.2	0.0	0.1
Total:	613	26.7	127.0					
Other:								
White pine	24	40.6	76.2	972.8	3.48	36.4	63.6	50.0
Hemlock	9	29.7	50.8	266.7	0.68	13.6	12.5	13.1
Spruce	11	21.1	30.5	231.1	0.42	16.7	7.7	12.2
Tamarack	10	22.9	35.6	228.6	0.45	15.2	8.2	11.7
White Cedar	5	23.4	30.5	116.8	0.22	7.6	4.0	5.8
Balsam fir	4	17.3	20.3	68.6	0.09	6.1	1.7	3.9
Red maple	2	20.3	30.5	40.6	0.08	3.0	1.5	2.3
Red pine	1	25.4	25.4	25.4	0.05	1.5	0.9	1.2
Total:	66	29.5	76.2					

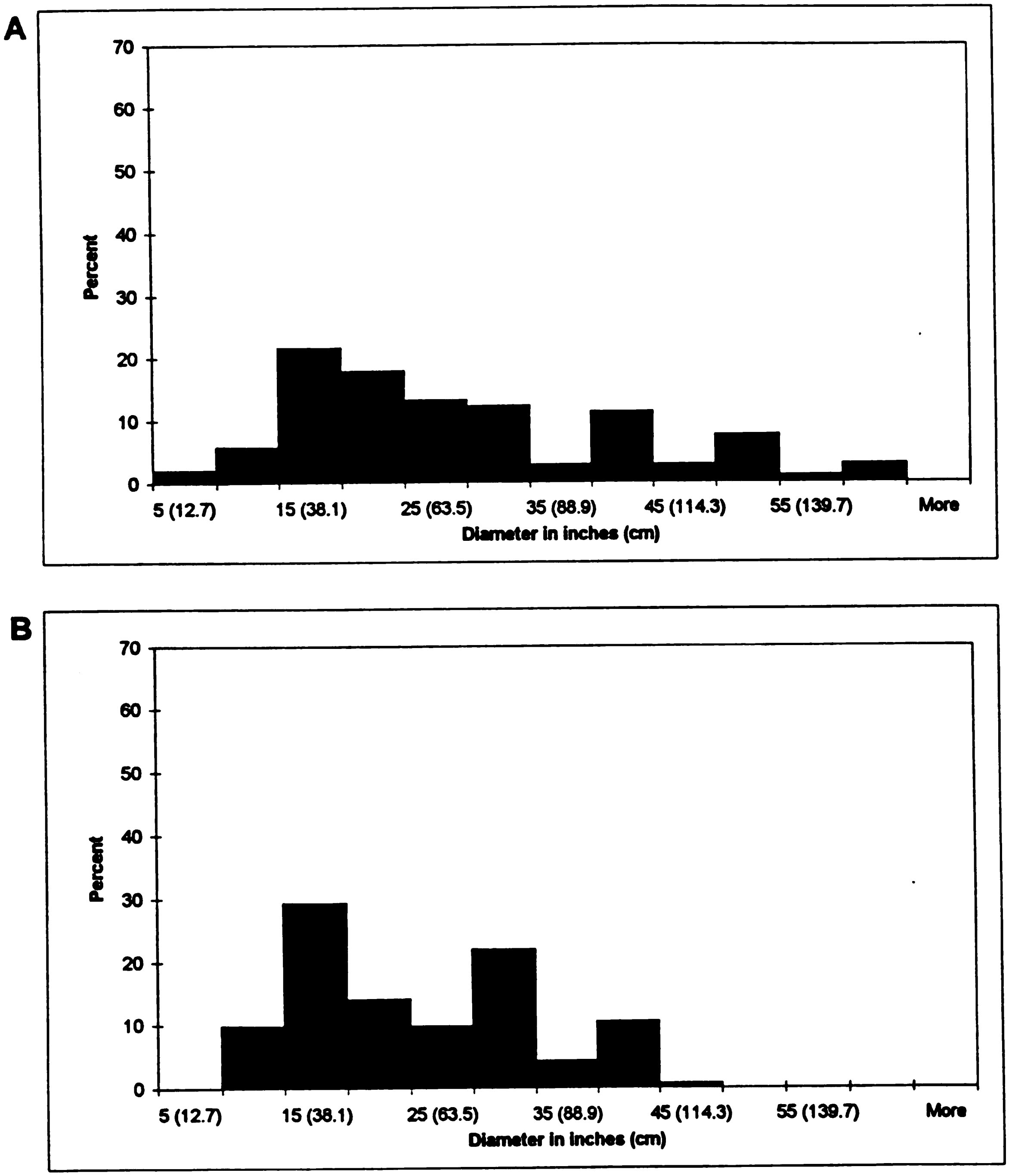

Figure 22. Diameter size class distributions from GLO notes for white pine trees in A) areas currently mapped as upland forest and B) areas currently mapped as stump prairie.

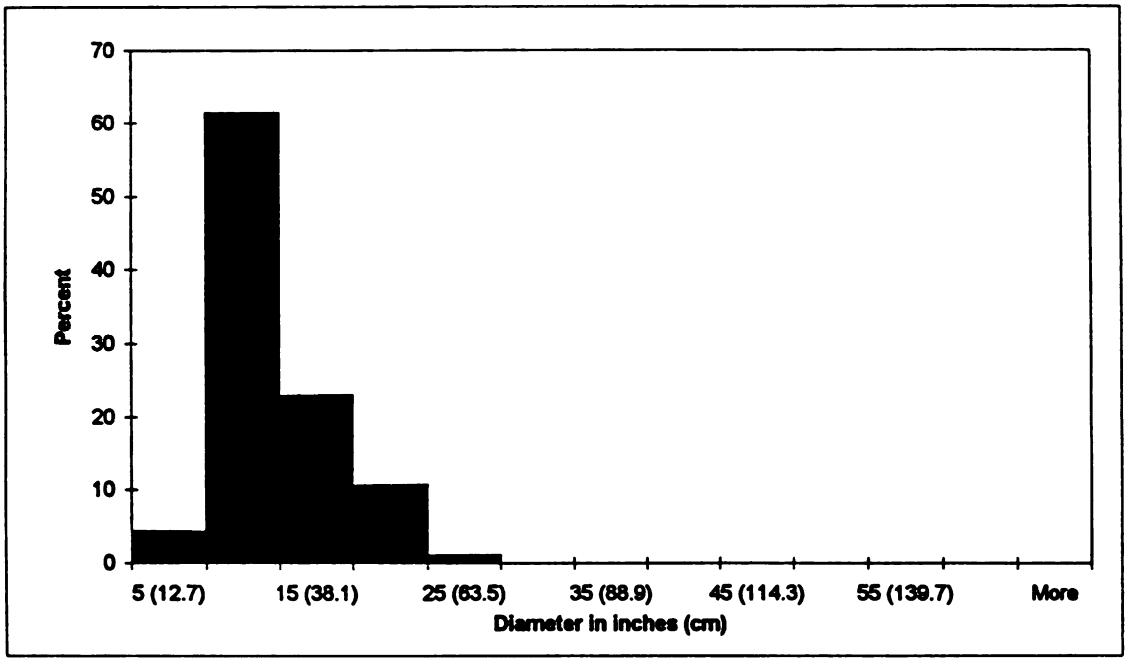

Figure 23. Diameter size class distributions from GLO notes for beech trees in areas currently mapped as upland forest.

a diameter larger than 15 inches. This may indicate that beech reproduction on the stump prairie was of relatively recent origin at the time of the survey, perhaps due to a disturbance that had occurred previously, killing the beech trees. The distribution of sugar maple diameters in the upland forest polygons is similar to that of the beech trees (Figure 24).

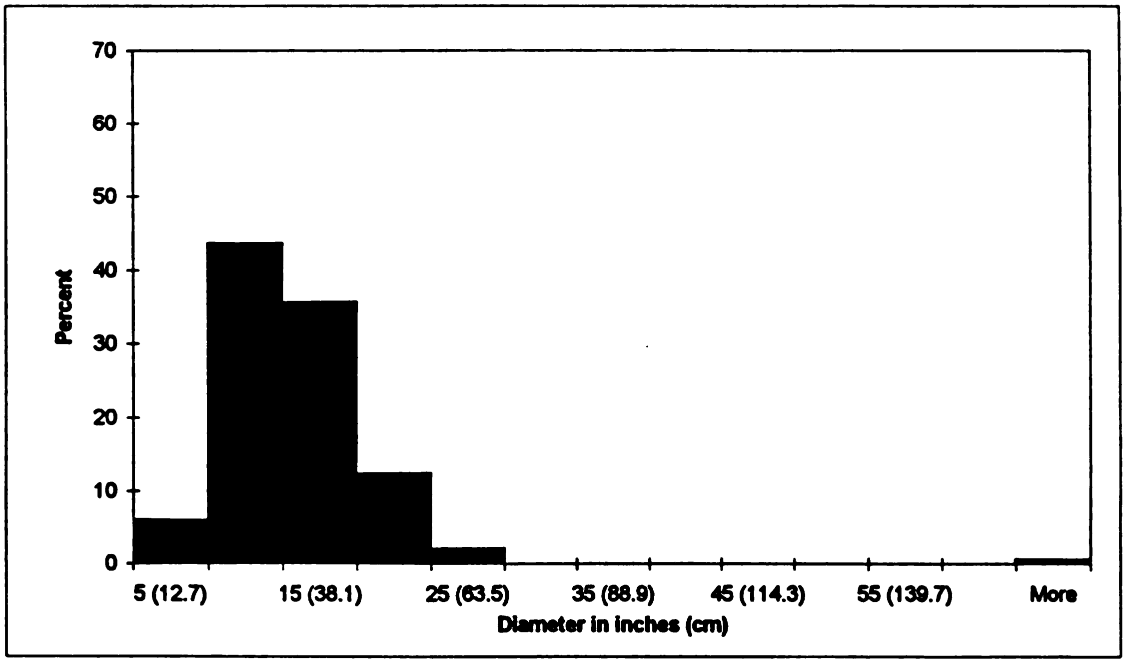

Figure 24. Diameter size class distributions from GLO notes for sugar maple trees in areas currently mapped as upland forest.

Stumps

The stumps from nineteenth century logging are the last remaining physical evidence of the character of the pre-disturbance forest. The evidence available from the stumps must be interpreted with caution because the effects of a century of decay on the stumps are not known. On the stump prairies, many stumps appear to be well-preserved as to the original placement and dimensions of the stumps, although the interiors of many of the stumps are rotting (Figure 25). Some stumps are in a more advanced state of decay, and are thus more difficult to measure. Bark is lacking on all stumps, but exterior rings of wood on stumps of the open prairies are, in most cases, intact. In the forests, however, the moister microenvironment has often apparently hastened the decay process and the exterior wood of the stumps is usually rotting. In the forests there is also an additional sampling problem: one must distinguish between nineteenth century stumps and stumps from more recent logging efforts. The presence of bark on a stump was taken as evidence that it was not from the original logging. Underbrush and recent logging slash also occasionally made finding stumps in the forest difficult.

It is likely that all, or nearly all, of the stumps remaining from the nineteenth century represent white pine or red pine trees. Wood from five stump prairie stumps, one in good condition and four relatively decomposed, was identified to the genus level. All five are from the genus *Pinus*. Thus, the level of decomposition cannot be taken to indicate a difference in the stump's species. Stumps of hardwood trees have probably completely rotted away.

Density. On the average, there are slightly fewer stumps per hectare in the forested stands (91.8) than in the stump prairie areas (113.2; Table 9). This can be attributed to two factors:

Figure 25. A representative view of stumps on the stump prairie.

Table 9. Diameter at breast height (DBH)[1] and absolute density for logging era stumps in sampled stands.

Stand	Mean DBH	Maximum DBH	Total DBH	Total basal area	Absolute density
	cm	cm	cm	m^2	stumps ha^{-1}
FOR-1	54.4	100	1794	9.13	79.2
FOR-2	---[2]	---	---	---	---
FOR-3	53.1	110	2070	10.00	129.5
FOR-4	60.3	100	2230	11.38	72.0
FOR-5	59.5	100	2380	12.00	96.5
FOR-6	47.3	90	2270	9.15	221.9
FOR-7	67.3	120	2220	12.96	55.3
FOR-8	69.7	120	2580	15.80	76.8
FOR-9	52.1	100	2190	10.16	86.8
Total:	57.4	120			91.8
SAV-1	48.0	90	2830	11.80	88.7
SAV-2	45.6	90	2370	9.57	205.0
SAV-3	52.1	90	2500	11.58	127.2
SAV-4	50.9	110	2850	12.39	113.3
SAV-5	58.7	90	3520	17.40	159.6
SAV-6	57.8	120	3180	16.41	73.3
SAV-7	55.4	110	3105	15.50	101.8
SAV-8	51.5	110	2470	11.87	107.1
Total:	52.6	120			113.2

[1]Estimated diameter at breast height of tree based on diameter of top of stump.
[2]Stumps were not sampled in stand FOR-2 due to the large amount of recent logging slash in the stand.

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(1) The stumps remaining from the nineteenth century logging are primarily the stumps of white pine trees and thus represent only a partial record of the pre-disturbance forest. Based on the GLO notes, white pine represented a smaller proportion of trees in areas where the forest has regenerated than in present stump prairies (Table 8). If the stumps of other tree species have preferentially decayed, the density of the remaining stumps should be lower in the forest, where formerly there had been more trees of other species.

(2) Stumps in the forest are difficult to find and are more likely to decay than are stumps in the stump prairies, as discussed above. Thus, it is possible that some stumps in the forest went unsampled or have disappeared due to decay.

Diameters. The average diameters of stumps in the forested stands (57.4 cm) are slightly larger than the diameters of stumps in the stump prairies (52.6 cm; Table 9). In forest and stump prairie stands located near each other, the stumps in the forested stands are larger than the stumps in the adjacent stump prairie (Figure 26). Given the assumption that most stumps represent white pine trees (see above), this pattern would be expected if the white pine trees in the forested areas were scattered, emergent giants, while the forest in the stump prairie regions was dominated by white pine.

Alternatively, larger remaining stumps in the forested areas could be attributed to faster decay rates in the moister environment of the forest. It is possible that smaller stumps in the forested stands have decayed and disappeared, leaving only the larger stumps to be sampled, or that they were overlooked in sampling, as discussed above.

Mean diameters of the stumps in the sampled stands are roughly equivalent to mean diameters of white pine trees as recorded by the GLO surveyors. Average diameters of white pine trees from the GLO notes in regions that are now upland forest (25.6 inches or 65.0 cm) was slightly greater than diameters from the GLO notes of white

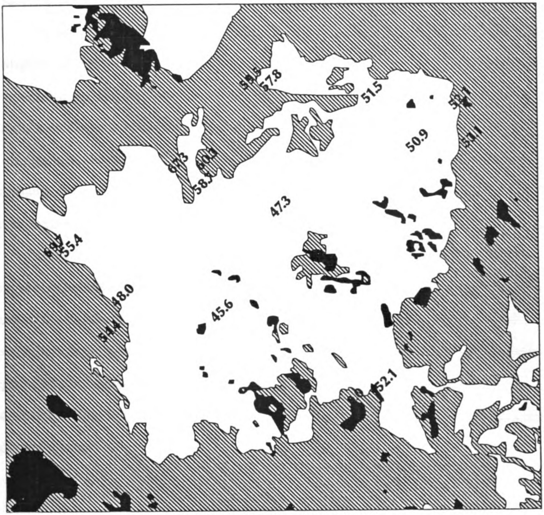

Figure 26. Average stump diameters by location of sampled stands.

pine trees in current stump prairie areas (21.0 inches or 53.3 cm; Table 8). Both of these values are slightly larger than the mean diameters of the stumps in the sampled stands (forest stands, 57.4 cm; stump prairie stands, 52.6 cm; Table 9), but are comparable considering the loss of bark (and possibly some outer wood layers) from the stumps.

The size class distribution of the stump diameters (Figures 27A and B) illustrates the slightly larger mean diameters of the stumps in the forested stands. Both distributions are broad, suggesting that the trees they represent were of uneven ages, and did not reproduce solely as a response to widespread disturbance. The size class distributions of the stumps are comparable to the distributions of white pine tree diameters in the pre-disturbance forest as indicated by the GLO surveyor's notes (Figures 22A and B), which also showed broad diameter distributions in both current landcover types.

Information from stump locations and dimensions appears to support inferences about presettlement forests derived from the GLO notes. Specific conclusions about the nature of the forests are difficult to make on the basis of the stump data alone due to uncertainties about preferential decay and decay rates. Nevertheless, the stump data do suggest that the forests that existed on the sampled sites were similar to the forests reconstructed from the GLO notes of the region as a whole in the two contrasting current landcover classes.

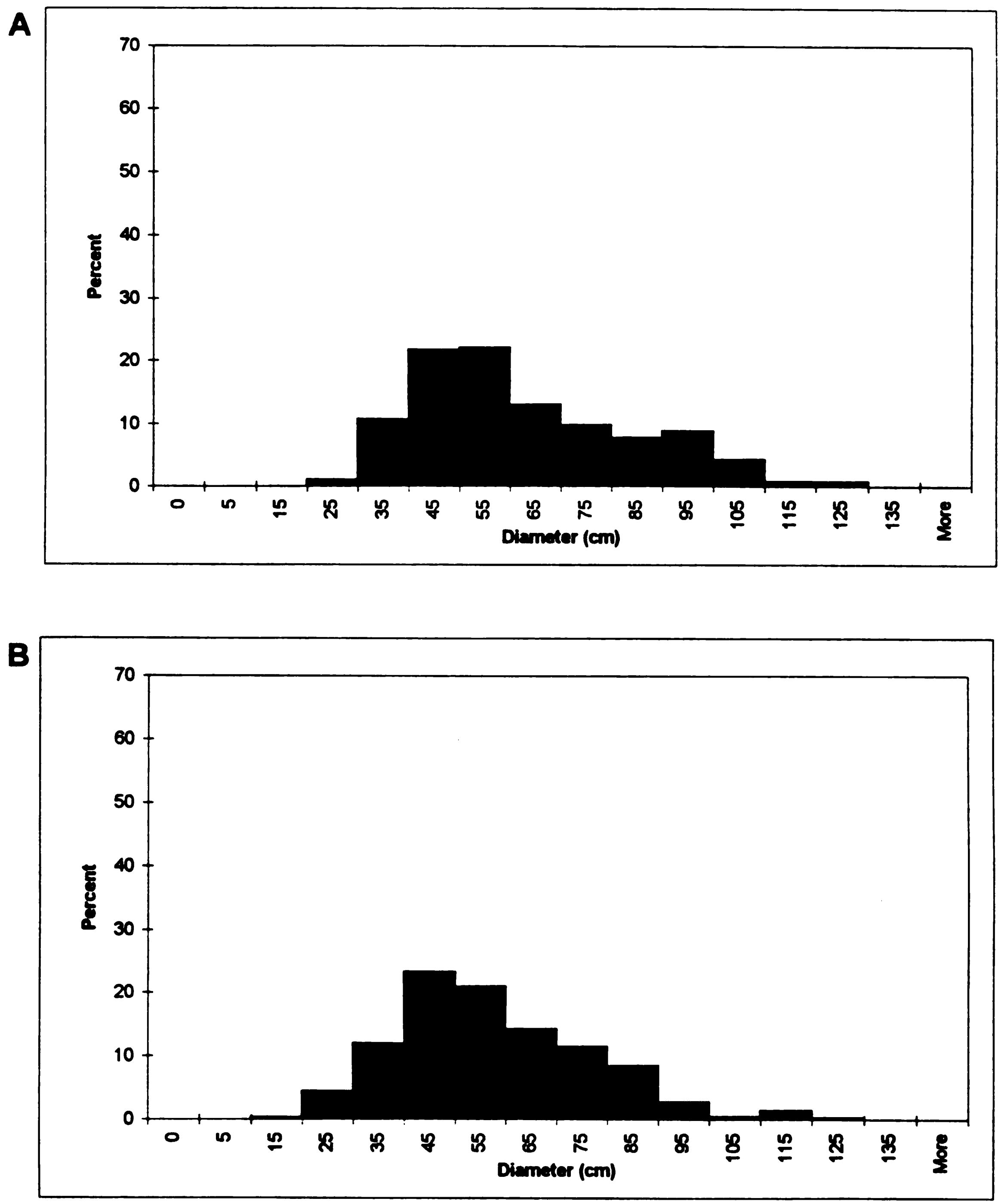

Figure 27. Diameter size class distributions for stumps in A) forest stands and B) stump prairie stands.

Comparisons with current stand composition

A comparison of the present species composition of the sampled forest and stump prairie stands (Table 2) with the pre-disturbance species composition of these areas as reconstructed from the GLO notes (Table 8) illustrates the changes that have taken place presumably due to repeated disturbance (Table 10). The disturbances affecting the species composition of the study area include both the original nineteenth century logging and associated fires, as well as more recent timber harvesting and land management practices.

In regions that are currently forested, three of the four most common species today (white pine, beech, and hemlock) were also the species with the highest modified importance values in the GLO surveyor's notes for the same regions (Table 10). Red maple, which has the highest importance value (38.4) in the sampled stands, however, ranked sixth in modified importance value in the GLO notes, behind yellow birch and sugar maple (Table 10).

Neither yellow birch nor sugar maple were encountered in any of the sampled forested stands. I have seldom seen either species in any of the forests adjacent to the stump prairie boundaries, except for some sugar maple in the extreme northeastern corner of the study area (sections 2 and 3 of T 48 N, R 15 W) and also in the southwestern corner of the study area (section 30 of T 48 N, R 15 W). A few yellow birch trees have been observed near Wise Lake in section 27 and also in the southwestern corner of the study area (section 30). Although sugar maple and yellow birch were both prevalent species in the pre-disturbance forest in regions that are today upland forest, sugar maple was not recorded by the surveyors in the upland forests immediately adjacent to the current stump prairie study area (Figure 17A). Yellow birch was found nearer to the stump prairie areas (Figure 17B), yet it was most common in other parts of the upland forest as well. Thus, the importance of sugar maple and yellow birch in the presettlement forests of areas currently mapped as upland forest was probably greater farther away from

Table 10. Importance values and ranks of tree species as compiled from GLO notes and from modern sampled stands.

Species	GLO notes Mod. Imp. Val.	GLO notes Rank	Modern sampled stands Imp. Val.	Modern sampled stands Rank	Change in Imp. Val.
Forest:					
Balsam fir	4.3	7	9.2	5	+4.9
Beech	19.0	2	17.2	3	-1.8
Hemlock	16.3	3	9.9	4	-6.4
Red maple	6.2	6	38.4	1	+32.2
Red pine	0.1	>8	2.9	7	+2.8
Spruce	2.1	8	0.3	>8	-1.8
Sugar maple	14.3	5	absent	absent	-14.3
White birch	0.2	>8	4.2	6	+4.0
White pine	20.0	1	17.3	2	-2.7
Yellow birch	15.1	4	absent	absent	-15.1
Stump Prairie:					
Balsam fir	3.5	>8	0.2	8[1]	-3.3
Beech	8.4	3	absent	absent	-8.4
Black cherry	absent	absent	5.0	3	+5.0
Black spruce	6.5	5	2.5	6	-4.0
White cedar	3.6	8	absent	absent	-3.6
Hemlock	11.5	2	absent	absent	-11.5
Jack pine	1.0	>8	3.9	4	+2.9
Juneberry	absent	absent	3.5	5	+3.5
Red maple	4.4	6	8.7	2	+4.3
Red pine	8.1	4	2.3	7	-5.8
Tamarack	2.1	>8	absent	absent	-2.1
White pine	46.8	1	47.8	1	+1.0
Yellow birch	3.6	7	absent	absent	-3.6

[1]Quadrants of point-quarter sampling in which no tree was recorded due to location > 30 m from the sampling point ("missing" trees) have been omitted in the ranking in this table.

the current stump prairie than in places immediately adjacent to it, where the current stands were sampled. Therefore, this apparent change in forest composition may be an artifact of different geographical areas of sampling (i.e., six survey townships vs. stands immediately adjacent to the stump prairie border) rather than a real shift away from sugar maple and yellow birch in the sampled stands. The fact that both sugar maple and yellow birch are common today in some nearby upland forests tends to support this interpretation.

In areas that are today stump prairie, white pine was the species with the highest modified importance value (46.8) in the pre-disturbance forest; it remains the predominant species in the stump prairie stands (importance value = 47.8; Table 10). Hemlock and beech, the second- and third-ranked species from the GLO notes, were not encountered in any stump prairie sampled stand. The next-ranked species from the GLO notes, red pine and spruce, have relatively low importance values in the present sampled stands (red pine, 2.3; black spruce, 2.5; white spruce, 1.5). Red maple, however, has become proportionately more important following the disturbance, and is now the second-ranked tree species in terms of importance value. Other common trees of the stump prairie today, such as black cherry and juneberry, were not recorded by the surveyors.

The absence of hemlock and beech from the stump prairie is probably due to the reproduction requirements of the species. Hemlock is characteristic of cool, moist, highly acid sites and typically requires moist, cool, shady sites to establish (Barnes and Wagner 1981). If the hemlock trees in the stump prairie areas were killed by fires or logging at the end of the last century, the heat and drought that prevail on the deforested stump prairie might have prevented its re-establishment. Likewise, mature beech trees are highly susceptible to fire, and therefore were unlikely to have survived the fires which followed logging. Beech seeds are produced in large numbers only at infrequent intervals, and much beech reproduction is from root sprouts (Curtis 1971). These

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characteristics make re-establishment following the logging and burning which took place on the stump prairie unlikely.

Red maple has increased in prominence in both the forested and stump prairie regions (Table 10). In forested areas, it ranked sixth in the pre-disturbance forest, but today it ranks first (Table 10). In stump prairie stands today, it ranks second only to white pine (Table 10). The increase in prominence is probably due to the species' ability to grow in a wide range of site conditions (Barnes and Wagner 1981) and to the fact that it sprouts vigorously following injury by fire, cutting, or browsing (Walters and Yawney 1990). Thus those few trees that were present in the pre-disturbance forest were able to reproduce following logging and fires, and survive the harsh, dry conditions that prevailed on the post-disturbance stump prairie. White birch has also increased in prominence in the forested sites, though not to the degree of red maple (Table 10), probably because it, too, can regenerate from sprouts following cutting or fire (Safford et al. 1990).

In stump prairie stands, jack pine has increased in prominence (Table 10). Jack pine is a fire-dependent species and is adapted to reproducing following fires (Barnes and Wagner 1981), so the increase in prominence may be due to increased jack pine reproduction following late nineteenth century fires. The increase in prominence may also be associated with widespread planting of jack pine in the study area. Jack pine appeared to be more common in those stands that were near jack pine plantations, and some of the jack pine trees encountered in sampling may be descended from the planted trees.

Summary

In summary, evidence from the General Land Office survey notes suggests that considerably different forest types existed in the areas that have reforested after the logging of the last century, when compared to those that have remained in stumps. In particular, the forests in the stump prairie areas were predominantly pine forests, with major components of white and red pine. Hemlock and hardwood species did exist in these areas, but in comparison to their role in the surrounding forest types they were relatively unimportant. Especially notable is the near lack of any record of sugar maple trees in the areas that today remain stump prairies, and its prevalence in the GLO notes in areas currently mapped as upland forests. Forests in current upland forest areas were primarily beech-sugar maple-yellow birch forests, but also contained some white pine and hemlock. Today sugar maple and yellow birch are absent from the forested stands immediately adjacent to the stump prairie, and the forests are predominantly red maple-white pine-beech forests. Red maple has especially increased in prominence in these forests.

The pre-disturbance forest of the stump prairie regions does not appear to have been a particularly impoverished forest community, or a forest grading towards a savanna. It was dominated by large white pine trees, with a sizable admixture of hemlock and hardwoods such as beech and yellow birch. Rather, the contrast between the forests of the stump prairie and upland forest regions appears to have been more of species composition than of density or basal area per ha (dominance). Today the stump prairie stands have only scattered trees, and the most common of those include white pine, red maple, and black cherry. White pine has continued to be the first ranked tree in the stump prairie stands.

Due to the high proportion of white pine in the forest, the stump prairie areas were the most attractive sites for lumbering in the late nineteenth century. Where white pine was most common, the true "pineries", logging and subsequent fires had preferentially removed the forest vegetation by the end of the nineteenth century, leaving large tracts of bare land "where the ground is sparsely covered with weeds and grass, sweet fern, and a few scattering runty bushes of scrub oak, aspen, and white birch" (Roth 1898, p. 13). In the hardwood-dominated areas, however, the removal of scattered giant pines was less noticeable, and, according to contemporary accounts, fire damage to the forest was minimal except where it bordered on pine slashings (Roth 1898, p. 12).

Factor 2: Substrate and soil properties

An understanding of soil and its parent material is important in a study of an ecosystem, because the soil and the vegetation are interrelated components of a single system, and thus influence each other. This chapter is divided into two parts. In the first, soil and substrate properties and their relationship to, and possible influences on, the spatial patterns of forest and stump prairie in the study area are discussed. The second part examines the soil data, including information from both the solid phase of the soil and from buried resin bags, for insight into the active processes of soil development in the forest and stump prairie areas.

Substrate, soil, and current forest patterns

Parent material properties and forest patterns

Although the stump prairie/forest boundary does not follow any obvious topographic or geomorphological boundary, it is possible that the stump prairie and forest regions have different depositional and sedimentary histories, and, therefore, that the parent materials of the soils are different. Because of the extremely sandy textures of the soils in the study area, slight variations in parent material silt and clay content could affect forest regeneration by controlling water holding capacity. This section will discuss the relationship between the texture of the parent materials and spatial patterns of forest regeneration.

C horizon particle size distribution. A comparison of soil C horizon particle size distributions between pedons in the forested region and those under stump prairie shows that there is no significant difference between the two groups in terms of sand, silt, or clay content (Table 11). The C horizons of all sampled pedons are almost devoid of silt and clay.

Table 11. Uppermost C horizon particle size distributions for sampled pedons.

Pedon	Sand 2.0-0.05 mm	Silt 0.05-0.002 mm	Clay <0.002 mm	VCS 2.0-1.0 mm	CS 1.0-0.5 mm	MS 0.5-0.25 mm	FS 0.25-0.1 mm	VFS 0.1-0.05 mm
	------% of fine earth------			------------% of sand fraction------------				
FOR-1	99.6	0.2	0.2	1.7	16.7	61.4	19.3	0.8
FOR-2	99.5	0.1	0.4	3.5	15.7	70.1	10.3	0.3
FOR-3	99.7	0.1	0.2	0.2	4.4	71.5	23.3	0.7
FOR-4	99.5	0.3	0.2	0.4	8.5	51.0	38.4	1.8
FOR-5	99.6	0.1	0.2	0.2	10.7	77.3	11.6	0.3
FOR-6	98.0	1.7	0.3	5.2	16.2	48.8	27.1	2.7
FOR-7	99.6	0.2	0.2	1.2	20.4	68.4	9.7	0.3
FOR-8	99.5	0.3	0.2	2.7	18.3	61.5	16.9	0.7
FOR-9	99.6	0.2	0.2	0.7	12.7	60.1	25.5	1.0
Mean[1]	99.4	0.4	0.2	1.7	13.7	63.3	20.2	0.9
SAV-1	99.3	0.2	0.5	2.1	7.9	51.1	37.3	1.6
SAV-2	99.8	0.1	0.1	0.2	5.1	81.1	13.3	0.3
SAV-3	99.6	0.1	0.4	0.0	0.3	37.9	60.3	1.4
SAV-4	99.8	0.1	0.1	0.8	14.4	77.2	7.4	0.2
SAV-5	99.8	0.1	0.1	1.8	5.7	59.7	31.2	1.6
SAV-6	99.5	0.3	0.2	0.0	1.1	55.4	42.0	1.4
SAV-7	99.7	0.2	0.1	2.0	11.6	64.8	21.2	0.4
SAV-8	99.4	0.2	0.4	9.3	38.2	43.4	8.6	0.5
Mean[1]	99.6	0.2	0.2	2.0	10.5	58.8	27.7	0.9

[1]Means are not significantly different at $p < 0.05$ (Kolmogorov-Smirnov) for all columns.

In many pedons, faint banding or stratification of sands was observed below the solum (Table 12). Clay content increases, as determined in the field, were minimal in most of the bands. Many bands were apparently sedimentary concentrations of darker colored or iron-rich sands that were continous around the entire pit. Most were too thin for separate sampling or color determination. Bulk samples from the affected depths show no clay content increase over the upper C horizon (Table 22 in Appendix A). Similar banding and faint lamellae occurred in both forested and stump prairie pedons.

Three forested pedons (FOR-6, FOR-7, FOR-9) do contain sedimentary lenses of finer, pinker sands. In the case of FOR-6, an increase in roots was observed in the stratum (sampled as the 2C horizon). The stratum contains little clay, but almost 9% silt, as well as more fine sand than the surrounding horizons (Table 22 in Appendix A). The pinker stratum in FOR-7 has more clay (2.9%) and silt (2.0%) than the adjacent C horizon (clay 0.2%; silt, 0.2%; Table 22 in Appendix A). In FOR-9, the stratum occurs well below the solum (270 - 290 cm), and has a notable increase in silt, fine sand, and very fine sand over adjacent horizons (Table 22 in Appendix A). These sedimentary strata may have had an effect on tree growth by increasing the soil's water holding capacity, especially in pedon FOR-6 where tree roots were observed in the stratum. Nonpedogenic textural bands have been shown to affect forest composition (Host et al. 1988; Host and Pregitzer 1992) and site index (Hannah and Zahner 1970), especially when they occur within 2 m of the soil surface. Nevertheless, not all forest pedons examined for the present study have such sedimentary strata within the upper three m, and some stump prairie pedons do. Thus, deep textural bands and finer-textured sedimentary strata do not appear to be directly related to the recovery of the forest from the nineteenth century logging disturbances.

Solum particle size distribution. For all pedons, weighted solum means show that more than 96% of the fine earth fraction falls into the sand size class (Table 13). This percentage is slightly lower than that of the C horizon alone (98%, Table 11), probably

Table 12. Banding and lamellae encountered below the solum in sampled pedons.

Pedon	Depth	Description
	cm	
FOR-1	140 - 200	Few lamellae, 1 mm thick, 7.5 YR 6/4.
FOR-2	200	Few very fine lamellae.
FOR-3	74 - 150	Thin dark strata, some orange strata, up to 2 mm thick, 1 - 2 cm apart.
FOR-4		none
FOR-5		none
FOR-6	98-108	Sedimentary band 10 cm thick, finer sand, some field-detectable clay increase, 7.5 YR 5/4.
FOR-6	108-130	Few reddish lamellae.
FOR-7	115 - 120	Single continuous stratum of 5 YR 5/4 sand, no increase in clay or field-detectable change in sand texture, sampled separately.
FOR-7	150 - 200	Few possible lamellae.
FOR-8		none
FOR-9	90-120	Lamellae 7.5 YR 4/4, 2 mm thick, 10 cm apart. Some thin black strata.
FOR-9	270 - 290	Silty stratum, sampled separately.
SAV-1	180	Few fine lamellae around a gravel lens.
SAV-2	260	Few very faint lamellae.
SAV-3	90 - 180	Continuous and level bands 7.5 YR 5/6, < 1 mm thick, 2 cm apart, very little clay.
SAV-4	120 - 180	Very thin bands, some orange, some black, no clay increase. Two thicker orange strata 2 mm thick, 12 cm apart.
SAV-5	120	Single 4 mm thick band of orangish sand.
SAV-6	110 - 230	Very thin reddish and black bands.
SAV-7	170 - 250	Possible few fine lamellae.
SAV-8		none

Table 13. Solum weighted particle size distributions for sampled pedons.

Pedon	Sand 2.0-0.05 mm	Silt 0.05-0.002 mm	Clay <0.002 mm	VCS 2.0-1.0 mm	CS 1.0-0.5 mm	MS 0.5-0.25 mm	FS 0.25-0.1 mm	VFS 0.1-0.05 mm
	------% of fine earth------			---------------% of sand fraction---------------				
FOR-1	97.6	1.4	1.0	2.9	14.0	56.3	25.4	1.3
FOR-2	97.6	1.5	0.9	1.8	10.3	62.3	24.6	0.9
FOR-3	97.8	1.3	0.9	0.7	5.2	55.5	36.3	2.3
FOR-4	97.2	1.5	1.3	1.4	9.8	62.4	25.6	0.8
FOR-5	96.8	1.8	1.4	1.5	12.2	66.0	19.6	0.7
FOR-6	95.5	3.2	1.3	1.4	10.4	55.0	29.2	4.0
FOR-7	97.8	1.3	0.9	2.0	14.0	61.3	22.1	0.7
FOR-8	96.4	2.1	1.5	7.7	24.0	52.0	15.2	1.1
FOR-9	96.7	2.0	1.3	0.6	5.7	50.9	40.5	2.3
Mean[1]	97.0	1.8	1.2	2.2	11.7	58.0	26.5	1.6
SAV-1	97.6	1.5	0.9	3.1	16.6	54.9	24.2	1.1
SAV-2	98.3	1.0	0.7	3.7	16.6	58.8	20.2	0.7
SAV-3	96.9	2.0	1.1	1.1	5.8	57.6	33.1	2.3
SAV-4	97.4	1.7	0.9	1.3	9.6	50.6	36.6	1.9
SAV-5	97.0	2.0	1.0	3.4	8.8	52.0	33.8	2.0
SAV-6	97.7	1.3	1.0	0.5	3.8	59.1	35.7	0.9
SAV-7	97.6	1.5	0.9	2.0	17.3	57.1	22.7	0.9
SAV-8	97.0	1.7	1.3	1.7	11.6	60.3	25.3	1.1
Mean[1]	97.5	1.6	1.0	2.1	11.3	56.3	29.0	1.4

[1]Means are not significantly different at $p < 0.05$ (Kolmogorov-Smirnov) for all columns.

due to weathering and soil development processes. Means for all solum weighted particle size fractions are not significantly different between forested and stump prairie pedons (Table 13). Mean clay content is slightly higher in forested pedons than in stump prairie pedons, but the difference is not significant at $p < 0.05$ (Kolmogorov-Smirnov). This slight difference is due to a small increase in clay in the B horizon, possibly illuvial in nature, as discussed below (p. 112). Therefore, while the parent materials of forested soils and stump prairie soils show no textural differences, soil development processes may have caused a slight elevation of what was initially a very low clay content in the forested soils. The increased clay content, though small, may increase the water holding capacity and CEC of the soil.

Sand fraction distribution. For most horizons in both forest and stump prairie soils, the sand fraction distribution is maximal in the medium sand size class, but in a few cases it falls instead in the fine sand size class (Table 22 in Appendix A). Although the dominant sand fraction, the percent medium sand can vary erratically within a single pedon (Figure 28), as can the ratio of coarse to fine sands (Figure 29). No statistically significant difference between forested and stump prairie soils exists for any sand size fraction (Table 13), nor for the ratios between the coarser and finer sand fractions, either in the C horizon or weighted for the solum as a whole (Table 14). Within each group, however, there is much variability in these ratios (Table 14).

The slight variations in sand fraction distributions within and between pedons are to be expected in an outwash environment where depositional energy can vary widely over time, leading to numerous variations in grain size both horizontally and vertically (Flint 1971, p. 186). In that sense these pedons can be seen as typical of soils developed in outwash sands (Schaetzl 1992). The lack of significant differences between the two groups suggests that differences in the sand size fractions are unlikely to have affected forest regeneration following nineteenth century logging.

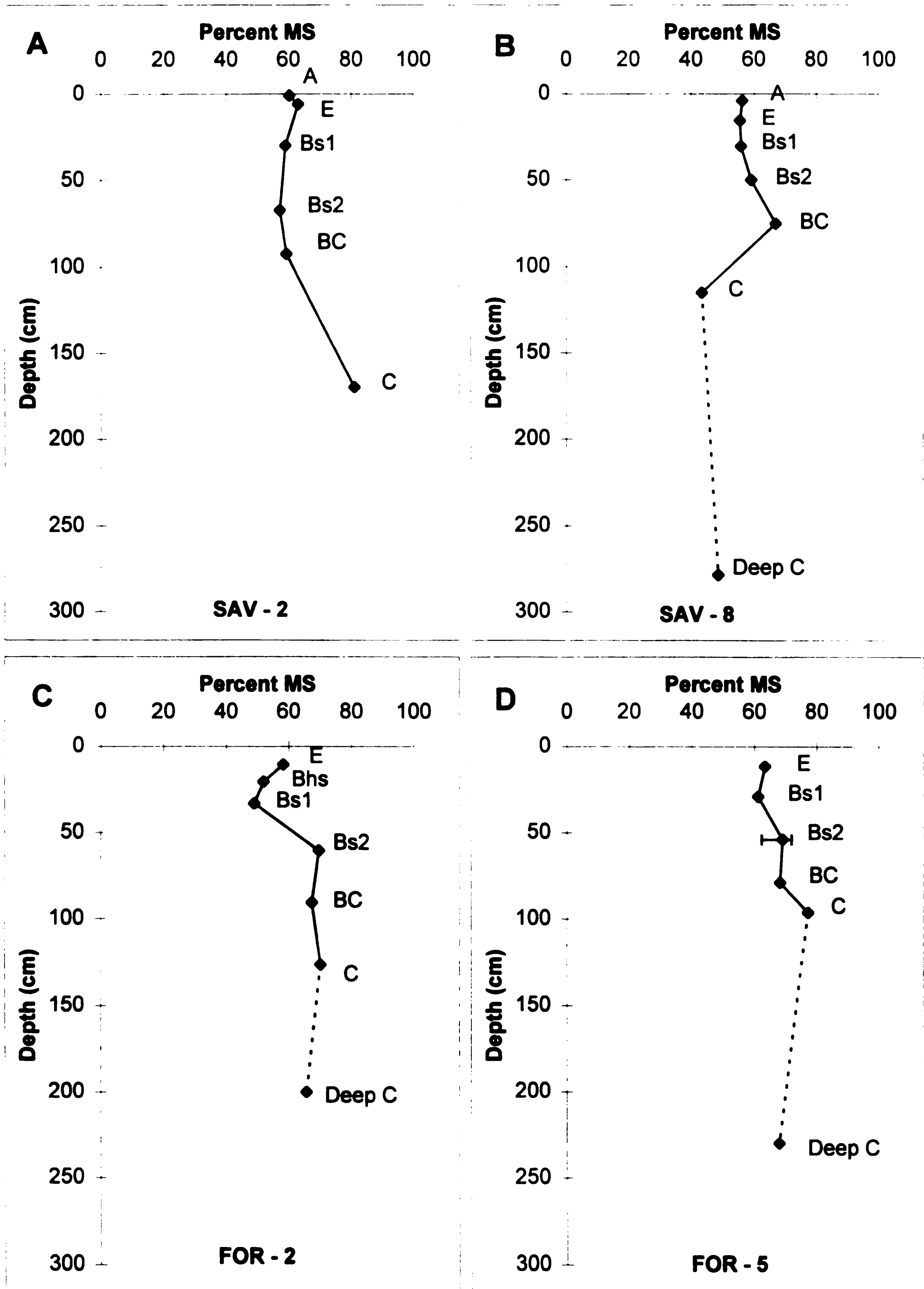

Figure 28. Percent medium sand by depth for four representative pedons. Error bars signify high and low values in horizons where ortstein was sampled separately.

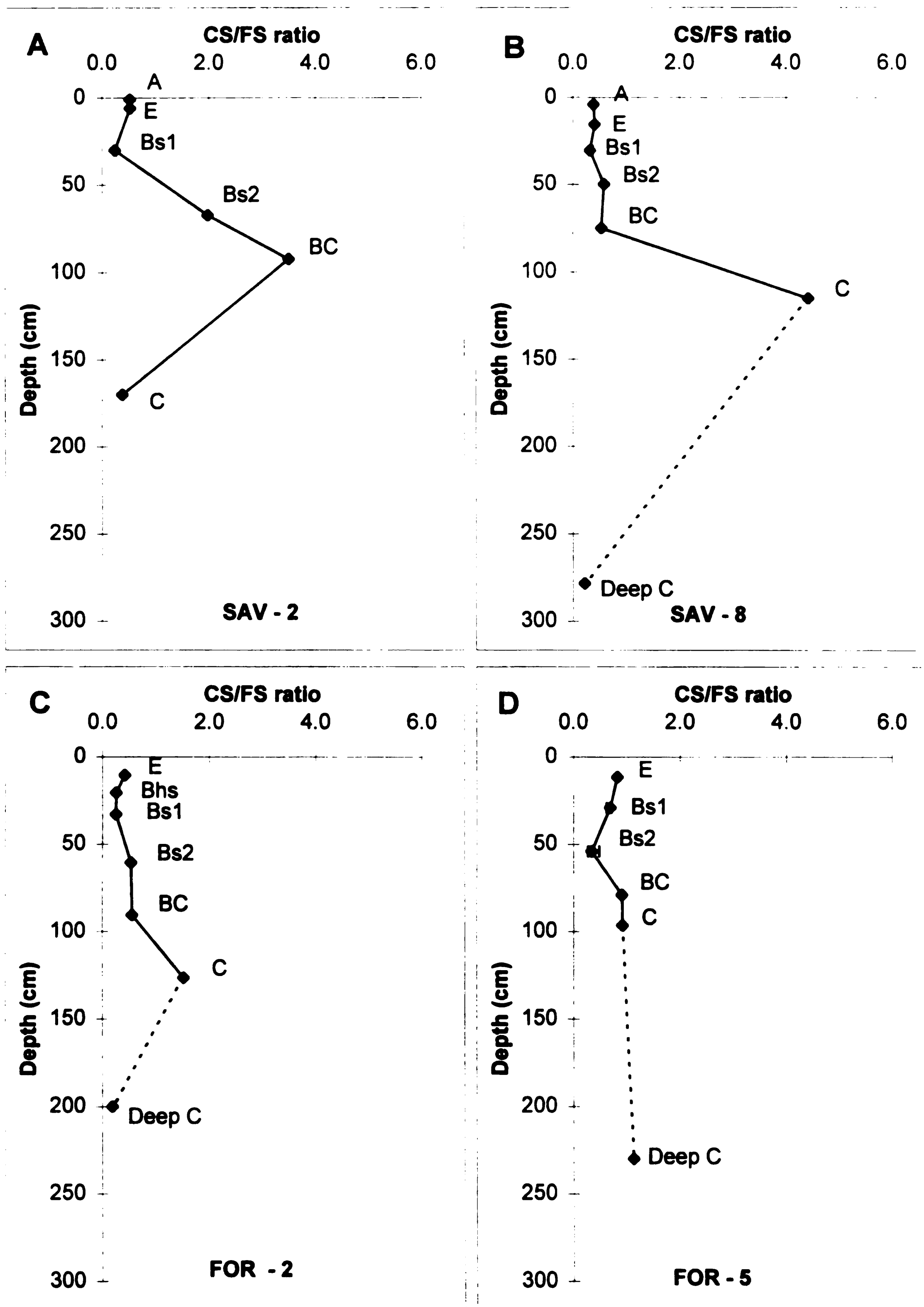

Figure 29. Ratio of the coarse sand fraction to the fine sand fraction by depth for four representative pedons. Error bars signify high and low values in horizons where ortstein was sampled separately.

Table 14. Ratios between coarse and fine sand fractions.

	C horizon		Solum weighted	
Pedon	CS/FS[1]	Coarser/ Finer[2]	CS/FS[1]	Coarser/ Finer[2]
FOR-1	0.86	3.96	0.55	2.75
FOR-2	1.52	8.37	0.42	2.92
FOR-3	0.19	3.18	0.14	1.59
FOR-4	0.22	1.49	0.38	2.79
FOR-5	0.92	7.45	0.62	3.93
FOR-6	0.60	2.35	0.36	2.01
FOR-7	2.10	9.01	0.63	3.39
FOR-8	1.08	4.69	1.58	5.14
FOR-9	0.50	2.77	0.14	1.34
Mean[3]	0.89	4.81	0.54	2.87
SAV-1	0.21	1.57	0.69	2.95
SAV-2	0.38	6.34	0.82	3.78
SAV-3	0.01	0.62	0.18	1.82
SAV-4	1.96	12.24	0.26	1.60
SAV-5	0.18	2.05	0.26	1.80
SAV-6	0.03	1.30	0.11	1.73
SAV-7	0.55	3.63	0.76	3.24
SAV-8	4.42	10.00	0.46	2.79
Mean[3]	0.97	4.72	0.44	2.46

[1]Ratio of coarse sand to fine sand fractions.
[2]Ratio of (very coarse sand + coarse sand + medium sand) to (fine sand + very fine sand).
[3]Means are not significantly different at $p < 0.05$ (Kolmogorov-Smirnov) for all columns.

Properties of soil development and forest patterns

B horizon properties affected by soil development processes show some statistically significant differences between the forest and stump prairie (Table 15). This section will discuss how the soil characteristics affected by developmental processes relate to the vegetation patterns in the Kingston Plains. The next section (p. 112) will consider the implications of these data to an understanding of soil development processes.

Differences between forest and stump prairie pedons in weighted B horizon means for OC, ODOE, Fe_o, Fe_p, and Al_d are statistically significant; means are higher in forest pedons (Table 15). Higher weighted B horizon means of OC and some forms of Fe and Al in forest soils suggest stronger spodic horizon development in these pedons due to illuvial accumulations of OC, Fe, and Al. Solum weighted means for ODOE, Fe_o, Fe_p, Al_d, and Al_p are also significantly different between forest and stump prairie (Table 16).

Pedons in the forested areas have more ortstein than pedons in the stump prairie (mean Bs1 ortstein content of forest pedons is 39.4%; of stump prairie pedons, 22.5%). Forest and stump prairie pedons have no statistically significant difference in OC and extractable Fe and Al contents of ortstein subsamples of Bs1 horizons (Table 17). Likewise, Bs1 *matrix* subsamples are not significantly different in OC, Fe, and Al contents between forest and stump prairie pedons (Table 17). Mean OC, ODOE, and Fe_p contents, however, are higher for all Bs1 ortstein subsamples than for Bs1 matrix subsamples; Si_o is higher in matrix than in the ortstein subsamples (Table 18). Although not statistically significant, means for other forms of Al and Fe are also higher in ortstein than the matrix subsamples, except for Al_o. Therefore, it appears that the higher weighted B horizon means for OC, Fe, and Al in the forested pedons over the stump prairie pedons may be primarily associated with higher ortstein content in the former.

Like OC, ODOE, and Fe_p, mean clay content is significantly higher in Bs1 ortstein subsamples than in matrix subsamples for all pedons (Table 18), but there is no

Table 15. B horizon weighted means for selected soil properties.

Pedon	Silt	Clay	pH 2:1 H_2O	ODOE	OC	Fe_d	Fe_o	Fe_p	Al_d	Al_o	Al_p
	------%------				-----------------------$g\ kg^{-1}$-----------------------						
FOR-1	1.3	1.3	4.9	0.131	3.4	1.1	0.7	0.4	1.0	1.7	1.0
FOR-2	1.4	1.3	5.0	0.122	3.3	1.5	0.9	0.5	1.3	2.0	1.1
FOR-3	1.2	1.3	4.7	0.228	5.5	1.3	0.8	0.6	1.2	1.7	1.1
FOR-4	1.7	1.9	4.6	0.276	6.9	2.0	1.4	0.7	1.6	2.8	1.3
FOR-5	1.5	1.7	4.8	0.191	6.1	1.6	1.1	0.7	1.5	2.1	1.8
FOR-6	3.0	1.3	5.1	0.133	4.5	1.8	1.1	0.4	1.3	2.5	1.3
FOR-7	1.0	1.4	5.2	0.197	5.4	1.5	1.0	0.6	1.3	2.7	1.5
FOR-8	2.0	2.0	5.1	0.252	7.3	1.9	1.2	0.8	1.8	2.9	2.1
FOR-9	2.2	1.8	4.9	0.239	6.7	1.7	1.0	0.7	1.5	2.2	1.5
Mean	1.7	1.6**	4.9*	0.196*	5.5**	1.6	1.0**	0.6**	1.4*	2.3	1.4
SAV-1	1.2	0.9	5.4	0.056	1.6	0.9	0.5	0.3	0.8	1.6	0.9
SAV-2	0.7	0.7	5.5	0.059	1.5	0.8	0.5	0.2	0.6	1.6	0.8
SAV-3	2.0	1.2	5.2	0.107	4.2	1.6	0.8	0.4	1.4	2.3	1.5
SAV-4	1.6	1.1	4.6	0.093	3.2	1.5	0.8	0.3	1.1	2.7	1.0
SAV-5	1.8	1.1	5.3	0.081	2.7	1.8	0.8	0.4	1.2	2.5	1.1
SAV-6	1.2	1.2	5.1	0.195	4.5	1.5	0.9	0.5	1.3	2.4	1.1
SAV-7	1.2	1.2	5.2	0.153	4.2	1.3	0.8	0.4	1.2	2.7	1.0
SAV-8	1.3	1.5	6.0	0.126	3.3	1.4	0.8	0.3	1.2	2.4	1.0
Mean	1.3	1.1**	5.3*	0.109*	3.1**	1.3	0.7**	0.3**	1.1*	2.3	1.1

*Differences in column means statistically significant at $p < 0.05$ (Kolmogorov-Smirnov).

**Differences in column means statistically significant at $p < 0.01$ (Kolmogorov-Smirnov). All other, unmarked columns, are not statistically significant.

Table 16. Solum weighted means for selected soil properties.

Pedon	Silt	Clay	pH 2:1 H_2O	ODOE	Organic C	Fe_d	Fe_o	Fe_p	Al_d	Al_o	Al_p
	------%------				------------------------g kg^{-1}------------------------						
FOR-1	1.4	1.0	4.9	0.081	2.5	0.9	0.4	0.3	0.7	1.2	0.7
FOR-2	1.5	0.9	5.0	0.082	2.9	1.1	0.6	0.3	0.9	1.4	0.8
FOR-3	1.3	0.9	4.9	0.140	4.0	0.9	0.5	0.4	0.7	1.1	0.8
FOR-4	1.5	1.3	4.9	0.173	4.7	1.3	0.9	0.5	1.1	1.9	0.9
FOR-5	1.8	1.4	4.9	0.123	5.2	1.1	0.7	0.5	1.0	1.4	1.2
FOR-6	3.2	1.3	5.1	0.087	5.9	1.3	0.8	0.3	0.8	1.6	0.9
FOR-7	1.3	0.9	5.3	0.106	3.7	0.9	0.6	0.4	0.8	1.5	0.9
FOR-8	2.1	1.5	5.1	0.166	5.5	1.4	0.8	0.5	1.2	2.0	1.5
FOR-9	2.0	1.3	5.0	0.148	4.7	1.2	0.6	0.5	1.0	1.5	1.0
Mean	1.8	1.2	5.0**	0.123**	4.3	1.1	0.7*	0.4**	0.9*	1.5	1.0*
SAV-1	1.5	0.9	5.4	0.043	3.9	0.7	0.4	0.2	0.6	1.2	0.7
SAV-2	1.0	0.7	5.5	0.046	2.4	0.7	0.4	0.2	0.5	1.3	0.7
SAV-3	2.0	1.1	5.2	0.067	5.0	1.0	0.5	0.3	0.9	1.5	1.0
SAV-4	1.7	0.9	4.9	0.058	3.8	1.1	0.5	0.2	0.7	1.7	0.7
SAV-5	2.0	1.0	5.2	0.047	4.5	1.1	0.5	0.2	0.7	1.5	0.7
SAV-6	1.3	1.0	5.1	0.129	4.3	1.0	0.6	0.4	0.9	1.7	0.9
SAV-7	1.5	0.9	5.3	0.084	4.5	0.8	0.4	0.2	0.7	1.5	0.7
SAV-8	1.7	1.3	5.7	0.062	4.8	0.8	0.4	0.2	0.6	1.2	0.6
Mean	1.6	1.0	5.3**	0.067**	4.1	0.9	0.5*	0.2**	0.7*	1.5	0.7*

*Differences in column means statistically significant at $p < 0.05$ (Kolmogorov-Smirnov).

**Differences in column means statistically significant at $p < 0.01$ (Kolmogorov-Smirnov). All other, unmarked columns, are not statistically significant.

Table 17. Means of Bs1 ortstein and Bs1 matrix subsamples for selected soil properties compared for forest and stump prairie soils.

	Ortstein		Matrix	
Soil property	Forest	Stump Prairie	Forest	Stump Prairie
pH (2:1 H_2O)	4.7*	5.2*	4.7*	5.2*
Clay %	2.7	2.6	2.0	1.7
Silt %	2.3	2.3	2.5	2.6
OC g kg^{-1}	9.6	9.1	6.1	4.4
ODOE	0.425	0.415	0.179*	0.128*
Fe_d g kg^{-1}	2.3	2.7	2.2	2.1
Fe_o g kg^{-1}	1.6	1.7	1.4	1.1
Fe_p g kg^{-1}	1.1	1.0	0.6	0.4
Al_d g kg^{-1}	2.1	2.7	2.0	1.7
Al_o g kg^{-1}	2.8	3.6	3.9	3.6
Al_p g kg^{-1}	1.9	1.4	1.8	1.5
Si_o g kg^{-1}	1.2	1.6	2.4	2.4
Fe_o/Fe_d	0.70	0.63	0.67*	0.54*
$(Fe_o-Fe_p)/Fe_p$	0.55	0.72	1.78	1.62
Al_o/Al_d	1.33	1.33	1.97	2.27
$(Al_o-Al_p)/Al_p$	0.49	0.57	1.14	1.46
Al_o-Al_p	0.87	1.24	2.11	2.13
$(Al_o-Al_p)/Si_o$	0.85	0.83	0.91	0.89
Fe_p/Al_p	0.29	0.22	0.14	0.14

*Means significantly different at $p < 0.05$ (Kolmogorov-Smirnov).

Table 18. Selected mean soil properties of Bs1 ortstein and Bs1 matrix subsamples for all the sampled pedons.

Soil Property	Ortstein	Matrix
pH (2:1 H_2O)	4.9	4.9
Clay %	2.6**	1.8**
Silt %	2.3	2.5
OC g kg^{-1}	9.4*	5.3*
ODOE	0.420*	0.155
Fe_d g kg^{-1}	2.5	2.2
Fe_o g kg^{-1}	1.7	1.3
Fe_p g kg^{-1}	1.0*	0.5
Al_d g kg^{-1}	2.4	1.9
Al_o g kg^{-1}	3.2	3.7
Al_p g kg^{-1}	1.7	2.1
Si_o g kg^{-1}	1.4*	2.4
Fe_o/Fe_d	0.67*	0.59
$(Fe_o-Fe_p)/Fe_p$	0.63	1.70**
Al_o/Al_d	1.33	2.10**
$(Al_o-Al_p)/Al_p$	0.52	1.29**
Al_o-Al_p	1.04	2.12**
$(Al_o-Al_p)/Si_o$	0.84	0.90
Fe_p/Al_p	0.26**	0.14

*Means significantly different at $p < 0.05$ (Kolmogorov-Smirnov).
**Means significantly different at $p < 0.01$ (Kolmogorov-Smirnov).

statistically significant difference between forest and stump prairie in Bs1 ortstein and matrix subsamples considered separately (Table 17). Silt content is essentially the same for both ortstein and matrix samples, and pH is significantly different between stump prairie and forest pedons, but not between ortstein and matrix subsamples (Tables 17 and 18). Thus, clay content, like OC, Fe, and Al contents, appears to be associated closely with the presence of ortstein, such that the differences in B horizon weighted mean clay content between forested and stump prairie pedons is primarily dependent on the differences in estimated ortstein content in the two soil groups. In contrast, differences in pH between the two groups do not depend on ortstein content, but are primarily associated with differences in current landcover type.

Illuvial accumulations of OC and free Fe in the spodic horizons of sandy soils are associated with increased water availability in the soil and with increased forest growth (Shetron 1974). In Michigan, strength of spodic horizon development has also been associated with forest type, with jack pine forests commonly found on weakly developed Udipsamments, and white pine and hardwood forests on the more strongly developed Spodosols (Mokma and Vance 1989). There are, therefore, two possible explanations for the association of greater illuvial accumulations of OC, Fe, and Al with currently forested areas:

(1) The greater water retention of more strongly developed soils was more favorable to tree regeneration and forest recovery following logging and, therefore, the patterns of soil development directly influenced patterns of forest regeneration.

(2) Patterns of spodic horizon development are related to differences in pre-logging forest. Areas that today are forested were richer in hardwoods than were current stump prairie areas (p. 62). The differences in pre-logging forest type may have influenced forest recovery patterns independently of spodic horizon development.

The present data do not allow me to choose between these two possible explanations; most likely both have interacted and played a part.

Transects

In order to complement information derived from the 17 sampled pedons, transects spanning the forest/stump prairie boundary were completed to provide further data on both ortstein content and soil B horizon color of the forest and stump prairie soils. Because ortstein content appears to be important to the relationship between soil characteristics and forest recovery, transects were thought to provide an additional means to evaluate whether the differences in ortstein content observed in the sampled pedons are representative, and whether the ortstein content changes near the forest/stump prairie boundary.

For all transects, ortstein content is greater on the forested side of the boundary than on the stump prairie side ($p < 0.001$, Kolmogorov-Smirnov; Figure 30). Similarly, the darkest, reddest B horizon color has lower (redder) Munsell hue and lower (darker) value and lower chroma on the forested sides of the transects (Kolmogorov-Smirnov $p < 0.001$; Figures 31 - 33). Increasing ortstein content in sandy soils is associated with increasing spodic horizon development (Wang et al. 1978; Barrett and Schaetzl 1992, 1993). In Spodosols, redder hue and darker value are indicative of stronger soil development (Schaetzl and Mokma 1988). Hue becomes redder and value and chroma decrease with increasing amorphous organo-metallic complexes (Mokma 1993), and with increasing soil age (Barrett and Schaetzl 1993) in Michigan Spodosols. In Ontario, redder hues and lower values are correlated with Fe accumulation, and lower chromas with OC accumulation (Evans and Cameron 1985).

The contrasts in ortstein content and color on either side of the forest/stump prairie boundary are most noticeable for transects 4 and 6, both of which are located along the southern border of the stump prairie area (Figure 30). Transect 4 is located in a region where the boundary has remained relatively stable between 1939 and 1986 (see p. 49), but the boundary near transect 6 has shifted, such that the current vegetation

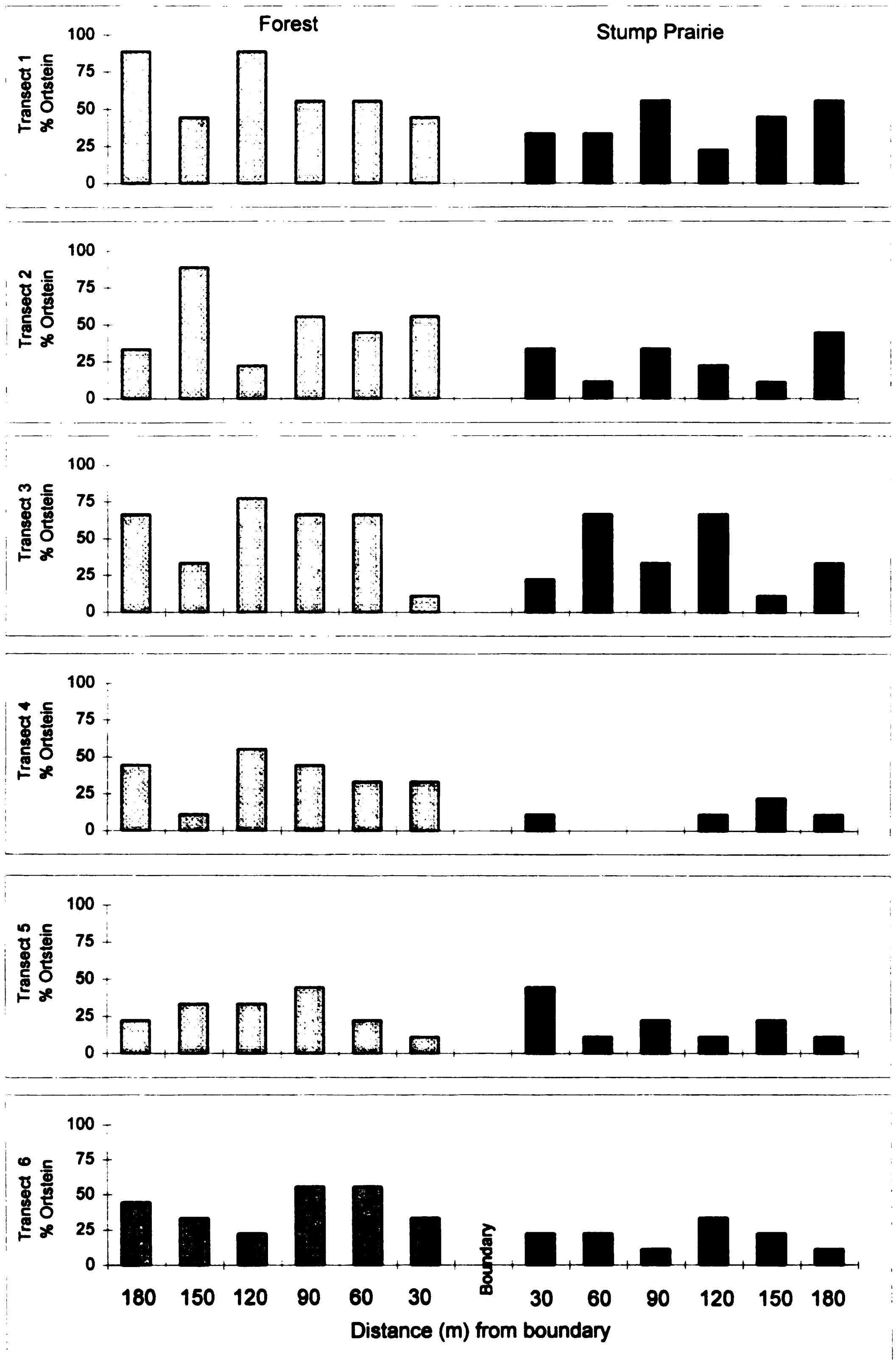

Figure 30. Percent of sample points in which ortstein was detected for each quadrat on forest/stump prairie transects.

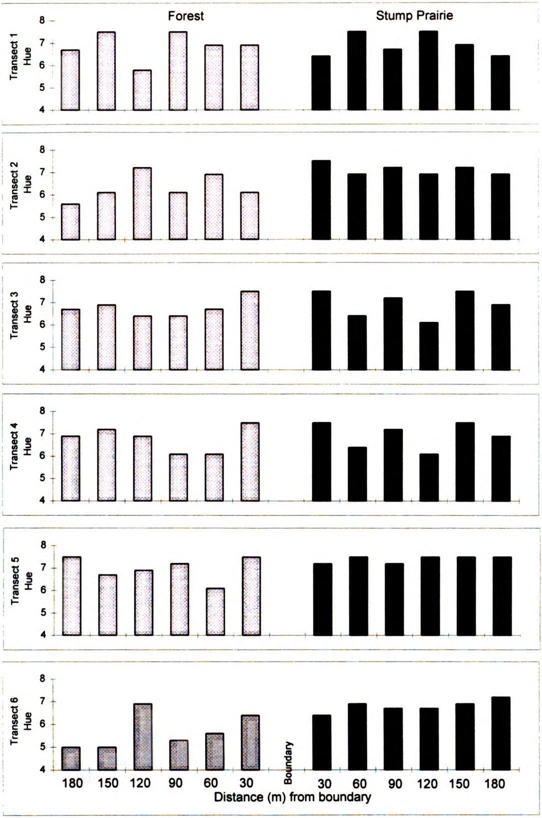

Figure 31. Arithmetic mean of recorded Munsell hue for the sample points in each quadrat on forest/stump prairie transects.

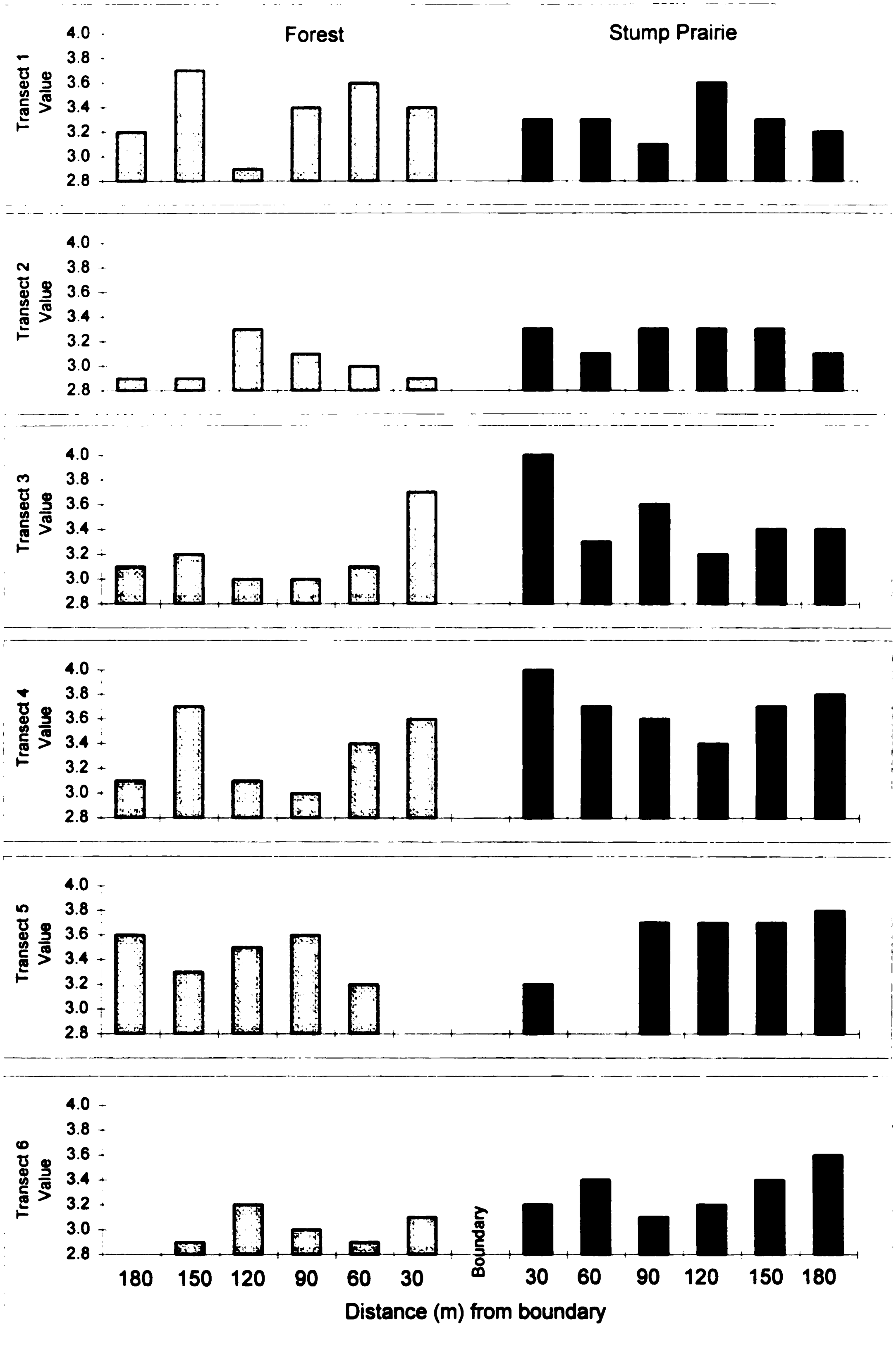

Figure 32. Arithmetic mean of recorded Munsell value for the sample points in each quadrat on forest/stump prairie transects.

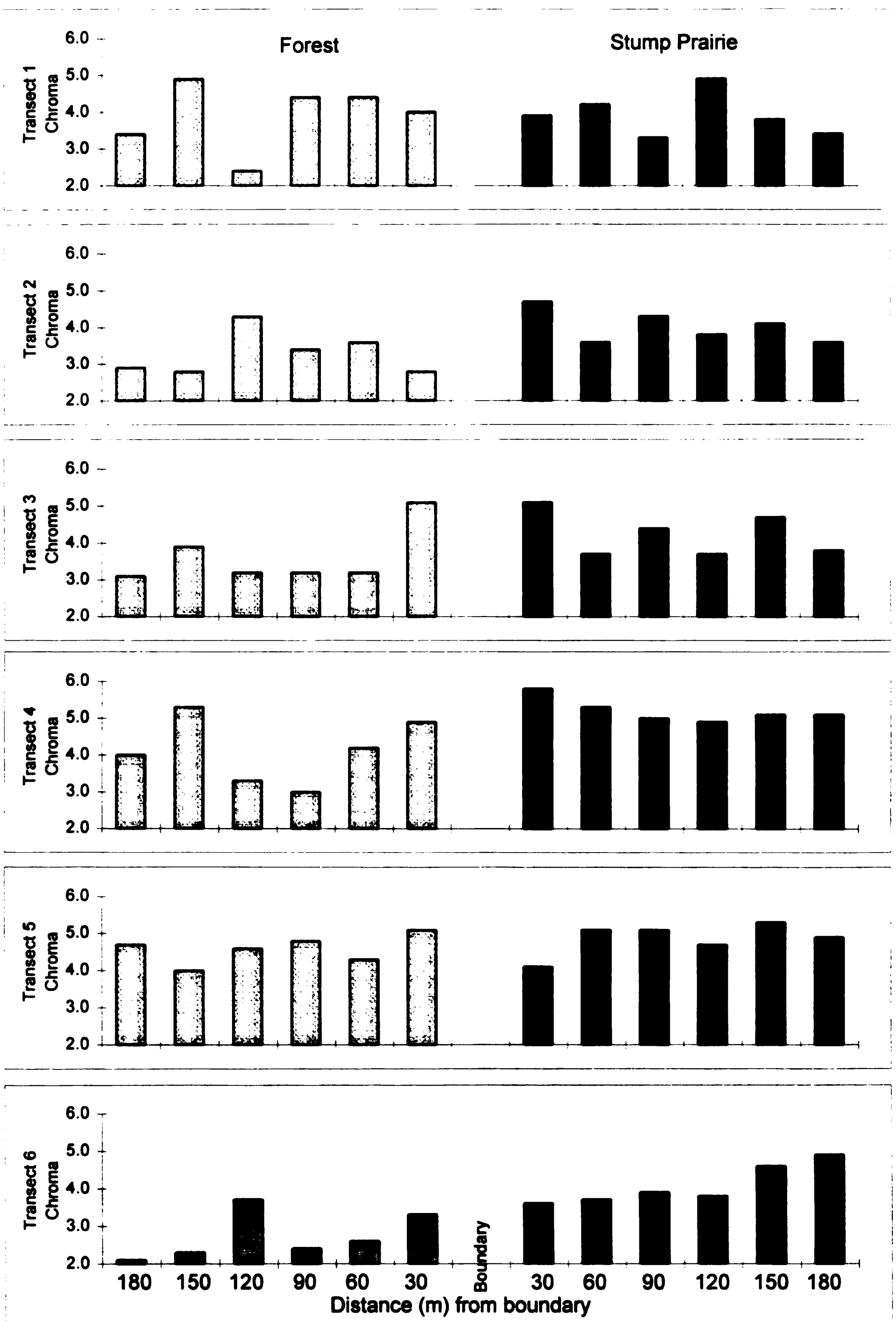

Figure 33. Arithmetic mean of recorded Munsell chroma for the sample points in each quadrat on forest/stump prairie transects.

boundary does not coincide precisely with the boundary as it was previously established. Nevertheless, based on the aerial photographic analysis of boundary stability (p. 44), it is probable that forest/stump prairie boundaries for all transects have not moved enough since the boundaries were established to be discerned by the 30 m spacing between transect samples.

Both soil color and ortstein content along these transects provide evidence that the soils in forested regions are currently more strongly developed than the soils of the stump prairie. Based on the transect data, it appears that the pedologic boundary between better developed and less developed soils approximately coincides spatially with the present biotic boundary.

Soil development processes

In this section, soil development processes in the study area are examined. First, soil morphological and chemical data will be discussed relative to soil forming processes. Then the issue of whether soil development processes are different between forested and stump prairie areas will be examined in light of both soil properties (solid phase data) and information on soil solution composition (active phase data).

<u>Clay, silt, and pH</u>

Clay depth plots demonstrate that, in both stump prairie and forest soils, a subsurface maximum in clay content is usually reached in the upper B horizon. Stump prairie pedons also often have a surface maximum in the A horizon (Figure 34). The clay content maximum in the upper B horizon, coupled with the association of ortstein subsamples from the Bs1 horizon with higher clay content (Table 18), suggests that the clay is being translocated into the B horizon from the surface horizons. Slight B horizon increases in clay, apparently illuvial in origin, have been observed in Spodosols and Spodosol-like soils in many areas (Brydon 1965; Wang and Rees 1980; Stanley and

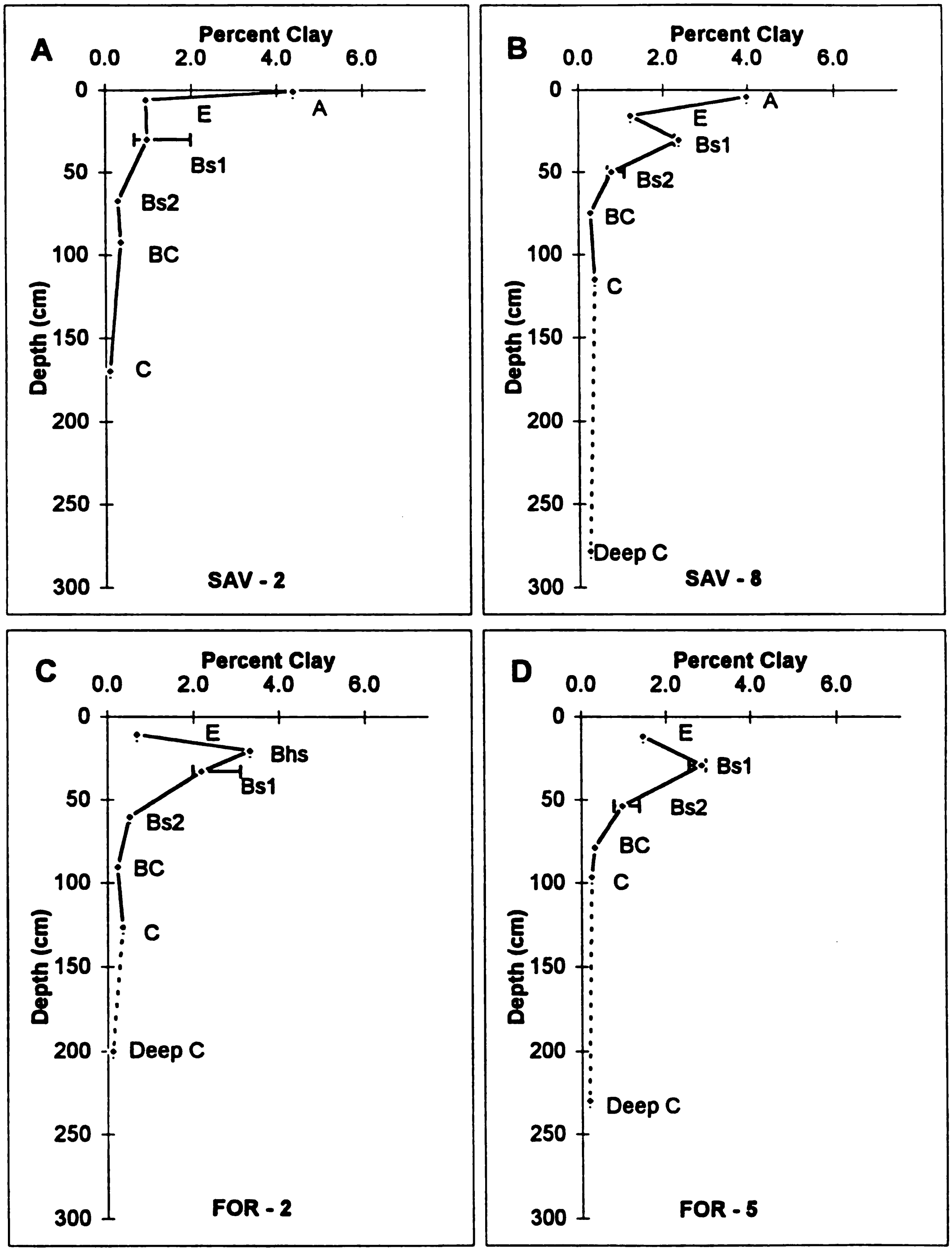

Figure 34. Percent clay by depth for four representative pedons. Error bars signify high and low values in horizons where ortstein was sampled separately.

Ciolkosz 1981). Franzmeier (1962), Nørnberg (1977), and Barrett and Schaetzl (1992) all reported slight clay increases with increasing soil age in B horizons of podzol chronosequences.

As is typical for many sandy soils undergoing podzolization, soils in both forest and stump prairie have a silt content maximum in the surface horizon (Figure 35). A similar silt maximum has been reported for Spodosol soils in many locations, and has been shown to increase with the age of the surface on which the soil is developing (Franzmeier 1962; Jauhiainen 1973; Nørnberg 1977; Barrett and Schaetzl 1992). Franzmeier (1962) and Nørnberg (1977; 1980) concluded that silt-rich surface horizons are the result of *in situ* physical weathering of sand-sized particles. An eolian origin for the silt cannot be ruled out in the present study, but surface weathering of sand-sized particles is the most likely explanation.

For both forest and stump prairie pedons, pH increases with depth (Figure 36). Higher acidity in the surface horizons, especially in the O horizons of forest pedons, is probably associated with the presence of organic acids. Acidity of the surface mineral horizons can also be associated with an increase in mineral weathering rates in these horizons.

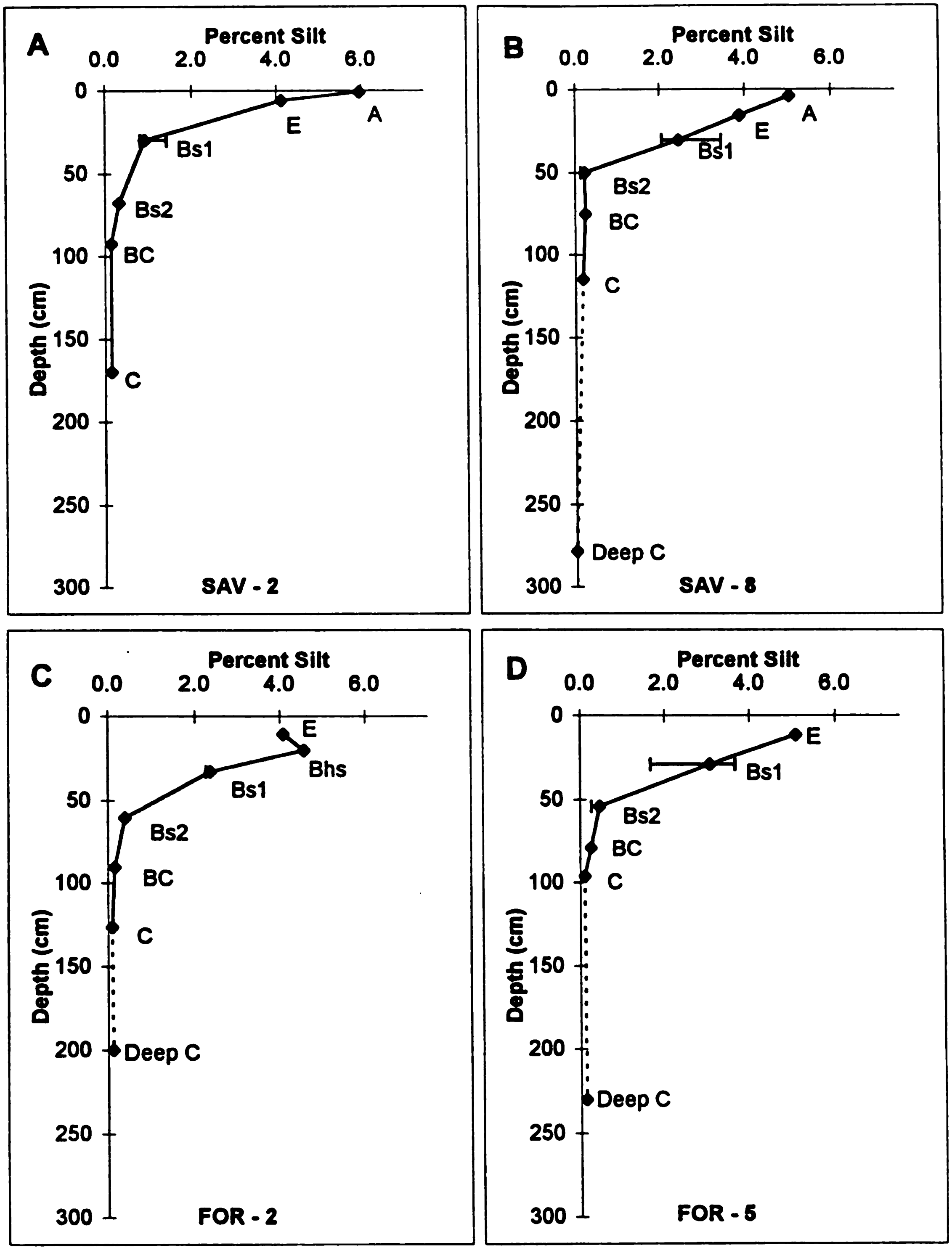

Figure 35. Percent silt by depth for four representative pedons. Error bars signify high and low values in horizons where ortstein was sampled separately.

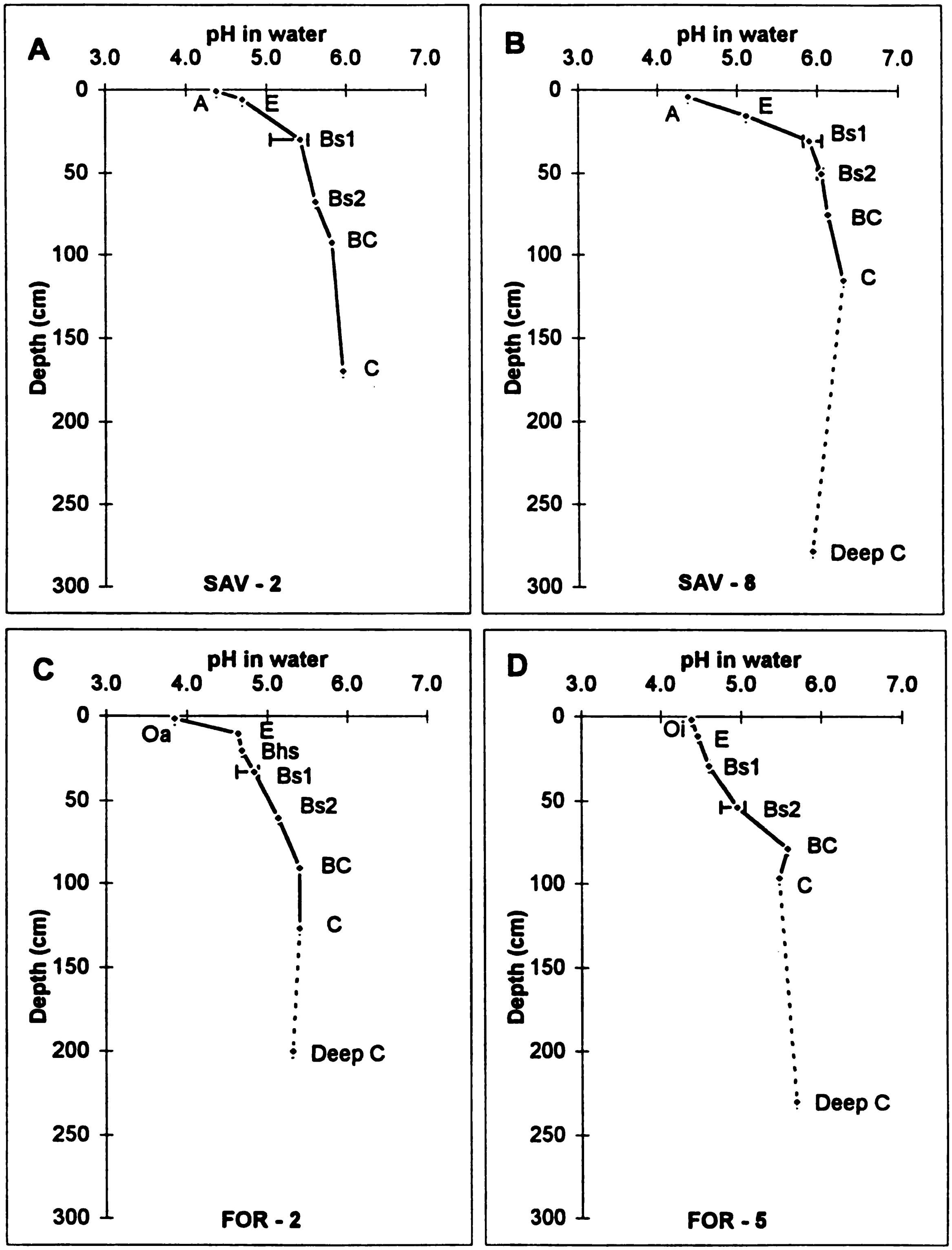

Figure 36. pH by depth for four representative pedons. Error bars signify high and low values in horizons where ortstein was sampled separately.

Fe, Al, and OC

In this section, I discuss evidence of podzolization processes in the solid phase of the sampled pedons, and whether any differences exist between pedons under forest vegetation and those in the stump prairie. The distribution within a pedon of forms of Fe, Al, and OC are indicators of podzolization. Solid phase soil properties, however, may provide evidence of processes that are no longer active in the soil. In the next section I will discuss evidence for whether podzolization processes are active in the study area.

In the sampled pedons, a large OC surface maximum is present, and also a smaller, subsurface maximum in the upper B horizon (Figure 37). The presence of some OC in the E horizon coupled with relatively low Bs1 horizon OC content masks the B horizon maximum in some stump prairie pedons (Figure 37A). The fulvic acid portion of organic matter has been theorized to be important in the podzolization process (De Coninck 1980). ODOE, which is related to fulvic acid content (Daly 1982), shows a large subsurface maximum in the uppermost B subhorizon of most pedons, with very low values in the E horizons of both stump prairie and forested pedons (Figure 38). Both OC and ODOE are higher in ortstein than in non-ortstein subsamples from the same horizon (Table 19).

All three forms of extractable Fe and Al usually have subsurface maxima in the B horizon (Figures 39 and 40). The maximum Fe content occurs in the uppermost B subhorizon, but the maximum content of extractable Al is in the Bs1 horizon for those pedons with Bhs horizons (Table 23, Appendix A), lower in the profile than the Fe maximum. Al maxima that occur deeper than the corresponding Fe maxima have been reported of podzols in the USA (Franzmeier and Whiteside 1963; Barrett and Schaetzl 1992), Japan (Mizota 1982), Finland (Koutaniemi et al. 1988), and Quebec (DeKimpe and Martel 1976; Kodama and Wang 1989). This phenomenon may occur because Al is more mobile than Fe, and thus initially deposited at greater depth (Mizota 1982), or

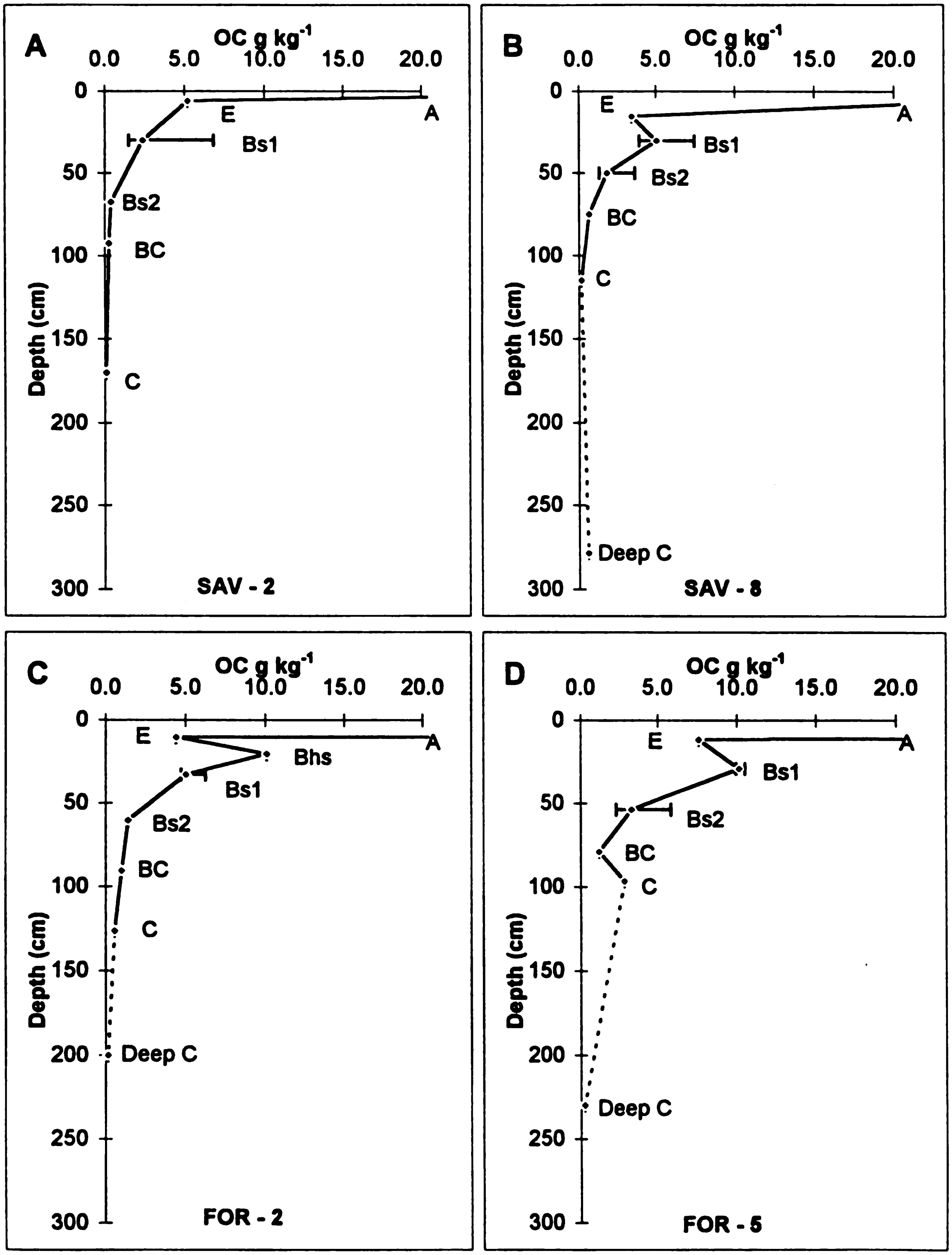

Figure 37. OC content by depth for four representative pedons. Error bars signify high and low values in horizons where ortstein was sampled separately.

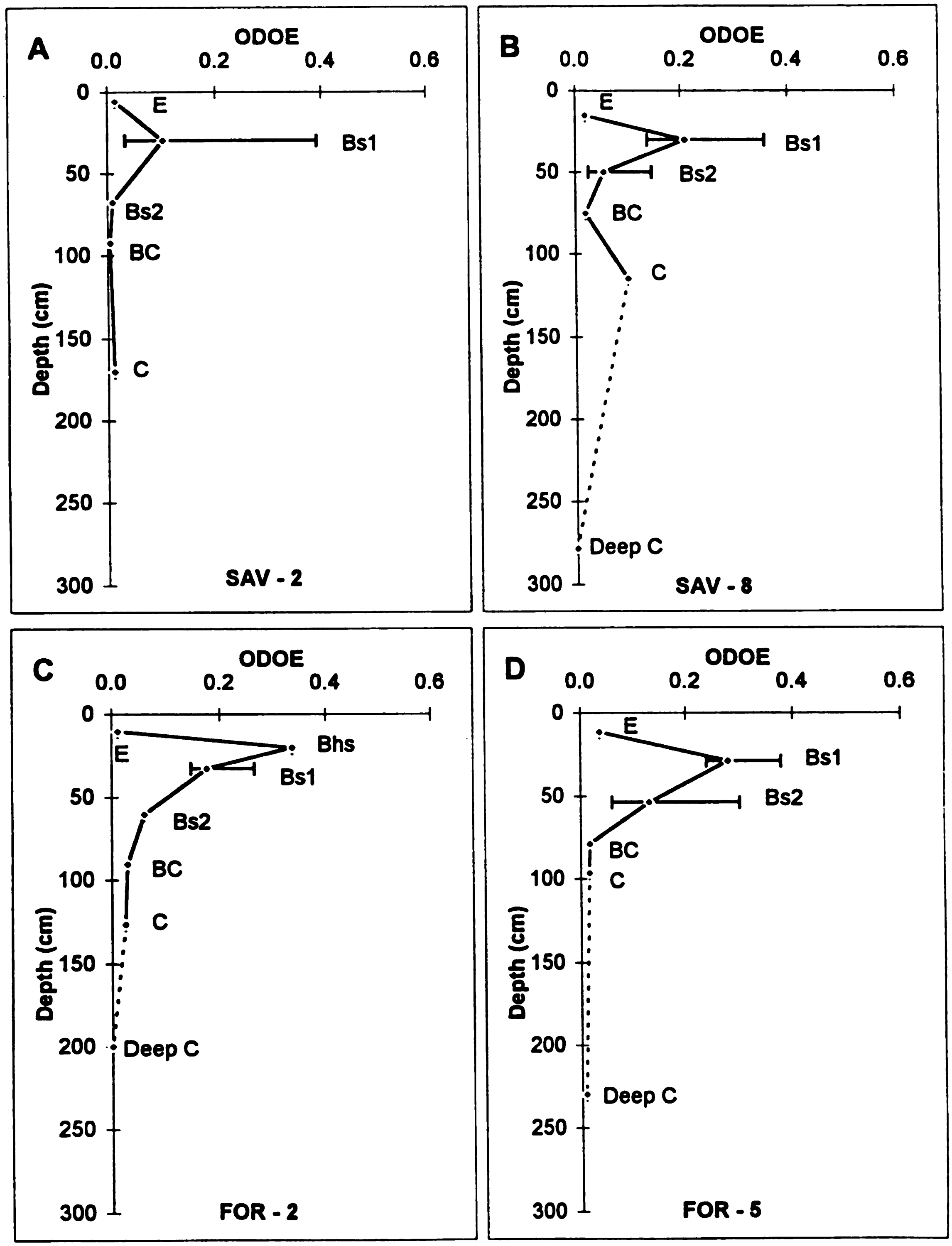

Figure 38. ODOE values by depth for four representative pedons. Error bars signify high and low values in horizons where ortstein was sampled separately.

Table 19. Summary of selected mean soil property relationships with regard to current landcover type and soil ortstein status.

	Mean is higher in:	
Soil property	Forest or Stump Prairie?	Orstein or Matrix?
pH 2:1 H_2O	Stump Prairie (B, S)[1]	--
Clay %	Forest (B, S)	Ortstein**
Silt %	Forest	Matrix
OC g kg^{-1}	Forest (B)	Ortstein*
ODOE	Forest (B, S)	Ortstein*
Fe_d g kg^{-1}	Forest	Ortstein
Fe_o g kg^{-1}	Forest (B, S)	Ortstein
Fe_p g kg^{-1}	Forest (B, S)	Ortstein
Al_d g kg^{-1}	Forest (B, S)	Ortstein
Al_o g kg^{-1}	Forest	Matrix
Al_p g kg^{-1}	Forest (B, S)	Matrix
Si_o g kg^{-1}	Stump Prairie	Matrix*
Fe_o/Fe_d	Forest	Ortstein*
$(Fe_o-Fe_p)/Fe_p$	Stump Prairie (B)	Matrix**
Al_o/Al_d	Stump Prairie (B, S)	Matrix**
$(Al_o-Al_p)/Al_p$	Stump Prairie (B, S)	Matrix**
Al_o-Al_p	--	Matrix**
$(Al_o-Al_p)/Si_o$	Stump Prairie	Matrix
Fe_p/Al_p	Forest (B, S)	Ortstein**

[1]"B" indicates a statistically significant difference ($p < 0.05$, Kolmogorov-Smirnov) in weighted B horizon values; "S" indicates a statistically significant difference ($p < 0.05$, Kolmogorov-Smirnov) in weighted solum values.

* $p < 0.05$, Kolmogorov-Smirnov

** $p < 0.01$, Kolmogorov,Smirnov

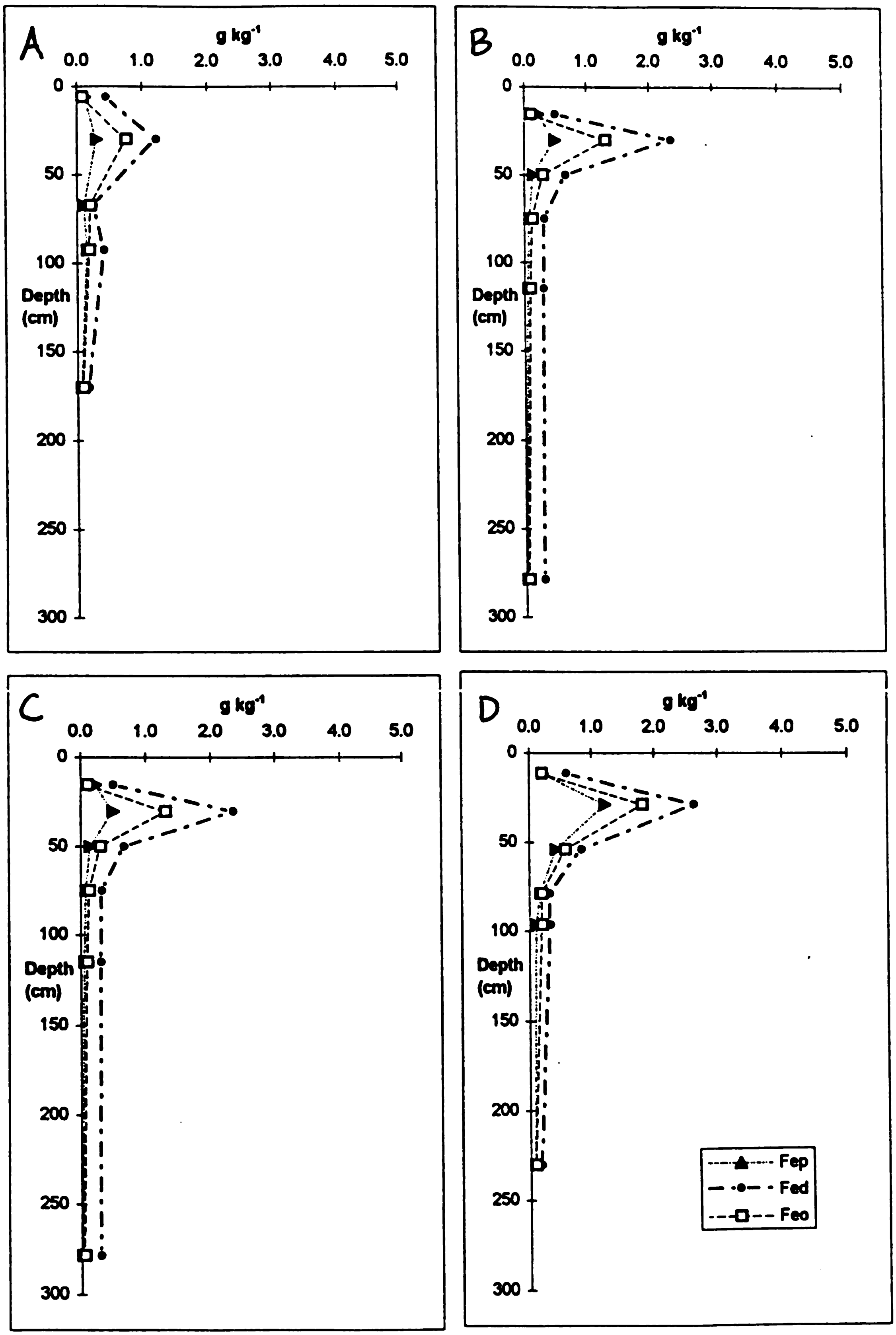

Figure 39. Extractable Fe content by depth for four representative pedons.

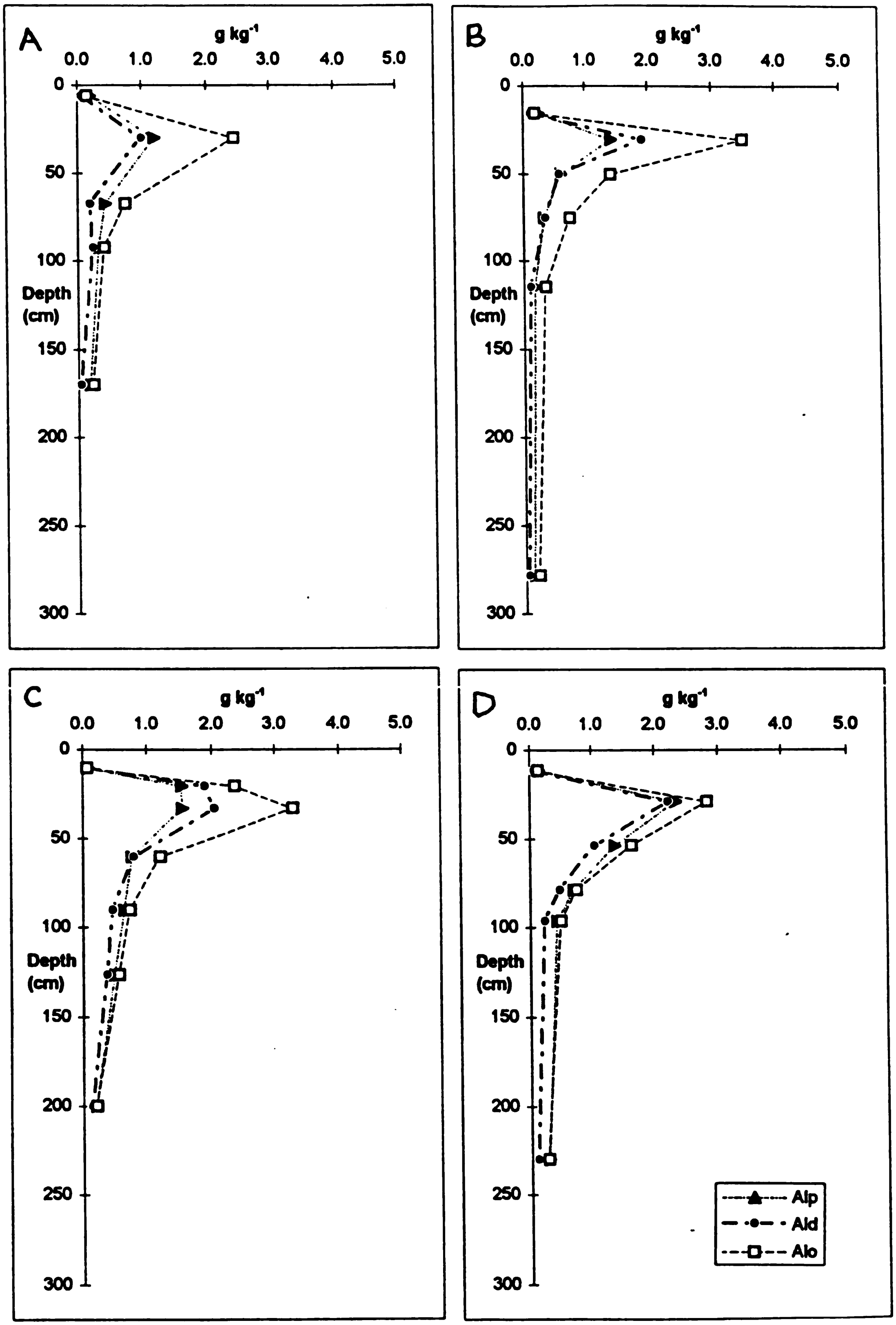

Figure 40. Extractable Al content by depth for four representative pedons.

because the Al is preferentially remobilized after deposition and translocated still deeper (DeKimpe and Martel 1976; Farmer 1984). The depth distribution of Si_o is similar to that for Al (Figure 41).

Comparisons of extractable forms of Fe and Al can provide insight into the nature of the Fe and Al in soils. Fe_p is considered to represent organically-bound, amorphous forms of Fe; Fe_o represents amorphous Fe, both organic and inorganic; and Fe_d is "free" Fe, both amorphous and crystalline (McKeague and Day 1966; McKeague 1978). Interpretation of extractable Al is analogous, but the exact nature of Al_d is not well understood, and Al_o content generally exceeds Al_d in the same horizon (McKeague and Day 1966; McKeague et al. 1971; Parfitt and Childs 1988). Farmer et al. (1983) have shown that, while acid ammonium oxalate is an effective extractant for poorly ordered phases of Fe and Al, only an ill-defined fraction of any allophane-imogolite complex in the soil is extracted by DCB. Oxalate-soluble Si (Si_o) is considered to represent amorphous Si forms such as are present in allophanes (Farmer et al. 1983; Parfitt and Kimble 1989).

The relative crystallinity of free iron oxides can be measured by the "activity ratio" or Fe_o/Fe_d (McKeague and Day 1966; Blume and Schwertmann 1969). Within a given profile, a lower Fe_o/Fe_d ratio indicates a larger proportion of crystalline Fe oxide compounds and, therefore, lower Fe mobility in the soil (Singer et al. 1978). The depth distribution of Fe_o/Fe_d in the sampled pedons usually shows a maximum in the upper B horizon (Figure 42), suggesting that the extractable Fe is, or recently has been, most mobile in the upper B horizon. In the E and C horizons, extractable Fe is in a relatively crystalline form. This finding differs from that of Singer et al. (1978), who reported that the minimum Fe_o/Fe_d value was in the upper B horizon of a Spodosol in the Cascades, possibly due to Fe recrystallization and retention in the B horizon. Within the Bs1 horizon, a statistically greater Fe_o/Fe_d ratio occurs in ortstein over non-ortstein

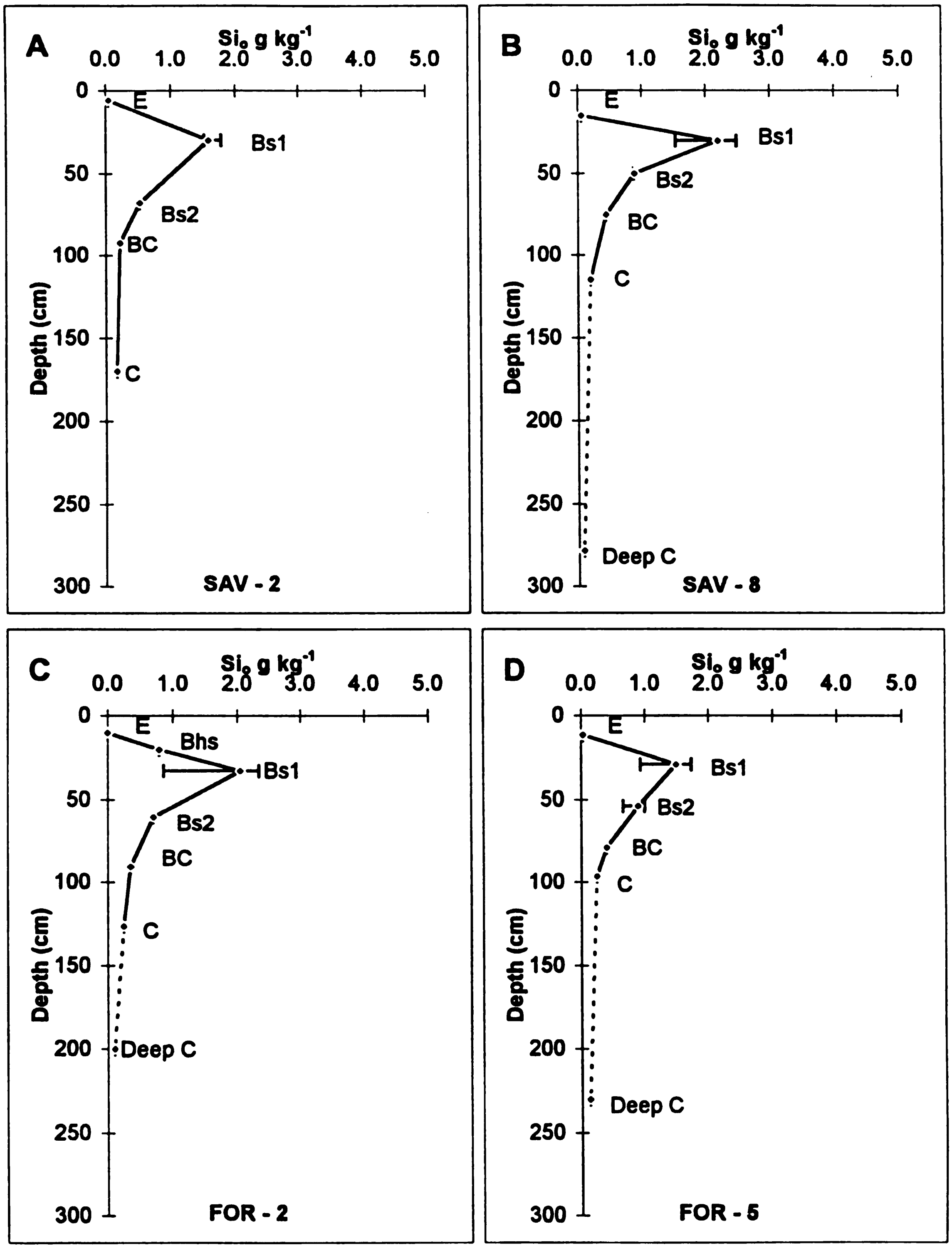

Figure 41. Si_o content by depth for four representative pedons. Error bars signify high and low values in horizons where ortstein was sampled separately.

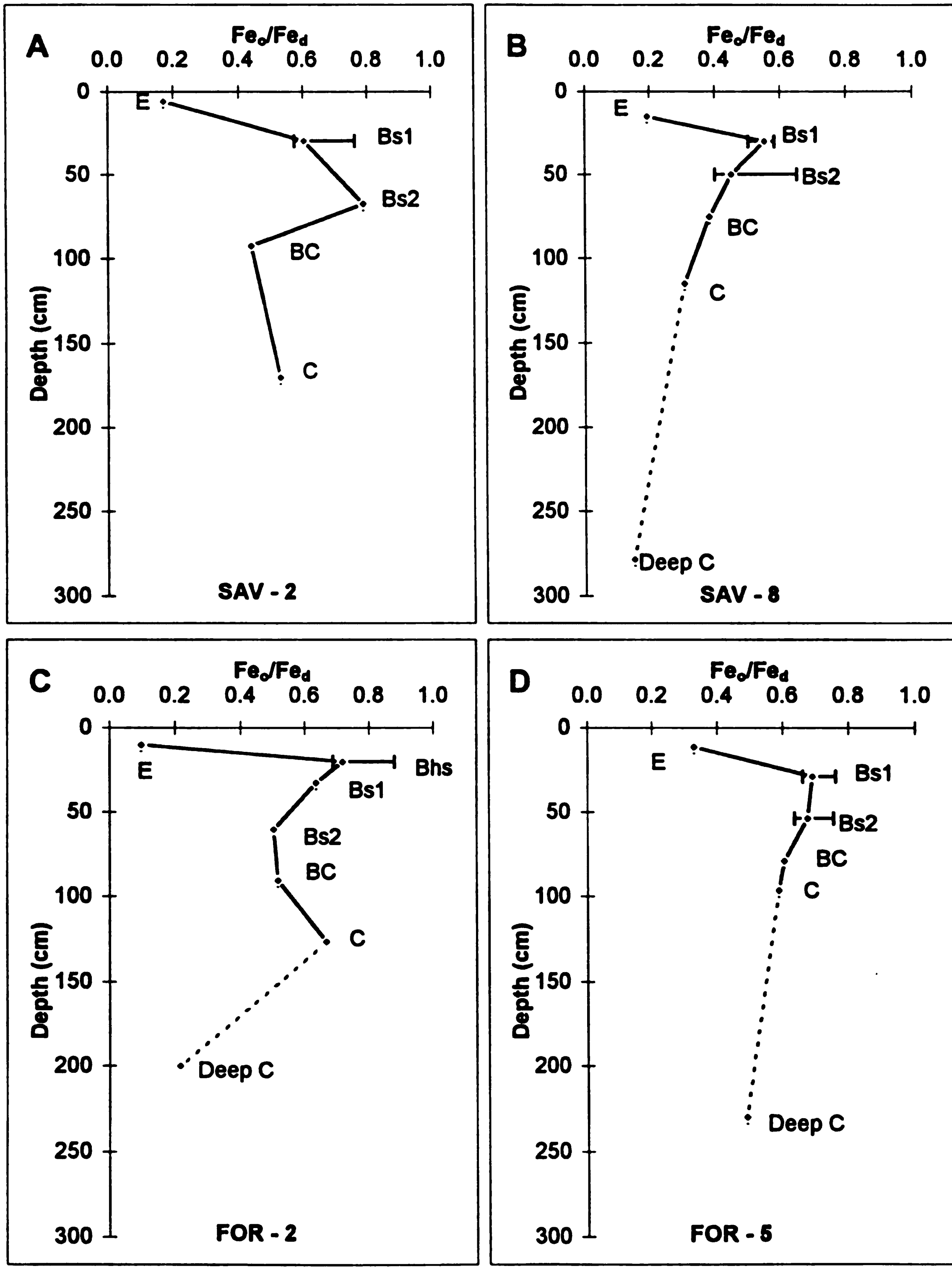

Figure 42. Fe_o/Fe_d values by depth for four representative pedons. Error bars signify high and low values in horizons where ortstein was sampled separately.

subsamples (Table 19), suggesting that the pedogenically "active" Fe forms are concentrated in the ortstein portion of the horizon.

The ratio of inorganic amorphous to organic amorphous Fe ($[Fe_o\text{-}Fe_p]/Fe_p$) is an indicator of the relative amounts of the non-crystalline Fe that is in organically-bound forms. It has a maximum value in the upper B horizon, but below the Bhs horizon in those pedons with a Bhs horizon (Figure 43). A similar profile distribution was reported in Spodosols of northern Quebec (Wang et al. 1986). The ratio is greater in the matrix than in the ortstein subsamples of the Bs1 horizons (Table 18), and is also significantly higher in stump prairie pedons over forested pedons (Table 17). Values in this study ranged from below 0 to 10.8 (mean 0.65), a range similar to those reported by Barrett and Schaetzl (1992) in Spodosols of northern Lower Michigan, but lower than that seen in northern Quebec (Wang et al. 1986). In the sampled pedons, most amorphous Fe is in organically-bound form, but inorganic amorphous Fe exceeds organically-bound Fe just below the Bhs horizon and in non-cemented portions of most upper Bs horizons. This may imply that Fe has been translocated out of the surface horizons in organically-bound form, but upon reaching the upper B horizon, it may be re-mobilized and translocated further in inorganic form.

The ratio of inorganic amorphous to organic amorphous Al ($[Al_o\text{-}Al_p]/Al_p$) shows a distribution similar to the analogous Fe ratio, with a maximum below the uppermost B subhorizon in many pedons (Figure 44). As for Fe, a higher proportion of inorganic amorphous Al than organic amorphous Al is found in the matrix over the ortstein subsamples of the Bs1 horizon (Table 19). This suggests that most of the Al and Fe in the cemented portions of the pedons are organically bound, and that the inorganic forms of Al exceed organically-bound forms below the organic-rich upper B horizon.

The distribution of inorganic amorphous Al ($Al_o\text{-}Al_p$), representing poorly crystalline aluminosilicates like imogolite and/or allophane (Parfitt and Kimble 1989; Jersak et al. 1995), also shows a maximum in the upper B horizon, below the Bhs in those

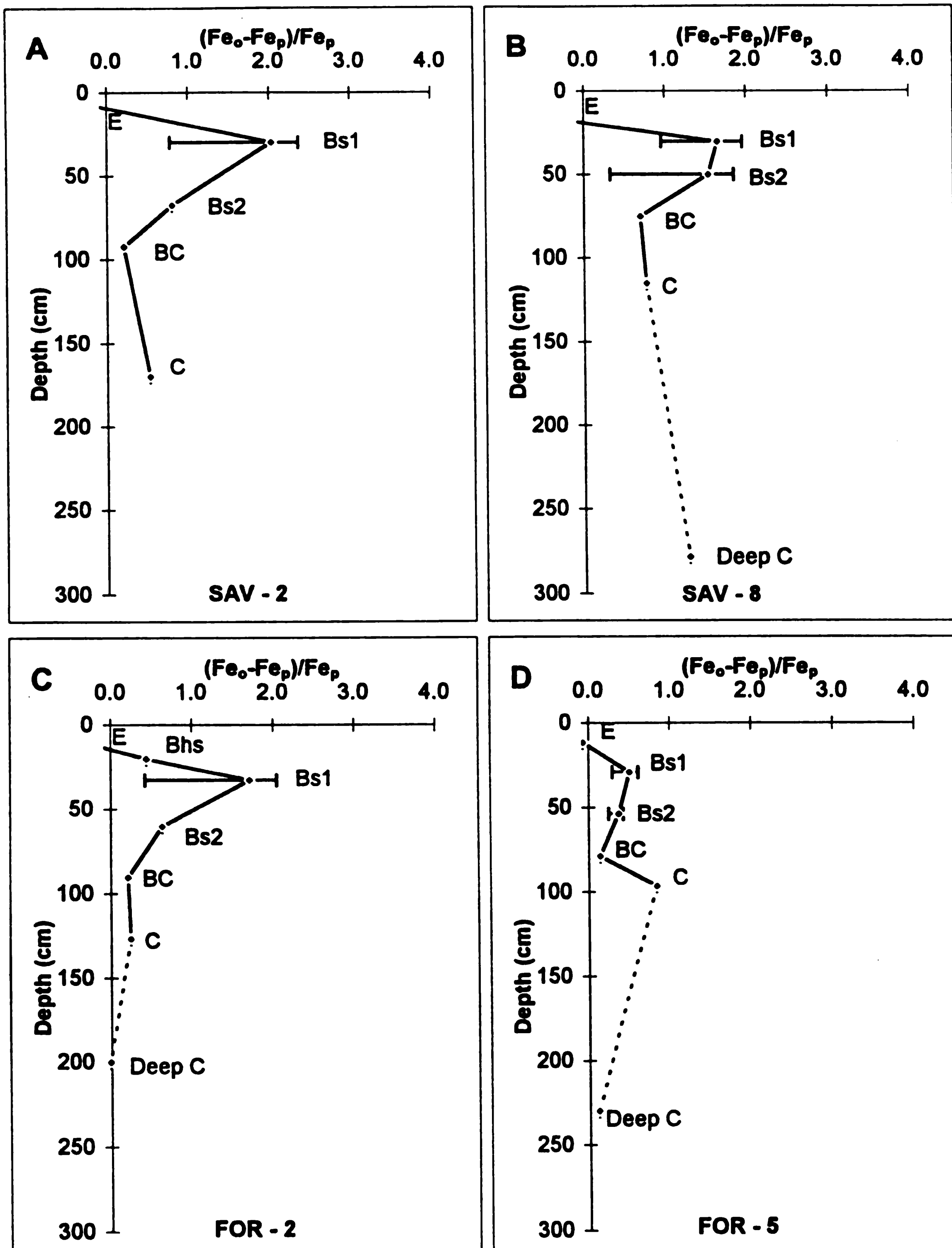

Figure 43. (Fe$_o$ - Fe$_p$)/Fe$_p$ values by depth for four representative pedons. Error bars signify high and low values in horizons where ortstein was sampled separately.

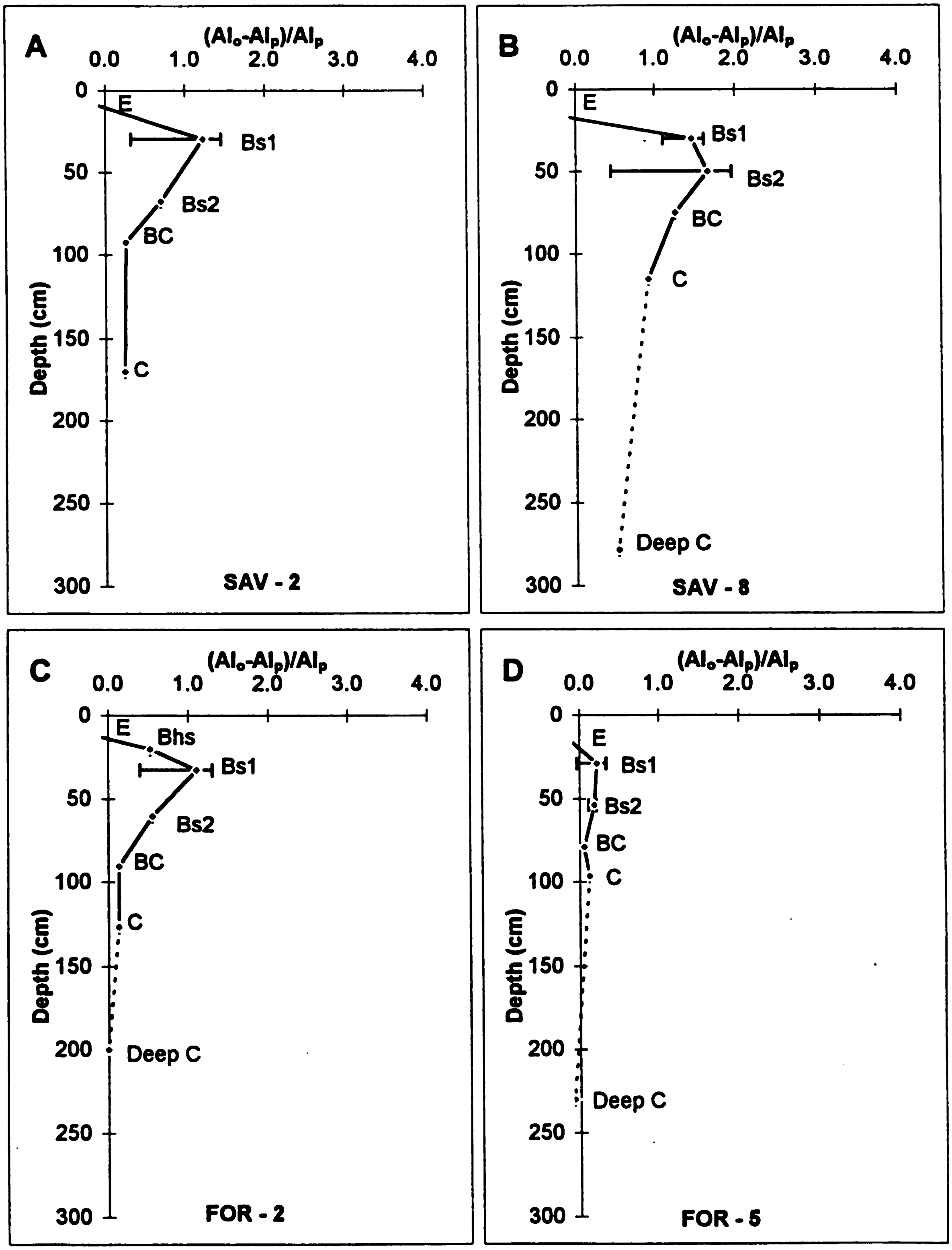

Figure 44. $(Al_o - Al_p)/Al_p$ values by depth for four representative pedons. Error bars signify high and low values in horizons where ortstein was sampled separately.

pedons with Bhs horizons (Figure 45). Very low (< 1.0 g kg^{-1}) Al_o-Al_p contents were found in some forested pedons (Figure 45D). Al_o-Al_p content is higher in matrix than in ortstein subsamples of Bs1 horizons (Table 19). The depth distributions of inorganic amorphous Al and the ratios of inorganic amorphous to organic amorphous Al could indicate translocation below the uppermost B horizon of Al in inorganic amorphous form, independent of organically-bound Al. Similar depth distributions and values were found by Wang and Kodama (1986) in pedons in which the presence of imogolite was detected in the lower B horizons. In this study, I did not examine samples for imogolite directly, so its presence in the lower B horizons cannot be confirmed.

A further indication of the presence of short-range ordered aluminosilicates in soils is the molar ratio of inorganic amorphous Al to oxalate-extractable Si ($[Al_o$-$Al_p]/Si_o$; Gustafsson et al. 1995; Takahashi et al. 1995). In the sampled pedons, $(Al_o$-$Al_p)/Si_o$ is usually at its maximum value in the B horizon (Figure 46). Values of the $(Al_o$-$Al_p)/Si_o$ ratio in the sampled pedons are low (most < 2.0; Table) compared to those reported for Spodosols in the literature (> 2.0; Evans and Wilson 1985; Parfitt and Kimble 1989; Dahlgren and Ugolini 1991; Shoji and Yamada 1991; Gustafsson et al. 1995; Takahashi et al. 1995). Even though the ratio is low, Al_o-Al_p is a good predictor of Si_o in these soils ($Si_o = 0.20 + 0.97[Al_o - Al_p]$; $r^2 = 0.88$), indicating a 1:1 ratio of Al:Si. Farmer et al. (1983) reported that the Al:Si ratio in allophanic material is close to 2:1. Inoue and Huang (1986), however, found that precipitates formed in the presence of organic ligands with a strong affinity for Al at a Al:Si ratio of 1.0 are very similar to proto-imogolite, and are potentially mobile within the soil profile. Fulvic acids have been shown to affect the genesis of allophane and imogolite such that the Al:Si ratio will increase with increasing OC (Huang 1991). The $(Al_o$-$Al_p)/Al_p$ depth distribution (Figure 44) shows the highest Al:Si ratio in those horizons with the highest ODOE values (Figure 38). It is possible, therefore, that the low Al:Si ratios in these soils are a reflection of the amounts and types of organic matter present in the soils. Allophanes with Al:Si ratios < 2 are probably a

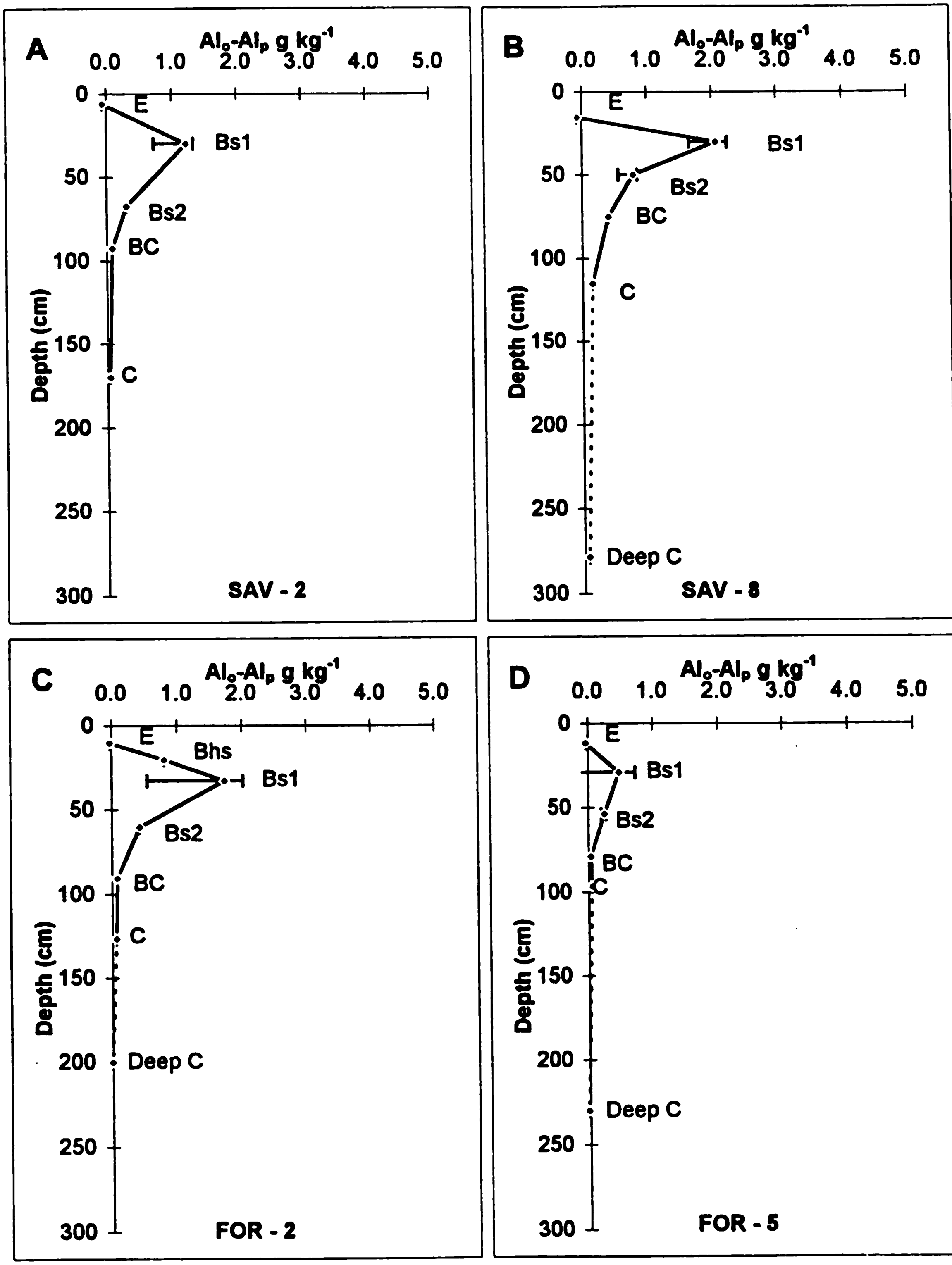

Figure 45. Inorganic amorphous Al (Al_o - Al_p) content by depth for four representative pedons. Error bars signify high and low values in horizons where ortstein was sampled separately.

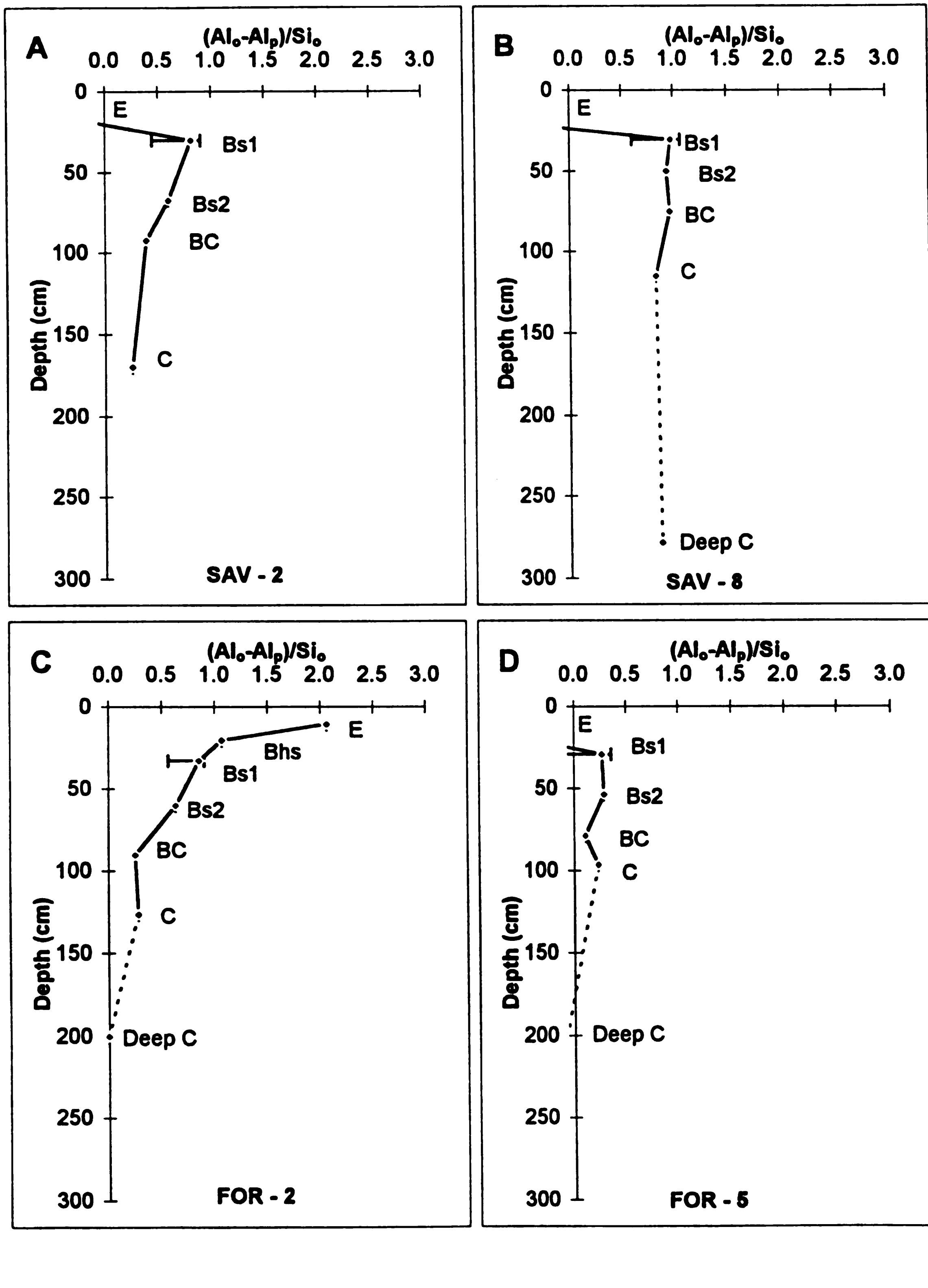

Figure 46. $(Al_o - Al_p)/Si_o$ values by depth for four representative pedons. Error bars signify high and low values in horizons where ortstein was sampled separately.

mixture of imogolite-like allophane and silica-rich allophane, but usually form in soils with high Si in solution and at higher pH (>6.0) than is present in the study area soils (Parfitt and Kimble 1989).

The molar ratio of Fe_p to Al_p illustrates the differences between organically-bound Fe and Al distributions within the profiles. The slight Fe_p/Al_p minimum values in the lowest Bs or BC horizon of many pedons (Figure 47) may be an indication of deeper translocation of organically-bound Al (Al_p) than organically-bound Fe (Fe_p). The E horizon maximum suggests that Al is more quickly mobilized than Fe in the surface horizons. Gustafsson et al. (1995) also found that molar Fe:Al ratios decreased with increasing depth in Spodosols of northern Scandanavia, with values similar to those of the present study. Fe(III):Al molar ratios > 0.5 have been reported to inhibit the formation of imogolite (Huang 1991). Fe_p/Al_p values are greater in ortstein subsamples than in matrix subsamples of Bs1 horizons (Table 19), possibly indicating that Fe is relatively important in cemented horizons, even though there is more Al than Fe in absolute terms. In other ortstein soils, Al-organic complexes have been reported to be the dominant cementing agent (McKeague and Wang 1980; Lee et al. 1988a, b).

The overall picture of the soils in the present study offered by the OC, Fe, and Al data is that there is a concentration of OC, especially fulvic acids (as indicated by ODOE), at the top of the B horizon and especially in cemented portions of Bs subhorizons. Most amorphous Fe and Al is present in organically-bound forms, but inorganic forms become more important below the Bhs horizon and in non-ortstein portions of the Bs subhorizons. Organically-bound Fe especially is concentrated in the Bhs and ortstein parts of Bs subhorizons, but a larger proportion of organically-bound Al than Fe has been translocated deeper in the solum into lower Bs subhorizons.

The data are consistent with a view of podzolization in which Fe and Al, released through weathering in surface horizons, are translocated into the upper B horizon as organo-metallic complexes (De Coninck 1980). In the upper B horizon, and in ortstein

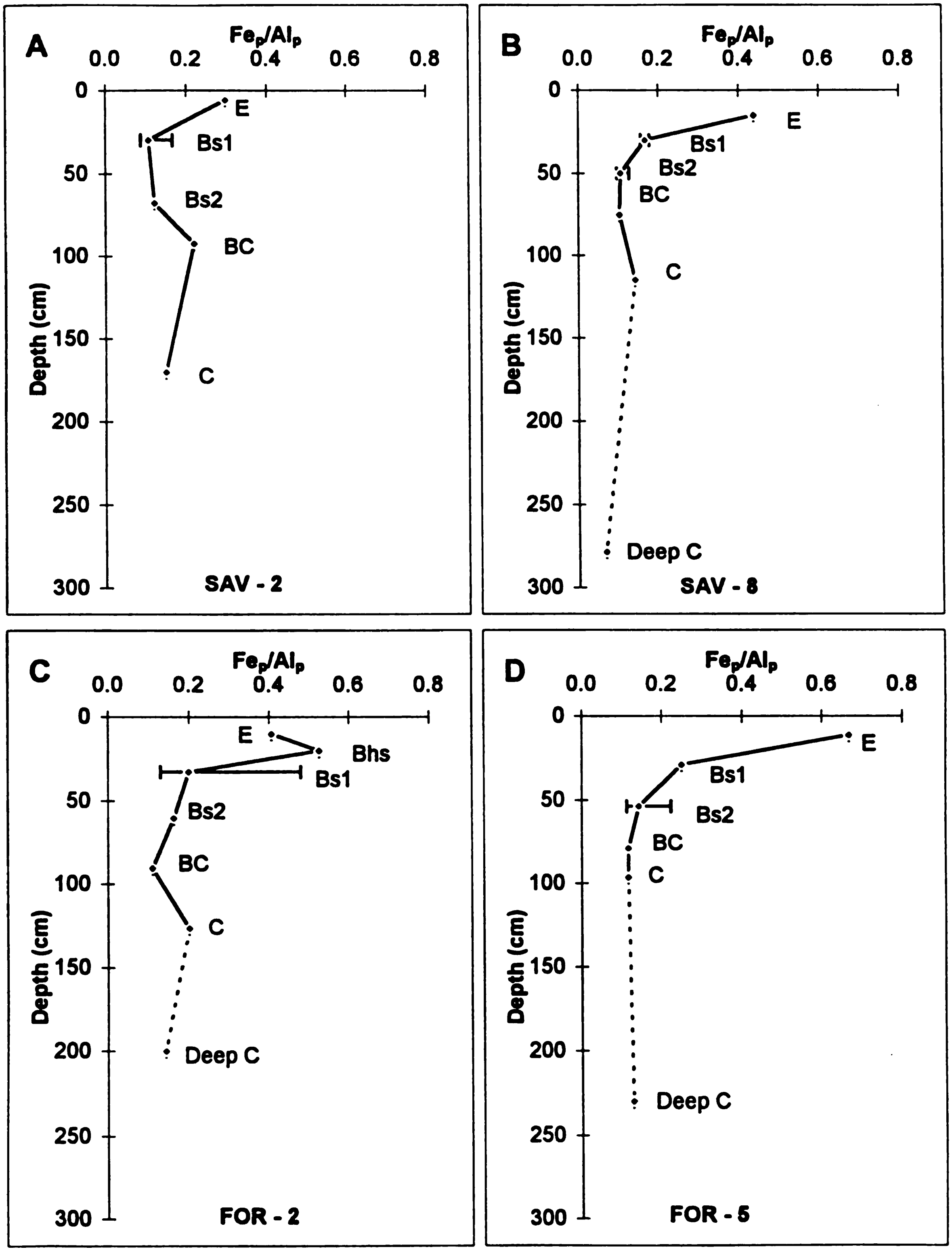

Figure 47. Fe_p/Al_p values by depth for four representative pedons. Error bars signify high and low values in horizons where ortstein was sampled separately.

columns in Bs subhorizons (which presumably indicate pathways of preferred water flow), the organically-bound forms of Fe and Al are deposited, accounting for the predominance of organic Fe and Al forms in these horizons. A possible re-mobilization of Fe and Al, with a preference for Al, causes the further downward migration, in inorganic form (possibly "proto-imogolite sols" *sensu* Anderson 1982), out of the Bhs and ortstein subhorizons and into the lower Bs horizons, and deposition there as short-range-order aluminosilicates. This scenario is consistent with the theory presented by Dahlgren and Ugolini (1989) for tephritic Spodosols, in which they proposed two "compartments" of soil processes, the upper compartment (A, E, and Bhs horizons) dominated by organic acid weathering and translocation of organo-metallic complexes, and the lower compartment (Bs, BC, and C horizons) dominated by H_2CO_3 weathering in equilibrium with the hydroxy aluminous interlayer of 2:1 layer silicates and imogolite. Some of the inorganic Al and Fe in lower Bs horizons may also result from incongruent dissolution of minerals *in situ* due to H_2CO_3 weathering (Ugolini and Sletten 1991).

From soil morphology and chemical data alone, it is unclear how soil development processes have been affected by the change in vegetation that occurred with the establishment of the stump prairie. The primary difference between the forested pedons and stump prairie pedons is the amount of ortstein present in the soils. Presumably, greater amounts of organic acids in the litter of forested pedons contributed to the formation of ortstein and Bhs horizons in these pedons, but it is impossible to distinguish whether current vegetation patterns or pre-disturbance forest types had a greater part in its formation. It does not seem likely that approximately a century of lowered organic acid production in the stump prairie soils could have led to ortstein disintegration to the degree to account for the current differences in morphology.

Because allophane and imogolite are particularly unstable in the presence of organic acids (Inoue and Huang 1986), upper Bs horizons could be easily transformed into Bhs horizons if the supply of organic acids were to increase (Gustafsson et al. 1995).

Thus, a mechanism exists for the development of the spodic horizon and an increase in ortstein and Bhs content in these soils if the production of organic acids increased following logging disturbance. It seems unlikely, however, that organic acid production in forested pedons would have increased; rather, a *decrease* would be expected in stump prairie pedons. Whether the reverse mechanism is possible, however, remains unclear. That is, it is unknown whether a decrease in the supply of organic acids would lead to the decomposition of already deposited organo-metallic complexes and favor the formation of amorphous aluminosilicate-rich Bs horizons, and the disintegration of ortstein which appears to have occurred in the stump prairie pedons.

In situ monitoring of soil processes

The properties of the solid phase of the soil can provide insight into the processes that have contributed to soil formation. Because soil properties are determined by the cumulative effects of all processes active during soil formation, some properties may be relict features of processes no longer active. Relict soil features may reveal that the soil is polygenetic due to changes in climate or vegetation (Bryan and Albritton 1943; Johnson and Watson-Stegner 1987; Ugolini et al. 1987; Ranger and Nys 1994). Studying the soil solution can help to identify those processes still active and identify soil properties that may be relict (Ugolini et al. 1987; Righi et al. 1990). Often lysimeters are used to study the soil solution by direct analysis (e.g., Grier 1975; Singer et al. 1978; Ugolini et al. 1988; Schaetzl 1990). In the present study, bags of chelating resins and cation exchange resins were buried in the soil to deduce the movement of various cations in the soil solution (Righi et al. 1990; Ranger et al. 1991; Ranger and Nys 1994). The advantage of using resin bags over lysimeters to study soil solution processes is that the resin bags require much less on-going maintenance than the lysimeters, allowing study of pedons in relatively inaccessible sites. It also more readily allows replication of the tests over space, requiring the installation only of the bags, and not a complex lysimeter system. The purpose of this part of the study was to determine whether active soil forming processes in the forest soils were different from those in the stump prairie soils, especially with respect to the forms and amounts of Fe and Al being translocated (see pp. 132 - 135).

For both the cation exchange resin and the chelating resin, absolute amounts of sorbed cations were very small (Tables 25 and 26, Appendix A) compared to results reported by Ranger et al. (1991) in France. The low cation capture totals may be due to the short period of burial (< 10 months) or to the small amounts of percolating soil solutions due to low precipitation amounts (43.3 cm actually recorded at Munising by the

National Weather Service cooperative observer vs. 50.9 cm for the 30 year mean at the same site) during the burial period (Ranger et al. 1991). Nevertheless, despite the small absolute values, *relative* amounts of sorbed cations, by horizon, appear to reflect the soil processes.

Amounts of Mg and Ca sorbed on the cation exchange resin are generally greatest at the top of the E horizon, with the exception of Ca in the stump prairie pedons, where top of the B horizon values are higher (Figure 48). Forest pedons usually showed larger amounts of both Mg and Ca sorbed at the top of the E horizon than stump prairie pedons, probably due to greater cation recycling by the forest vegetation and release from the decomposition of the litter layer (Ranger and Nys 1994). For most horizons, amounts of sorbed Ca were higher than sorbed Mg values. Very little Ca or Mg (Ca mean 76 mg kg^{-1} dry resin; Mg mean 26 mg kg^{-1} dry resin) is present in soil solutions reaching the top of the BC horizon, implying that the lower part of the B horizon is dominated by inorganic processes and carbonic acid weathering (Ugolini and Dahlgren 1987) .

In both forested and stump prairie pedons, and both resin types, sorbed Ca was four to six times higher than sorbed Mg (Table 20). Relative amounts of sorbed Ca and Mg are in agreement with measurements of cation cycling in a forested ecosystem in New Hampshire (Likens et al. 1977, p. 101). In Alfisols of northern Minnesota, Ca:Mg ratios in the forest floor and in mineral soil horizons ranged from 6 to 10 (Alban 1982). The ratio of Ca to Mg in the biogeochemical cycles of both spruce and broadleaved stands in France also were determined to be approximately 6 (Ranger and Nys 1994).

Amounts of sorbed Al are generally higher than sorbed Fe for both the cation exchange resin (Figure 48) and the chelating resin (Figure 49). Most of the Fe and Al in the soil solution appears to be in organically complexed forms because the amounts of Fe and Al sorbed on the chelating resin are much higher than amounts sorbed on the cation exchange resin. For most pedons, sorbed Fe and Al on both the cation exchange resin and the chelating resin are at a maximum at the top of the B horizon. This depth pattern

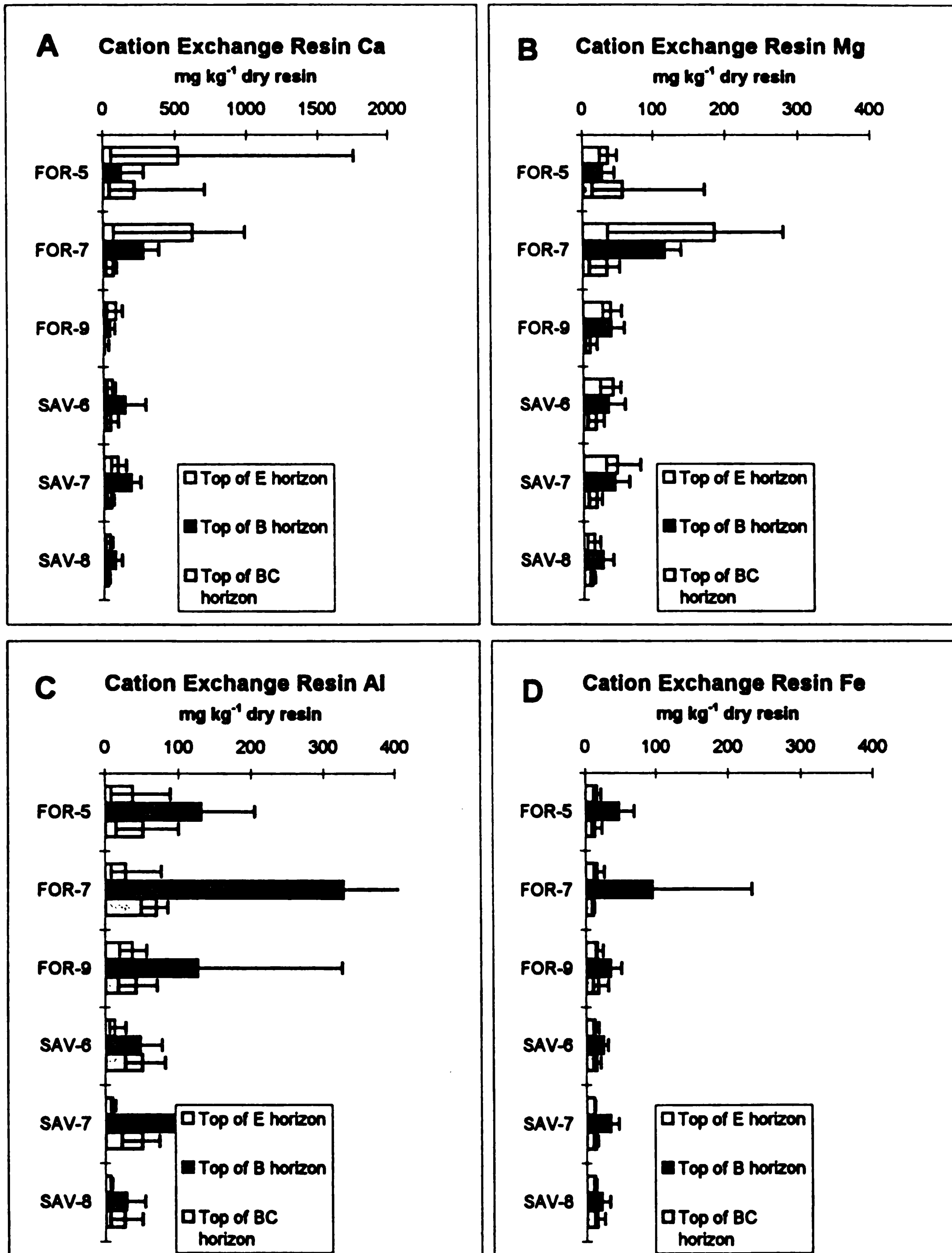

Figure 48. Amounts of cations sorbed on cation exchange resins for the six sampled pedons. Error bars indicate minimum and maximum values from replicate bags. Note that part A has a different axis scale than other parts. A) Ca; B) Mg; C) Al; D) Fe.

Table 20. Mean amounts 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	30.5
Ca	226.2	87.4
Fe	30.1	18.7
Al	93.9	37.3
Chelating resins (all horizons)		
Fe	117.3	64.0
Al	473.4	282.7
Cation exchange resin (top of B horizon only)		
Mg	65.5	36.9
Ca	155.3	142.3
Fe	60.8	27.6
Al	201.4	59.6
Chelating resin (top of B horizon only)		
Fe	255.6	130.9
Al	959.0	550.7

*For all rows, column means are not significantly different ($p = 0.05$, Kolmogorov-Smirnov).

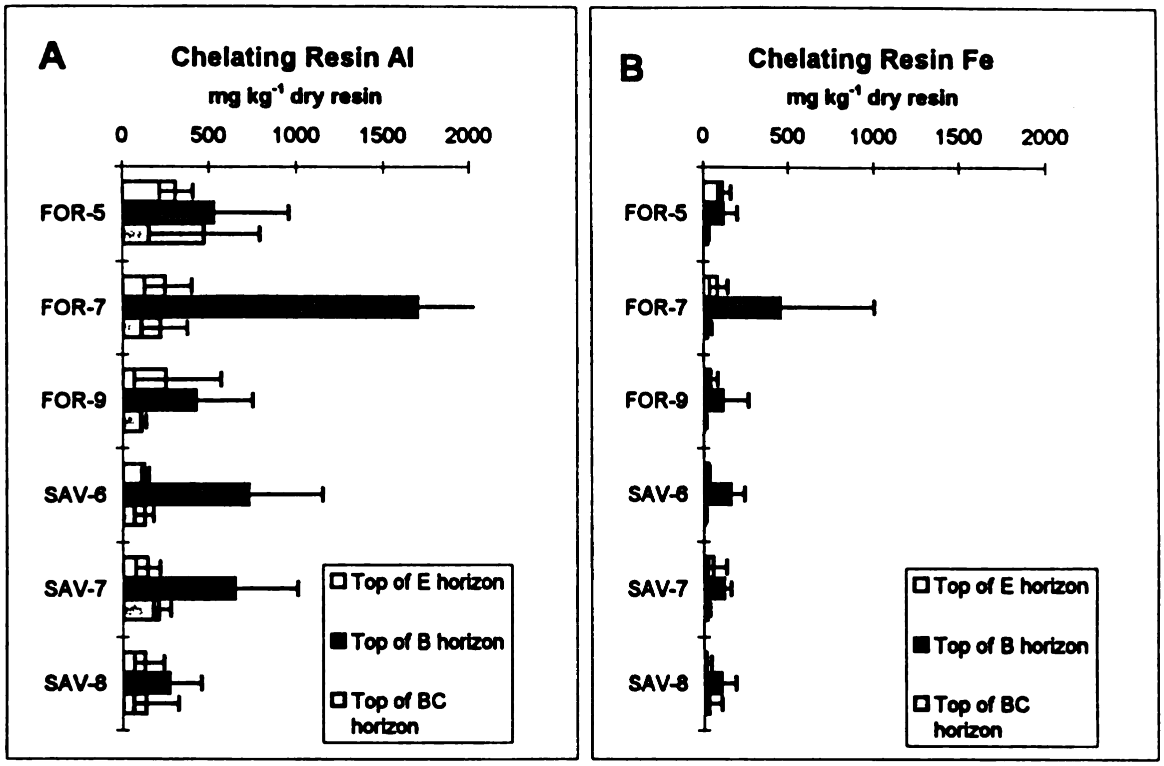

Figure 49. Amounts of cations sorbed on chelating resins for the six sampled pedons. Error bars indicate minimum and maximum values from replicate bags. A) Al; B) Fe.

suggests that amounts of Fe and Al leaving the litter layer in the soil solution are relatively small, and, therefore, that the source of soil solution Fe and Al is weathering in the E horizon. The soil solution leaving the B horizon also has very low Fe and Al content, suggesting that most of the Fe and Al is immobilized within the B horizon (Ugolini et al. 1977; David and Driscoll 1984; Schaetzl 1990; Ugolini and Sletten 1991).

Although not statistically significant, mean amounts of sorbed Fe and Al appear to be slightly greater in the forest pedons than in the stump prairie pedons (Table 20). Variability both within and between pedons is very high, however. Pedon FOR-7, located in a relatively undisturbed forested area with little evidence of recent logging and larger trees than most other forest in the area, consistently shows the largest amounts of all sorbed cations; pedon SAV-8 is consistently low (Figures 48 and 49). If greater amounts of cations have been sorbed on resins in forested pedons, this has happened despite the fact that less water typically moves through soils in forested than in unforested locations due to interception by tree crowns (Schaetzl and Isard 1990). From the data available it appears that podzolization processes may be more active in the forest than on the stump prairie. Nevertheless, podzolization seems to be an on-going process in the stump prairie soils as well.

The patterns of Fe and Al sorbed on the chelating resin are typical of patterns found in studies of soil solutions using lysimeters in podzol soils, in which Fe and Al concentrations in soil solutions are low just beneath the litter layer, highest as the solution enters the Bs horizon, and low again as it leaves the horizon. Such patterns have been found in Michigan (Schaetzl 1990), the Arctic (Ugolini et al. 1987), Washington (Ugolini et al. 1977; Ugolini and Sletten 1991), New York (David and Driscoll 1984), and northern Japan (Ugolini et al. 1988). It is likely, therefore, that the cations sorbed on the resins are qualitatively representative of the cations moving in the soil solutions in the study area soils.

The use of resin bags to study soil solutions has been employed to identify a soil in which active soil processes did not match morphology, suggesting a relict soil (Ranger et al. 1991), and also to distinguish soil processes resulting from differences in vegetation types (Carlyle and Malcolm 1986; Ranger and Nys 1994). In the present study, soil processes are in accord with soil morphology, and podzolization processes appear to be more active in the forest than in the stump prairie soils.

Summary

In summary, evidence from soil properties and an *in situ* examination of soil processes using resin bags suggests that the soils in the forest and the stump prairie are similar, but distinctions between the two groups do exist. Parent material texture is the same in both groups, but amounts of Fe, Al, and OC are higher in the forested than stump prairie soils. Most differences between the two groups of soils can be attributed to differences in ortstein content; forest soils have more ortstein than stump prairie soils, and ortstein samples typically have higher Fe, Al, and OC contents than matrix samples. Thus, the spatial relationship between forest regeneration patterns and soil patterns is best expressed in ortstein content of the soils.

Depth distributions of Fe, Al, and OC in both forest and stump prairie soils are consistent with current theories of podzolization, showing translocation of Fe and Al in organically complexed form in upper horizons, and possible further translocation of inorganic forms of Al primarily into lower horizons. Soil solutions, studied using resin bags, indicate that podzolization processes are active in both groups of soils but appear to be more so in the forested pedons. No evidence was found for the notion that differences in degree of soil development could be attributed to processes destroying the spodic horizon due to the change in vegetation type from forest to grassland in the stump prairie region.

Factor 3: Logging era fires and logging practices

Logging

No one questions that disturbance associated with nineteenth century logging has led to the establishment of the stump prairie. The general history of logging in the Upper Peninsula and on the Kingston Plains has been discussed above (pp. 13, 21). Whether logging practices in the areas that today are stump prairie were different from those where the forest has recovered, however, remains unclear. This section will examine historical records relating to the logging of the study area for evidence of whether logging practices in the two current landcover classes differed in either (1) character or (2) timing.

Specific records of dates and methods of logging at the end of the last century are difficult to obtain. As a surrogate, more easily-obtainable records pertaining to land ownership and property tax payment have been utilized in this study to establish who owned the land during the years the area was being logged, and the assessed value of that land. Two assumptions have been made relative to these records: (1) most logging that took place on the Kingston Plains was authorized by the owners of the land; and (2) the assessed value of a land parcel with standing, marketable timber was much higher than its value after it had been stripped of its lumber. Since illegal logging by people other than the land owner was not uncommon in nineteenth century Michigan (Skeels 1898), it is possible that the first assumption does not strictly hold. Nevertheless, lands owned by large lumber companies were most likely logged by that company.

Pre-logging land ownership. The land in township in which the study area is located was purchased from the government over a period of about 20 years, with most activity taking place before 1880. This period is considerably before logging in the central Upper Peninsula was common, and well before any logging began in the vicinity of the Kingston Plains. The original purchasers can be divided into five main groups: (1) E. B. Ward; (2) the Sault Canal Company; (3) the Lac La Bell Harbor Improvement Company; (4) S. Q. Perry and associates; and (5) other individuals with smaller holdings (Figure 50). The land ownership patterns established in this period persisted through the logging era. For the most part, however, the actual ownership changed before logging took place. The spatial pattern of the dates of acquisition from the government reflect land ownership patterns because the major purchasers acqired their land at different times (Figure 51).

The first acquisition of land in the study area from the government was in 1855 by Eber B. Ward, a Detroit, Michigan, industrialist, later associated with the steel industry (Burton and Burton 1930). Mr. Ward's purchases were concentrated in, but not limited to, the areas that today are stump prairie. Also in 1855, the Sault Canal Company obtained land in the southeastern portion of the township, which is generally wet and forms the headwaters of a river. This land may have been a grant to the Sault Canal Company in exchange for canal improvements (Hibbard 1939, p. 238). Similarly, the odd-numbered sections of the township not already claimed were granted to the Lac La Belle Harbor Improvement Company in 1866. After 1870, acquisition by individuals, probably as lumber speculation, became common. Silas Q. Perry and a number of his associates, who later organized the Manistique-based North Shore Lumber Company (Hotchkiss 1898), acquired many parcels beginning in 1872. Mr. Perry's parcels were located both in stump prairie and in forested areas.

If forest composition of the stump prairie areas was of markedly greater quality for logging purposes because of its higher proportion of white pine, it might be expected that the stump prairie land should have been acquired before adjacent regions. Certainly E. B. Ward's early acquisition seems to follow that pattern (Figure 50). The fact that the Lac La Belle Co. was granted all odd-numbered sections in the 1860's, however, makes it difficult to discern whether this pattern continues in later purchases, because little stump

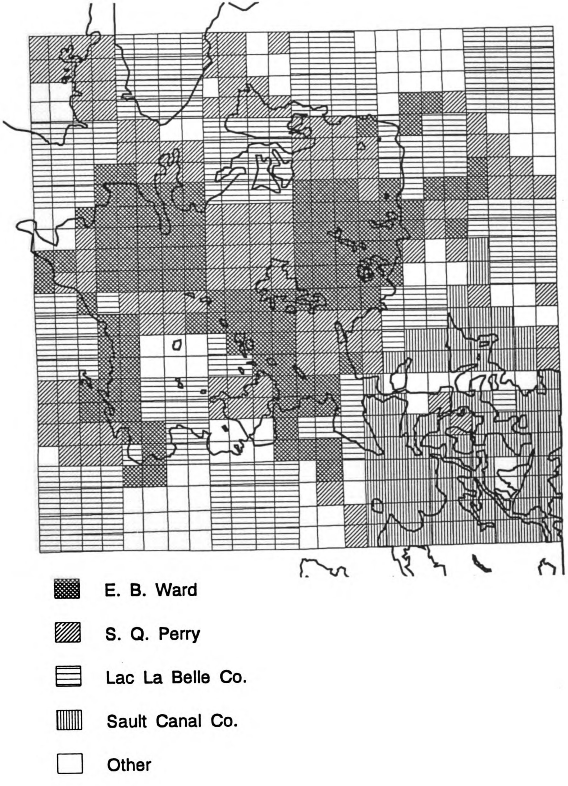

Figure 50. The original purchaser of land from the government, T 48 N, R 15 W, Alger County, Michigan. The stump prairie/forest boundary is shown for reference.

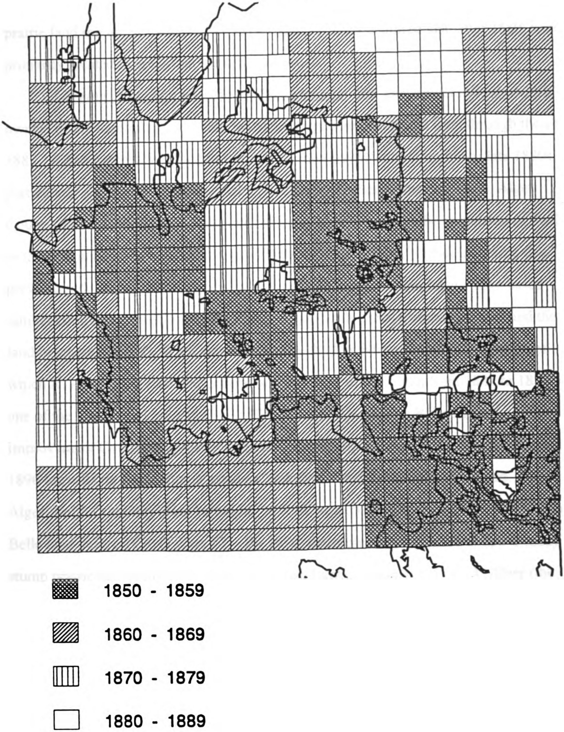

Figure 51. The date of the original purchase of land from the government, T 48 N, R 15 W, Alger County, Michigan. The stump prairie/forest boundary is shown for reference.

prairie land remained for sale after 1870. Those parcels acquired last, after 1880, were primarily located in areas that are today forested.

Logging era land ownership and land values. Tax assessment rolls show that the owners of the land in the township remained largely unchanged at least through the year 1887. A few parcels defaulted to the state for non-payment of taxes in the late 1880s, particularly some of S. Q. Perry's land (Abstracts of sales of state tax lands, Alger County, 1888, 1890, 1893). Between 1887 and 1890, however, the ownership of the land in the area underwent a major change (Figure 52). S. Q. Perry's land, including that previously defaulted on, was acquired by Hall and Buell, another Manistique-based lumber company (Hotchkiss 1898). Most of the Sault Canal Company's land and the land belonging to E. B. Ward was acquired by the Manistique Lumber Company, of which R. A. Alger, a civil war general and governor of Michigan from 1884 to 1888, was one of the major stockholders (Bell 1975, p. 134). The Lac La Belle Harbor Improvement Company apparently retained ownership of most of their land, but in the 1890 tax rolls its ownership is listed as "unknown" and the taxes were unpaid. The Alger-Smith Company (also belonging to R. A. Alger) did acquire some of the Lac La Belle land before 1890 (Figure 52). By 1890, therefore, most of the land that is today stump prairie had been acquired by one of two lumber interests: (1) R. A. Alger (the Manistique Lumber Company and the Alger-Smith Company) and (2) Hall and Buell. The holdings of these two companies were not entirely restricted to stump prairie land.

The assessed land value in 1890 generally ranged from $4.00 to around $7.00 per acre (Figure 53). Patterns of assessed value appear to be more closely related to the land ownership than forest patterns; e.g., most of the Manistique Lumber Company's land was valued at $7.00 per acre, but Lac La Belle's land was assessed at $4.00 per acre. From the assessed land values shown in Figure 53, it can be surmised that little logging had taken place in the township by 1890. Of interest here is the small parcel of land assessed at $1.00 per acre and owned by one of the minor landholders (Figure 53). It is possible

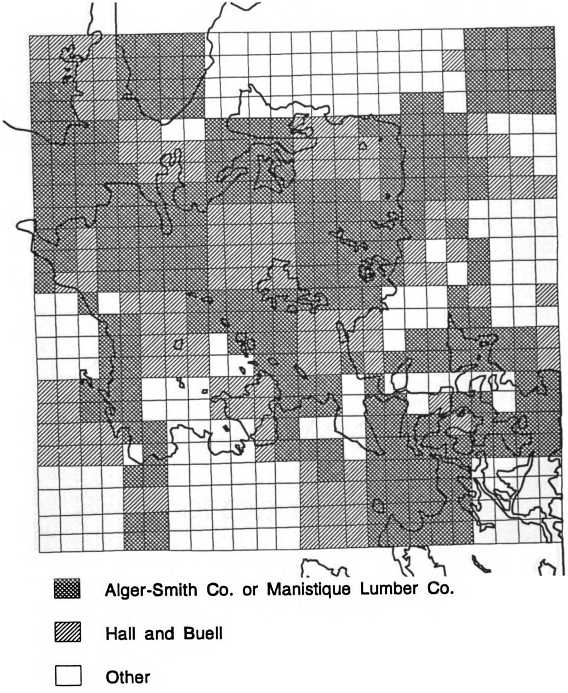

Figure 52. Land ownership in 1890, T 48 N, R 15 W, Alger County, Michigan. The stump prairie/forest boundary is shown for reference.

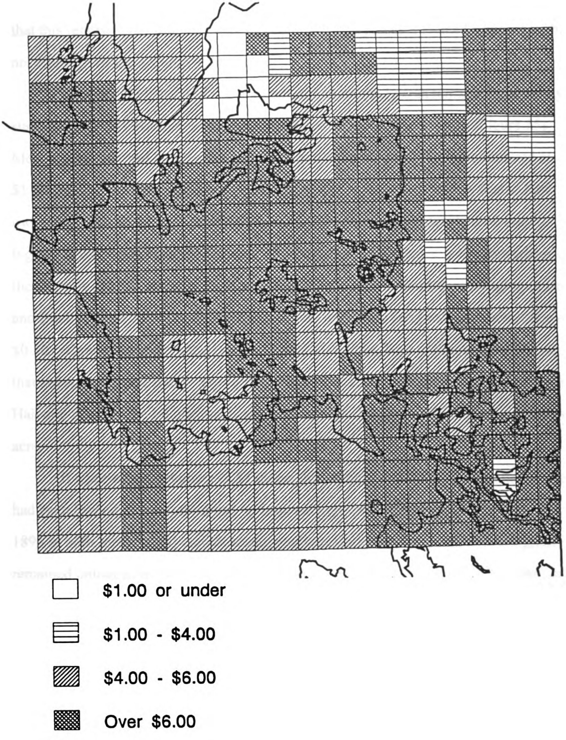

Figure 53. Per-acre assessed land value in 1890, T 48 N, R 15 W, Alger County, Michigan. The stump prairie/forest boundary is shown for reference.

that this represents an area that was logged early. The parcel is located adjacent to, but not entirely within, a stump prairie area.

Between 1890 and 1895 land ownership in the study area remained essentially stable (Figure 54), but major changes in assessed value had taken place (Figure 55). Most parcels that had been worth more than $4.00 per acre in 1890 were assessed at $1.00 per acre in 1895. Assessed valuation in 1895 is much less closely tied to land ownership than it had been in 1890, probably reflecting a major devaluation due to logging activity that occurred between 1890 and 1895. Of interest is the appearance on the tax rolls in 1895 of State Tax Land (Figure 54), all of it formerly belonging to Hall and Buell (Figure 52). The State Tax Land was uniformly assigned a per-acre value of $0.50. It was scattered among Hall and Buell's holdings, both within and outside regions that are stump prairie today. By 1899 the State Tax Land had been redeemed by either Hall and Buell or the Manistique Lumber Company. Most was still valued at $0.50 per acre.

If a per-acre assessment of $1.00 per acre or less is taken as evidence that a parcel had been logged, it is apparent that widespread logging took place between 1890 and 1895 in both forested and current stump prairie regions. Some stump prairie regions remained unlogged in 1895, but were probably logged shortly thereafter. By 1899, most of the township was assessed at $1.00 per acre or less (Tax assessment rolls, Alger County, 1899), with the major exception being the the swampy, Fox River headwaters in the southeastern corner of the township. Land ownership was largely unchanged. In 1899, the Manistique Lumber Company is recorded as having paid the taxes on its holdings, but the Hall and Buell parcels were again unpaid.

In conclusion, the tax assessment and ownership data suggest that most logging activity on the Kingston Plains took place between 1890 and 1895, and was virtually completed by 1899. These tax records show that land ownership patterns in the study area were constant from the time of its original acquisition through the end of the century.

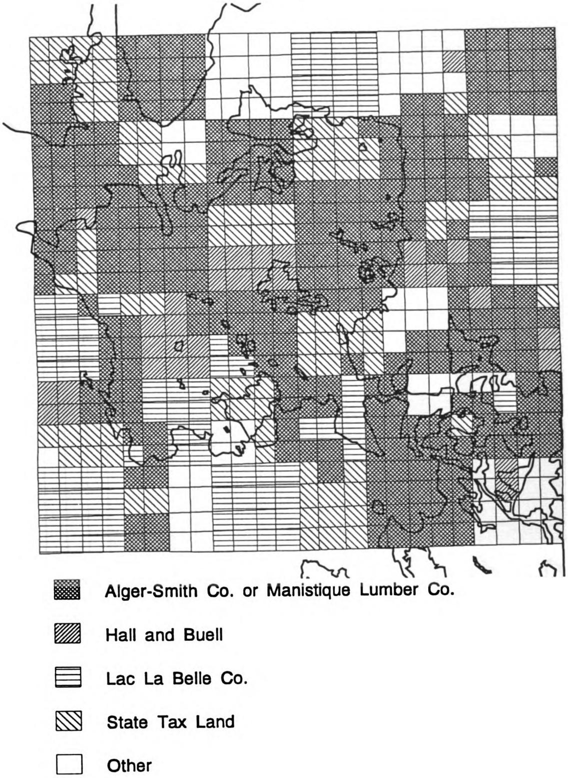

Figure 54. Land ownership in 1895, T 48 N, R 15 W, Alger County, Michigan. The stump prairie/forest boundary is shown for reference.

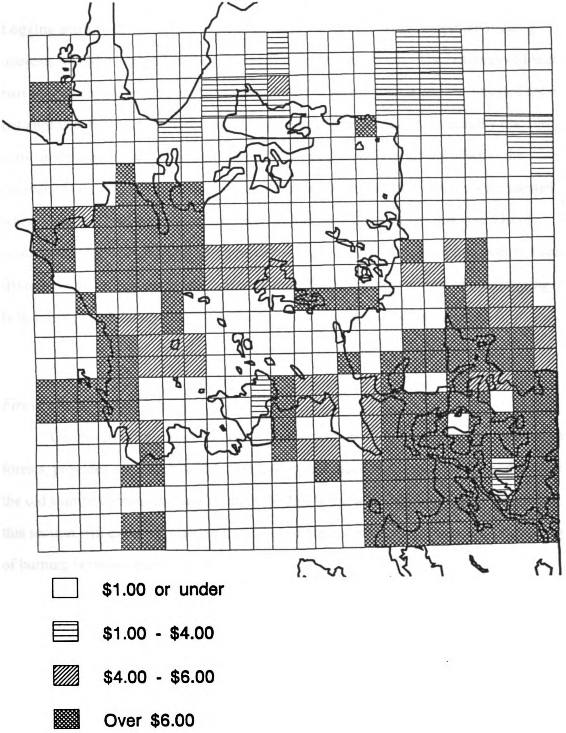

Figure 55. Per-acre assessed land value in 1895, T 48 N, R 15 W, Alger County, Michgan. The stump prairie/forest boundary is shown for reference.

Logging activity in the township was primarily carried out by two separate logging interests, the Manistique Lumber Company and Hall and Buell. The holdings of these two companies are intermixed throughout both the stump prairie and the forested areas, but appear to be slightly concentrated in the stump prairie area. It is unlikely that one company's logging practices were more detrimental than those of the other to the recovery of the forest. The minor landowners, however, whose holdings were located where it is now forested, might have had distinct logging practices that could have contributed to the recovery of those parcels. The apparent date of logging does not seem, from these data, to be associated spatially with the forest recovery pattern, as logging of both forested and stump prairie tracts occurred within the same time period.

Fires: Evidence for burning

Careful observation in the stump prairie portion of the study area, as well as in the forests, provides an unmistakeable impression that much of the area has burned. Many of the old stumps contain charcoal, both in the forest and in the stump prairie. Therefore, this section will examine whether there were differences in either frequency or intensity of burning between the two areas.

Historical discussions of logging in the area commonly mention fire. A short description of the Kingston Plains, apparently written for game managers around 1940, states that the former superintendant of the Cusino C. C. C. camp claimed that a crown fire occurred while the timber was being taken out, and necessitated a speed-up in operations to salvage the standing burned timber. The description claimed that the last fire in the area must have occurred before 1910 because a few widely spaced pine trees were found to be about 30 years old in 1940 with live limbs down to the ground, indicating that they had not been burned. The only other recorded fire that took place in August, 1936; it burned part of the eastern portion of the Kingston Plains.

Specific information about the fires that took place is difficult to obtain. The Kingston Plains area is distant from any permanent settlement even today, and fires were so common during the logging era that many must have burned, unknown to local inhabitants. Therefore, it is difficult to establish whether there was a difference in frequency or intensity of burns between the stump prairie and the surrounding forested areas. Some surrogate evidence indicating the general nature of burning patterns, however, is available.

Charcoal. Charcoal found in the soil can indicate whether the site has experienced burning, but it does not indicate the intensity of the burn. Once formed, it may persist in the soil for centuries, so its presence in any of the sampled soils does not necessarily indicate that burning took place following nineteenth century logging. Of the pedons sampled, all except two contained at least some charcoal in the surface horizons. The two that did not are FOR-2 and FOR-7. FOR-7 is located among a stand of particularly large trees, including white pine and hemlock, which also show no evidence of having been burned (see below). It is possibly FOR-2's location near a lake (Figure 3) shielded it from burning. Extensive evidence of charcoal in soils of forested sites indicates that most did burn, at least lightly, at some time in the past.

Tree ages. Perhaps the best evidence for differences in burning patterns between forest and stump prairie can be obtained from the trees and stumps themselves. The ages of living trees can be established by means of ring counts. A living tree may have survived a fire, although some species are more susceptible to fire injury than others, and a severe fire should at least have left a scar on the tree. Thus the presence of a tree with no scars, especially a fire-susceptible tree, older than about 100 years, would suggest that that region had escaped severe fire. Similarly, stumps from recent logging activity can be examined for ring counts and fire scars. In this section evidence obtained from tree increment boring and stump ring counts will be compared to general field observations, to address the question of whether fire affected the stump prairie more severely than the forested areas.

Evidence of this type must also be considered with logging patterns in mind. The lack of surviving trees older than about 100 years in an area may have resulted from burning, or it may have been the result of a complete removal of all trees by the loggers. Thus, differing logging patterns would also contribute to differences in tree survival. The question is, (1) did the loggers leave any living trees, and (2) did the trees that were left survive the fires which followed the logging?

In the areas where the forest has regenerated, abundant evidence exists, despite modern logging efforts, that at least some trees remained alive through the time of logging and the fires that followed, including some white pine trees (Table 21). Apparently in these areas the loggers left some larger trees, considered inaccessible or unsuitable, as well as trees too small to be valuable for lumber.

A few very large white pine trees (> 80 cm DBH), located along with large trees of other species, were encountered in stands FOR-7 and FOR-8, though their age was not determined. While it is possible that these trees could have sprouted following lumbering, their growth form suggests that they grew under closed-canopy conditions. Similarly, very large stumps in stand FOR-4, both white pine and hemlock, remain from a selective cutting long enough ago for decay to have begun, although bark remains intact.

The best evidence that not all trees were removed during the original logging, however, comes from stumps left following recent logging efforts. Stand FOR-1 was logged in the spring of 1995, and an area near the border of sections 29 and 30 at the southwestern corner of the stump prairie was logged in the fall of 1994 or spring of 1995. Many large white pine and hemlock trees were removed from stand FOR-1, some of which had nearly 200 annual rings, although some stumps of similar diameter had fewer than 80 rings. Many hardwood trees in the stand also had well over 100 annual rings. Prior to this recent logging, large hemlock stumps from a logging episode approximately

Table 21. Representative ages from ring counts of selected large trees in sampled stands.

Stand	Species	Evidence type	Diameter (cm)	Age[1]	Comments
FOR-1	White pine	tree	87	75	
	White pine, Hemlock	stumps	80-100	200	Logged spring 1995; no scars
	White pine, Hemlock	stumps	80-100	80	Logged spring 1995; no scars
FOR-2	Beech	stump	50	120	Logged 10 yrs ago
	White pine	stump	67	67	
	White pine	stump	50	74	
	White pine	stump	87	87	
	Hemlock	stump	<50	197	
FOR-4	Beech	tree	40		Long scar on trunk
	White pine, Hemlock	stumps	80	?	Largest trees cut approx. 30 years age
FOR-5	White pine	tree	75	72	
FOR-6	White pine	stump		85	Logged approx. 10 years ago
FOR-7	White pine	tree	99.5	?	Not open grown
FOR-8	White pine	tree	84	?	Scar on side of trunk
SAV-1	White pine	tree	70	43	On side of railroad grade
	White pine	tree	30	32	Probably descendent of above tree
	White pine	tree	87	44	Double-stemmed
	White pine	tree	83	61	
SAV-2	White pine	tree	30	24	Growing in old stump
	Black cherry	tree	14	25	
	Red maple	tree	21		
SAV-3	White pine	tree	81	69	Many smaller white pine growing near it
	White pine	tree	22	20	
	Black cherry	tree	11	18	
SAV-4					Almost no trees due to controlled burns
SAV-6	White pine	stump	60	56	Logged approx. 10 years ago
	White pine	tree	81	61	
Sec.30	Beech, Red maple	stumps	60-80	120 +	Logged 1994; no scars

[1]Rings counted at breast height (1.4 m) or at the top of the stump.

30 - 40 years previous had been observed, suggesting that a selective cutting of large trees had already occurred in that stand. Many red maple and beech stumps in section 29 had well over 100 rings; the trees had a diameter of 15 - 20 cm at the time of logging 100 years ago. A hemlock stump with 197 rings was also observed near stand FOR-2.

On the other hand, no conclusive evidence could be found that any tree on the stump prairie remained after nineteenth century logging operations (Table 21). Very large, isolated white pine trees exist on some parts of the stump prairie, but these trees are open-grown with many branches along the lower trunk, and apparently grow rapidly. In many cases the largest trees on the stump prairie are growing on the disturbed soil (small borrow pits or cuts) along the sides of former logging railroad grades, and therefore must have sprouted at or following the time of logging. Some large white pines on the stump prairie were harvested about 10 years ago, especially in the vicinity of stand SAV-6 and in a stump prairie located in the southwestern part of section 8. All of these trees had grown to diameters of 60 - 80 cm or more, and all were less than 90 years old.

The fact that no tree from before the time of logging could be found on the stump prairie, in contrast to the ample evidence of pre-logging trees remaining in currently forested areas, suggests that the treatment of the stump prairie during nineteenth century logging was distinct from that of the surrounding areas. Apparently the white pine stand located in the stump prairie was pure enough that nearly all trees were cut in the initial logging. If small white pine trees and trees of other species and were left by the loggers, they must have been killed either in the fires that followed or due to the altered microclimate resulting from the sudden removal of the canopy trees.

None of the recently logged stumps showed evidence of scarring due to fire, whether on the stump prairie or in the forest. Living trees in the forest do not have obvious fire scars either. Logging-era burned pine snags and stumps are encountered, however, even in forested areas, suggesting that some fire must have passed through at least portions of the forests. Some 120+ year-old beech and red maple stumps with no fire scarring found in some recently logged stands indicates that these places either did not burn or did not burn intensely following logging. If many more trees were left standing in regions that are today forested than on the stump prairie, it could have provided shade for regeneration and helped to conserve moisture and prevent the intense conflagrations and repeated burning that must have occurred in the stump prairie regions.

SUMMARY AND CONCLUSIONS

The forest and stump prairie patterns that exist in the Kingston Plains area are remarkable, especially given that they have persisted since the logging and disturbances of the late 19th century. In this dissertation I examined the spatial patterns of a number of factors, both physical and anthropogenic, that may have influenced the formation or maintenance of the stump prairie. The study focused on three factors: (1) pre-disturbance forest patterns; (2) substrate and soil properties; and (3) logging era fires and logging practices. A secondary purpose of the research was to explore the relationship between forest vegetation and soil development (podzolization) processes in sand soils of northern Michigan, and to examine whether, in fact, the long-term elimination of the forest has altered the pathways of soil development, or even caused soil degradation. Thus, the study has been organized around the assumption that both physical processes *and* human actions have had important influences on the spatial patterns of forest regeneration in the region, and, in fact, that specific conditions of pre-existing forest type, soil development properties, and logging practices were pivotal in the establishment of the stump prairie.

The pre-disturbance forest that existed in current stump prairie areas was considerably different from the forest that existed where it has regenerated, as shown in the General Land Office survey notes. In particular, the forests in the stump prairie areas were predominantly pine forests, with a major component of white pine. Especially notable is the near lack of any record of sugar maple trees in the areas that today remain stump prairie, and its prevalence in areas that today are upland forests. Current upland forest areas were occupied primarily by beech-sugar maple-yellow birch forests, which also contained some white pine and hemlock.

Evidence from soil properties suggests that the soils in the forest and the stump prairie are similar, but subtle distinctions between the two groups do exist. Parent material texture is indistinguishable between the two regions, but amounts of Fe, Al, and OC are higher in the forested than stump prairie soils. Most differences between the two groups of soils can be attributed to differences in ortstein content; forest soils have more ortstein than stump prairie soils. Thus, the spatial relationship between forest regeneration patterns and soil patterns is best related to the ortstein content of the soil.

The distributions of Fe, Al, and OC within the profiles of both forest and stump prairie soils are consistent with current theories of podzolization, suggestive of translocation of Fe and Al in organically complexed form in upper horizons, and possible further translocation of inorganic forms of Al primarily into lower horizons. Soil solutions, studied using bags of cation exchange and chelating resins, indicate that podzolization processes are active in both groups of soils but appear currently to be stronger in the forested pedons. Little evidence was found to suggest that differences in degree of soil development could be attributed to processes destroying the spodic horizon due to the change in vegetation type from forest to grassland in the stump prairie region.

Tax assessment and ownership data show that land ownership patterns in the study area were constant from the time of its original acquisition in the 1860s and 1870s through the end of the century. Logging activity was primarily carried out by two separate logging interests, and the holdings of these companies were centered on the stump prairie areas, suggesting that the stump prairie areas may have received somewhat different treatment than the surrounding areas when they were logged. The date of logging, in the early 1890s for the entire region, was apparently not associated spatially with the forest recovery pattern. Based on the presence of burned stumps and snags, as well as charcoal found in the soil, logging-era fires probably affected both forested and stump prairie areas to some degree. Unscarred trees in some currently forested areas dating from well before the logging era suggest that fires may have been less severe and logging efforts less complete in forested regions than in adjacent stump prairie areas.

The patterns of soils, pre-disturbance forests, logging practices, and fires suggest that both physical and anthropogenic factors have a spatial correspondence with the pattern of forest recovery in the Kingston Plains area today. No differences in substrate texture between forests and stump prairie were observed, but the distinctions in the pre-disturbance forest of the two regions probably led to differences in logging practices and fire frequency and intensity that precluded the rapid return of forest species in the stump prairie. Observations from historical aerial photographs show, however, that the character of the stump prairie is slowly changing, such that more trees, especially white pine trees, are present today than in the 1930s. It seems likely that, left undisturbed, the stump prairie areas will slowly recover, and with the passage of time, a pine forest could become established there.

The Kingston Plains stump prairie presents a unique opportunity for studying the adverse effects of human activity on the landscape. At first glance, the obvious change in vegetation type on the stump prairie would seem to point to gross mismanagement of the land by the lumber companies in the late nineteenth century. What this study has shown, however, is that specific natural conditions unique to this site also played a part in the development of the stump prairie. The forest that existed on the Kingston Plains in the late nineteenth century was rich in white pine, a species that the lumber companies sought. The concentration of white pine invited the loggers to cut the forest there especially thoroughly. In the cultural climate of the time, the nearly inevitable consequence of this type of logging activity on xeric upland sites was frequent and intense fire. The combination of fires and dry, infertile soils meant that conditions were unfavorable for forest regeneration, and the result was a stumped landscape of rolling sand plaines, lichen, and bracken fern. It is likely, however, that if any of the links in this chain of conditions had been lacking, forest regeneration pathways in the area would have been quite different.

The Kingston Plains is an example of a site where the spatial coincidence of natural factors and human actions led to an abrupt change in the ecosystem. Although human actions were the impetus for the changes that occurred, the physical characteristics of the stump prairie site itself were prerequisite for catastrophic change due to logging. Thus this site was especially vulnerable ("environmentally susceptible"; Quinn 1991) to injury from this specific human activity. The aim of this dissertation has been to recount what happened in the Kingston Plains, and to investigate why it happened *there*, and not elsewhere. The Kingston Plains is, therefore, not simply an example of lack of environmental sensitivity on the part of greedy lumber companies. The Kingston Plains, like many cases of environmental degradation, represents the results of an interaction between the natural environment and human actions.

Recognition that a particular location may be environmentally susceptible does not negate or relieve the human responsibility for environmental degradation. Rather, it should remind us that in land management decisions we are responsible for understanding as much of the total landscape as possible before we undertake actions which could upset the balances that exist. Especially in sites which may be more ecologically fragile, such as areas prone to drought, it is imperative to attempt to determine the scope of our potential impact *before* undertaking wide-scale land management schemes. It is possible that a stump prairie might not have developed in the Kingston Plains if the logging disturbance had been accomplished in a "gentler" manner, even given the lack of fire controls of the time: i.e., using a selective cut rather than a clear cut. A selective cut might have retained enough trees for shade to allow forest regeneration to occur at a much faster rate. Granted, selective cutting was not the typical method in which logging was accomplished at the time. Similarly, we should be looking to see if our "usual" land management practices could be harboring an unintended threat to environmentally susceptible parts of the landscape.

Suggestions for future research

This dissertation has investigated spatial patterns of forest vegetation, logging, and soils in order to elucidate the factors that might have contributed to the origin and maintenance of the stump prairie in the Kingston Plains. Although the spatial coincidence of many of these factors is remarkable, causal mechanisms have not been established. Further investigation of the causal mechanisms involved with tree regeneration following fire in the soils of the area should be undertaken.

The logging history of the Kingston Plains, and, in fact, of much of the Upper Peninsula, has received little attention from researchers to date. Research into actual logging dates and methods, perhaps using detailed lumber company records, if they exist, would help to establish the correspondence between the human actions and the resulting land use changes with greater precision than has been possible in this dissertation.

It is known that the stump prairie of the Kingston Plains is not a unique landscape type in northern Michigan, but the extent of stump prairie in Michigan has not yet been described. In connection with that description, an overview of pre-logging forest types and soil development would establish whether the factors contributing to stump prairie formation in the Kingston Plains were also common in nineteenth century northern Michigan, or whether other factors contributed to stump prairie formation at other sites.

In the Kingston Plains, pre-disturbance forest patterns are related to origin of the stump prairie landscape. The origins of those pre-disturbance forest patterns could thus be considered as contributors to the stump prairie landscape as well, or even an ultimate "cause" of the stump prairie. An investigation into the Holocene site history before the mid-1800s, with a focus on forest development and forest disturbance, would provide a more satisfying completion to the story of the stump prairie and also a better understanding of the site itself.

Finally, further investigation into soil development processes following vegetation change would help to establish whether the vegetation changes that have taken place in the Kingston Plains have had an effect on the soil development pathways there. Especially interesting in this regard is whether measurable degradation of the spodic horizon can actually take place on time scales of a century or so, and whether soil processes themselves have changed with the removal of the forest vegetation. The data presented in this study suggest that soil degradation due to removal of forest vegetation is minimal, or at least not easily measurable after only one century, and that soil processes in the stump prairie remain qualitatively similar to those in the forested areas. Nevertheless, further study is necessary to corroborate and establish these rather preliminary conclusions.

APPENDIX A: DATA TABLES

Table 22. Particle size analysis data from the sampled pedons.

Horizon	Clay <0.002 mm	Silt 0.05-0.002 mm	Sand 2.0-0.05 mm	VCS 2.0-1.0 mm	CS 1.0-0.5 mm	MS 0.05-0.25 mm	FS 0.25-0.1 mm	VFS 0.1-0.05 mm
	-------% of fine earth------			----------------% of sand fraction----------------				
				FOR-1				
E	0.9	4.0	95.1	0.6	8.9	56.0	32.3	2.3
Bhs	4.2	4.8	91.1	0.9	7.6	52.7	36.4	2.4
Bs1	1.7	2.0	96.3	1.1	7.0	58.4	31.6	1.9
Bs1*	2.0	1.3	96.8	0.9	7.0	57.9	32.7	1.5
Bs2	0.4	0.3	99.3	2.0	12.0	62.5	22.6	0.9
BC	0.4	0.3	99.4	7.8	27.8	48.1	15.8	0.6
C	0.2	0.2	99.6	1.7	16.7	61.4	19.3	0.8
				FOR-2				
E	0.7	4.1	95.2	1.0	11.6	58.2	27.4	1.7
Bhs	3.3	4.6	92.1	1.9	9.2	51.9	35.1	1.8
Bs1	2.0	2.3	95.7	3.3	9.6	48.9	36.9	1.2
Bs1*	3.1	2.4	94.5	2.5	9.3	49.0	37.8	1.3
Bs2	0.5	0.4	99.1	0.8	10.2	69.7	18.9	0.5
BC	0.2	0.2	99.6	2.7	10.5	67.4	18.9	0.5
C	0.4	0.1	99.5	3.5	15.7	70.1	10.3	0.3
C(200)[1]	0.1	0.1	99.8	0.6	5.3	65.7	27.1	1.3
				FOR-3				
E	1.4	5.1	93.6	0.5	5.5	44.0	45.7	4.3
Bhs	4.4	5.0	90.6	0.9	5.7	41.9	47.3	4.2
Bs1	1.2	2.2	96.7	0.9	4.7	41.3	49.4	3.8
Bs1*	2.6	2.2	95.2	0.7	4.0	32.9	57.9	4.5
Bs2	0.6	0.3	99.1	1.2	6.6	56.8	33.6	1.8
Bs2*	1.1	0.5	98.4	0.8	6.3	57.4	33.5	2.0
BC	0.2	0.1	99.6	0.4	4.4	68.0	26.4	0.9
BC*	1.0	0.3	98.7	0.2	3.9	63.8	31.0	1.1
C	0.2	0.1	99.7	0.2	4.4	71.5	23.3	0.7
C (200)	0.2	0.2	99.6	6.7	15.0	58.1	19.6	0.6
C (240)	0.2	0.1	99.7	0.0	0.4	36.9	61.2	1.4

[1]Indicates depth midpoint (cm) for deep samples.

*Indicates ortstein subsample.

Table 22. (Cont.)

Horizon	Clay <0.002 mm	Silt 0.05-0.002 mm	Sand 2.0-0.05 mm	VCS 2.0-1.0 mm	CS 1.0-0.5 mm	MS 0.05-0.25 mm	FS 0.25-0.1 mm	VFS 0.1-0.05 mm
	------% of fine earth------			----------------% of sand fraction----------------				
				FOR-4				
E	0.9	4.2	94.9	1.4	14.7	58.4	24.0	1.5
Bhs	3.6	5.1	91.3	2.7	12.4	54.8	28.8	1.3
Bs1	2.0	2.5	95.5	2.0	12.3	57.1	27.5	1.0
Bs1*	3.3	2.2	94.5	2.0	10.6	55.2	31.2	1.0
Bs2	0.8	0.5	98.7	0.4	6.5	62.8	29.6	0.7
Bs2*	1.6	0.5	97.9	0.7	8.3	65.6	25.0	0.4
BC	0.3	0.2	99.5	1.7	9.0	69.3	19.5	0.5
BC*	0.5	0.2	99.3	1.1	5.8	61.6	30.5	0.9
C	0.2	0.3	99.5	0.4	8.5	51.0	38.4	1.8
C (220)	0.1	0.1	99.8	0.2	7.9	69.7	21.7	0.5
				FOR-5				
E	1.5	5.1	93.4	1.3	15.4	63.4	18.6	1.3
Bs1	2.9	3.7	93.4	2.9	14.8	61.1	20.5	0.8
Bs1*	2.6	1.7	95.7	2.7	13.6	61.6	21.5	0.6
Bs2	0.8	0.5	98.7	0.6	6.0	71.9	21.1	0.4
Bs2*	1.4	0.3	98.3	2.0	11.6	62.3	23.8	0.3
BC	0.3	0.3	99.4	1.0	14.4	68.2	15.8	0.6
C	0.2	0.1	99.6	0.2	10.7	77.3	11.6	0.3
C (230)	0.2	0.1	99.7	4.7	14.5	67.9	12.7	0.2
				FOR-6				
A	9.0	7.8	83.3	0.7	10.4	55.9	30.0	2.8
E	1.4	6.2	92.4	0.9	9.5	53.4	32.4	3.7
Bs1	2.2	4.1	93.7	1.6	10.2	55.8	29.2	3.2
Bs1*	2.4	3.5	94.0	1.3	9.0	54.8	31.7	3.1
Bs2	0.5	2.4	97.1	1.4	7.0	46.1	38.7	6.8
Bs2*	0.8	1.9	97.3	1.8	10.1	56.1	28.3	3.6
BC	0.2	1.3	98.5	1.6	14.9	64.8	16.7	2.0
C	0.3	1.7	98.0	5.2	16.2	48.8	27.1	2.7
2C	0.8	8.7	90.5	0.2	1.1	35.1	53.0	10.7
3C	0.1	0.5	99.5	0.3	3.7	61.6	33.9	0.5

*Indicates ortstein subsample.

Table 22. (Cont.)

Horizon	Clay <0.002 mm	Silt 0.05-0.002 mm	Sand 2.0-0.05 mm	VCS 2.0-1.0 mm	CS 1.0-0.5 mm	MS 0.05-0.25 mm	FS 0.25-0.1 mm	VFS 0.1-0.05 mm
	------% of fine earth------			---------------% of sand fraction---------------				
				FOR-7				
E	0.6	4.0	95.3	0.8	11.7	62.2	24.1	1.3
Bhs	4.1	5.0	90.8	1.1	8.6	55.8	33.2	1.3
Bs1	2.2	1.0	96.8	0.9	10.5	64.6	23.3	0.7
Bs1*	1.5	0.6	97.9	2.2	17.6	64.9	14.9	0.4
Bs2	0.4	0.2	99.4	2.0	17.3	63.8	16.4	0.4
Bs2*	1.0	0.4	98.6	2.0	14.8	66.2	16.7	0.3
BC	0.2	0.3	99.5	3.1	13.7	56.7	25.8	0.6
C	0.2	0.2	99.6	1.2	20.4	68.4	9.7	0.3
C (122)	2.9	2.0	95.0	4.4	22.6	57.7	14.3	0.9
C (230)	0.2	0.2	99.6	11.3	36.3	44.1	8.1	0.3
				FOR-8				
E	0.9	5.0	94.1	2.3	17.9	60.4	17.4	1.9
Bhsm	5.5	5.5	89.0	4.2	15.7	56.9	21.6	1.6
Bsm1	2.1	2.2	95.7	3.7	19.3	60.0	15.8	1.2
Bsm1 *	2.4	2.8	94.7	3.0	14.9	60.7	20.1	1.3
Bsm2	0.9	0.5	98.6	5.1	24.0	55.6	14.6	0.7
2BC	0.4	0.7	98.9	21.4	41.0	29.7	7.2	0.7
3C	0.2	0.3	99.5	2.7	18.3	61.5	16.9	0.7
C (220)	0.1	0.2	99.7	2.2	10.0	71.5	16.0	0.4
				FOR-9				
E	1.2	5.1	93.8	0.8	8.0	48.2	39.6	3.4
Bhs	4.4	5.6	89.9	0.7	6.5	45.0	43.8	4.1
Bs1	1.6	2.7	95.7	1.0	6.8	44.0	45.2	3.0
Bs1*	4.1	3.9	92.0	0.7	6.0	43.9	45.7	3.7
Bs2	0.7	1.1	98.2	0.8	5.9	50.1	41.3	1.9
Bs2*	1.7	1.1	97.2	0.3	3.3	51.5	42.6	2.3
BC	0.4	0.3	99.3	0.3	4.9	57.7	35.7	1.3
C	0.2	0.2	99.6	0.7	12.7	60.1	25.5	1.0
C (270)	0.4	0.5	99.2	0.2	3.0	27.9	63.3	5.6
C (280)	4.8	27.8	67.4	0.1	1.0	14.3	49.2	35.4

*Indicates ortstein subsample.

Table 22. (Cont.)

Horizon	Clay <0.002 mm	Silt 0.05-0.002 mm	Sand 2.0-0.05 mm	VCS 2.0-1.0 mm	CS 1.0-0.5 mm	MS 0.05-0.25 mm	FS 0.25-0.1 mm	VFS 0.1-0.05 mm
	------% of fine earth------			----------------% of sand fraction----------------				
				SAV-1				
A	6.2	10.9	82.9	6.9	19.1	48.5	23.6	1.8
E	1.8	5.1	93.1	1.2	14.0	53.4	29.1	2.4
Bs1	1.2	1.8	96.9	3.4	10.9	48.5	35.5	1.7
Bs1*	2.0	2.1	95.8	2.5	9.2	49.9	36.7	1.6
Bs2	0.3	0.4	99.2	2.5	21.2	58.6	17.0	0.7
BC	0.3	0.1	99.6	4.4	20.2	60.5	14.6	0.3
C	0.5	0.2	99.3	2.1	7.9	51.1	37.3	1.6
				SAV-2				
A	4.4	6.0	89.7	0.7	13.0	60.2	24.9	1.1
E	1.0	4.1	94.9	0.9	11.9	63.1	22.6	1.6
Bs1	0.7	0.8	98.5	0.9	7.5	59.1	31.5	1.0
Bs1*	2.0	1.4	96.6	1.2	8.1	58.7	31.1	0.9
Bs2	0.3	0.3	99.4	6.9	23.6	57.2	11.9	0.4
BC	0.4	0.1	99.5	5.4	27.3	59.3	7.8	0.2
C	0.1	0.1	99.8	0.2	5.1	81.1	13.3	0.3
				SAV-3				
A	3.9	8.6	87.5	0.7	6.7	51.5	38.2	2.9
E	1.6	4.7	93.7	0.5	6.2	48.3	41.1	3.9
Bs1	2.1	4.2	93.6	1.2	4.2	39.8	49.4	5.4
Bs1*	2.8	3.9	93.4	1.5	3.6	37.4	51.6	5.9
Bs2	0.5	0.4	99.1	1.0	5.9	64.3	27.7	1.1
BC	0.2	0.1	99.6	1.3	6.9	70.3	21.2	0.3
C	0.4	0.1	99.6	0.0	0.3	37.9	60.3	1.4
				SAV-4				
A	2.9	8.6	88.5	0.6	8.2	45.9	42.6	2.6
E	0.8	5.0	94.2	0.4	6.0	41.6	48.8	3.2
Bs1	2.0	3.2	94.8	1.0	5.6	38.3	52.4	2.7
Bs1*	3.2	3.5	93.2	1.3	6.4	48.2	42.5	1.7
Bs2	0.4	0.5	99.1	2.1	13.0	57.2	26.6	1.2
BC	0.3	0.4	99.4	0.9	9.8	53.7	33.8	1.8
C	0.1	0.1	99.8	0.8	14.4	77.2	7.4	0.2
C (135)	0.1	0.3	99.6	0.0	2.6	47.7	47.9	1.7

*Indicates ortstein subsample.

Table 22. (Cont.)

Horizon	Clay <0.002 mm	Silt 0.05-0.002 mm	Sand 2.0-0.05 mm	VCS 2.0-1.0 mm	CS 1.0-0.5 mm	MS 0.05-0.25 mm	FS 0.25-0.1 mm	VFS 0.1-0.05 mm
	------% of fine earth------			---------------% of sand fraction---------------				
				SAV-5				
A	4.3	6.2	89.5	1.2	10.3	54.0	32.4	2.1
E	1.0	4.3	94.6	1.2	8.8	56.0	31.4	2.6
Bs1	1.8	3.0	95.2	2.8	9.2	53.0	33.0	2.0
Bs1*	2.3	2.3	95.3	3.8	7.9	50.6	35.7	2.1
Bs2	0.6	1.1	98.3	6.5	6.4	46.2	38.5	2.3
BC	0.2	0.5	99.3	1.5	11.4	56.2	29.7	1.2
C	0.1	0.1	99.8	1.8	5.7	59.7	31.2	1.6
C (250)	0.1	0.1	99.8	1.2	9.1	69.9	19.5	0.3
				SAV-6				
A	2.3	6.7	91.0	0.4	4.6	67.9	26.1	0.9
E	1.1	3.5	95.3	0.3	4.2	60.6	33.6	1.3
Bhs	2.6	3.8	93.6	0.4	3.4	59.3	35.8	1.2
Bs1	1.3	2.0	96.7	0.7	3.5	65.8	29.3	0.7
Bs1*	2.3	0.9	96.8	0.2	2.5	62.2	34.5	0.7
Bs2	0.5	0.4	99.1	0.1	2.1	63.6	33.5	0.6
Bs2*	1.1	0.5	98.4	0.2	1.2	41.8	55.6	1.2
BC	0.3	0.2	99.4	0.8	6.6	60.2	31.6	0.8
BC*	1.0	0.6	98.4	0.8	3.8	52.5	40.9	1.9
C	0.2	0.3	99.5	0.0	1.1	55.4	42.0	1.4
C (230)	0.1	0.1	99.8	0.3	3.6	48.3	47.0	0.8
				SAV-7				
A	2.3	6.4	91.4	1.2	11.7	55.7	29.8	1.7
E	1.1	4.9	94.1	1.6	12.3	54.9	29.5	1.7
Bs1	1.8	2.5	95.7	2.1	10.8	54.0	32.0	1.2
Bs1*	3.7	2.8	93.5	5.0	12.5	47.8	33.1	1.6
Bs2	0.3	0.4	99.3	0.4	6.2	59.3	33.2	0.9
Bs2*	1.3	0.5	98.2	0.3	6.4	55.7	36.7	1.0
BC	0.2	0.2	99.5	3.2	32.0	58.9	5.5	0.3
C	0.1	0.2	99.7	2.0	11.6	64.8	21.2	0.4
C (200)	0.1	0.2	99.7	0.6	4.5	51.4	42.4	1.2
C (300)	0.2	0.1	99.7	1.7	13.7	70.1	14.2	0.3

*Indicates ortstein subsample.

Table 22. (Cont.)

Horizon	Clay <0.002 mm	Silt 0.05-0.002 mm	Sand 2.0-0.05 mm	VCS 2.0-1.0 mm	CS 1.0-0.5 mm	MS 0.05-0.25 mm	FS 0.25-0.1 mm	VFS 0.1-0.05 mm
	------% of fine earth------			----------------% of sand fraction----------------				
				SAV-8				
A	4.0	5.0	91.0	0.8	11.7	56.4	29.7	1.5
E	1.2	3.9	94.9	1.3	12.2	55.6	29.3	1.7
Bs1	2.4	2.9	94.7	1.5	9.6	56.1	31.3	1.5
Bs1*	2.3	1.5	96.2	2.4	11.1	55.4	30.2	0.9
Bs2	0.7	0.2	99.0	2.3	13.6	60.2	23.3	0.5
Bs2*	1.1	0.3	98.7	2.7	15.5	54.9	26.3	0.6
BC	0.3	0.3	99.5	1.5	10.7	67.0	19.9	1.0
C	0.4	0.2	99.4	9.3	38.2	43.4	8.6	0.5
C (279)	0.3	0.0	99.7	1.5	8.9	48.5	39.7	1.4

Table 23. Chemical data from the sampled pedons.

Horizon	pH	pH	ODOE	OC	Fe_p	Fe_d	Fe_o	Al_p	Al_d	Al_o	Si_p	Si_o
	2:1 H_2O	2:1 KCl		g kg^{-1}								
					FOR-1							
Oa	3.9	2.9	--	363.8	--	--	--	--	--	--	--	--
E	4.6	3.3	0.003	2.1	0.1	0.6	0.0	0.1	0.0	0.0	0.2	0.0
Bhs	4.3	3.7	0.396	10.4	1.7	3.4	2.1	1.3	1.6	1.7	0.1	0.5
Bs1	4.7	4.6	0.088	3.2	0.3	1.6	0.9	1.4	1.7	3.1	0.2	1.7
Bs1*	4.4	4.1	0.405	8.2	0.7	1.6	1.0	1.3	1.6	2.0	0.1	0.7
Bs2	5.2	4.8	0.030	0.9	0.1	0.4	0.2	0.6	0.4	0.8	0.1	0.6
BC	5.2	4.8	0.010	0.5	0.1	0.4	0.2	0.4	0.3	0.6	0.1	0.3
C	5.6	4.8	0.009	0.1	0.1	0.3	0.1	0.2	0.1	0.3	0.0	0.1
					FOR-2							
Oa	3.9	2.9	--	418.1	--	--	--	--	--	--	--	--
E	4.6	3.3	0.012	4.4	0.1	0.5	0.0	0.1	0.1	0.1	0.1	0.0
Bhs	4.7	3.9	0.338	10.1	1.7	3.4	2.4	1.5	1.9	2.4	0.2	0.8
Bs1	4.9	4.5	0.152	4.7	0.4	2.1	1.3	1.6	2.2	3.6	0.3	2.3
Bs1*	4.6	4.1	0.272	6.2	1.4	2.7	1.9	1.4	1.5	1.9	0.2	0.9
Bs2	5.1	4.6	0.060	1.4	0.3	0.8	0.4	0.8	0.8	1.2	0.1	0.7
BC	5.4	4.7	0.029	1.0	0.1	0.3	0.2	0.6	0.5	0.7	0.1	0.4
C	5.4	4.7	0.025	0.6	0.2	0.4	0.3	0.5	0.4	0.6	0.1	0.2
C (200)[1]	5.3	4.8	0.001	0.2	0.1	0.3	0.1	0.2	0.1	0.2	0.1	0.1
					FOR-3							
Oa	3.9	2.7	--	419.4	--	--	--	--	--	--	--	--
E	4.5	3.3	0.031	5.8	0.2	0.9	0.2	0.2	0.1	0.2	0.1	0.0
Bhs	4.6	3.8	0.593	17.3	2.0	4.3	2.8	2.0	2.7	3.6	0.2	1.8
Bs1	4.6	4.4	0.179	5.8	0.5	1.7	0.9	1.5	1.8	2.8	0.2	1.3
Bs1*	4.5	3.9	0.599	11.4	1.3	2.2	1.5	1.6	1.7	2.1	0.2	0.4
Bs2	4.9	4.5	0.064	2.1	0.3	0.6	0.3	0.9	0.7	1.1	0.1	0.6
Bs2*	4.5	4.1	0.280	5.5	0.5	1.0	0.6	0.7	0.9	1.0	0.1	0.2
BC	5.4	4.8	0.016	0.6	0.1	0.2	0.1	0.4	0.2	0.4	0.0	0.2
BC*	4.8	4.2	0.301	5.6	0.5	0.8	0.7	0.9	0.9	1.0	0.1	0.2
C	5.5	4.7	0.014	0.5	0.1	0.2	0.1	0.2	0.1	0.3	0.0	0.1
C (200)	5.4	4.8	0.004	0.3	0.0	0.3	0.0	0.2	0.1	0.3	0.1	0.1
C (240)	5.9	4.7	0.004	0.2	0.1	0.5	0.1	0.2	0.1	0.2	0.0	0.1

[1]Indicates depth midpoint in cm for deep samples.

*Indicates ortstein subsample.

Table 23 (Cont.)

Horizon	pH	pH	ODOE	OC	Fe_p	Fe_d	Fe_o	Al_p	Al_d	Al_o	Si_p	Si_o
	2:1 H_2O	2:1 KCl		-----------------------------				$g\ kg^{-1}$				-----------------------------
						FOR-4						
Oa	4.4	3.3	--	353.8	--	--	--	--	--	--	--	--
E	4.8	3.3	0.000	4.0	0.1	0.4	0.0	0.1	0.0	0.1	0.1	0.0
Bhs	4.5	3.7	0.392	12.6	2.0	4.2	3.2	1.1	1.7	2.3	0.1	0.7
Bs1	4.6	4.4	0.180	6.2	0.6	2.8	1.9	1.8	2.4	4.2	0.2	2.4
Bs1*	4.3	4.0	0.605	10.5	1.3	2.7	2.1	1.9	2.3	3.4	0.3	1.3
Bs2	5.0	4.7	0.051	2.8	0.2	0.8	0.5	0.6	0.6	1.8	0.1	1.2
Bs2*	4.5	4.2	0.410	8.4	0.7	1.3	0.9	1.5	1.6	2.0	0.2	0.6
BC	5.4	4.8	0.020	0.4	0.1	0.3	0.2	0.4	0.3	0.7	0.1	0.4
BC*	4.9	4.6	0.063	1.7	0.2	0.5	0.3	0.6	0.6	1.1	0.1	0.4
C	5.2	4.9	0.020	0.5	0.1	0.3	0.1	0.4	0.3	0.5	0.1	0.3
C (220)	5.5	5.0	0.005	0.4	0.0	0.2	0.0	0.1	0.1	0.2	0.0	0.1
						FOR-5						
Oi	4.4	3.7	--	282.5	--	--	--	--	--	--	--	--
E	4.5	3.2	0.038	7.6	0.2	0.6	0.2	0.2	0.1	0.1	0.3	0.0
Bs1	4.6	4.1	0.237	10.0	1.1	2.8	1.8	2.2	2.1	2.9	0.2	1.7
Bs1*	4.6	4.0	0.380	10.6	1.4	2.3	1.7	2.7	2.4	2.6	0.4	0.9
Bs2	5.1	4.6	0.060	2.3	0.3	0.6	0.4	1.3	0.8	1.5	0.2	1.0
Bs2*	4.8	4.2	0.300	5.8	0.8	1.3	1.0	1.7	1.7	1.9	0.3	0.7
BC	5.6	4.7	0.018	1.2	0.2	0.3	0.2	0.7	0.5	0.7	0.1	0.4
C	5.5	4.8	0.017	2.9	0.1	0.3	0.2	0.4	0.2	0.5	0.1	0.3
C (230)	5.7	4.8	0.009	0.3	0.1	0.2	0.1	0.3	0.1	0.3	0.1	0.1
						FOR-6						
Oi	4.1	3.5	--	372.3	--	--	--	--	--	--	--	--
A	4.9	3.4	0.083	57.1	0.6	2.0	0.9	0.6	1.0	0.9	0.9	0.0
E	4.6	3.5	0.028	6.7	0.3	0.8	0.2	0.2	0.1	0.2	0.2	0.0
Bs1	5.1	4.4	0.230	7.8	0.7	3.3	2.2	2.0	2.2	4.4	0.2	2.5
Bs1*	5.0	4.3	0.322	8.6	0.7	2.2	1.2	1.5	2.3	2.8	0.2	1.4
Bs2	5.2	4.6	0.050	2.0	0.2	0.8	0.4	0.8	0.6	1.1	0.1	0.7
Bs2*	5.2	4.6	0.108	3.0	0.3	0.9	0.6	1.2	1.0	1.6	0.2	0.9
BC	5.3	4.7	0.015	0.7	0.1	0.2	0.1	0.4	0.2	0.6	0.1	0.4
C	5.4	4.9	0.010	0.5	0.1	0.3	0.1	0.4	0.2	0.4	0.1	0.3
2C	5.0	4.3	0.050	3.8	0.3	0.8	0.3	0.5	0.5	0.6	0.1	0.2
3C	5.6	5.0	0.002	0.1	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.1

*Indicates ortstein subsample.

Table 23 (Cont.)

Horizon	pH	pH	ODOE	OC	Fe_p	Fe_d	Fe_o	Al_p	Al_d	Al_o	Si_p	Si_o
	2:1 H_2O	2:1 KCl		-------------------------------				$g\ kg^{-1}$				-------------------------------
						FOR-7						
Oa	4.7	4.3	--	215.6	--	--	--	--	--	--	--	--
E	4.6	3.7	0.000	3.3	0.1	0.3	0.0	0.1	0.0	0.0	0.1	0.0
Bhs	4.7	3.7	0.545	16.9	2.6	5.1	2.9	1.5	1.9	1.8	0.1	0.5
Bs1	4.8	4.5	0.190	5.5	0.4	1.9	1.5	2.2	1.8	7.1	0.2	4.5
Bs1*	5.1	4.3	0.302	6.9	0.7	1.6	1.2	2.1	1.9	2.5	0.2	1.6
Bs2	5.5	4.9	0.030	1.2	0.2	0.4	0.3	0.8	0.5	1.3	0.2	0.8
Bs2*	5.3	4.6	0.180	4.5	0.4	0.7	0.6	1.5	1.3	2.6	0.2	1.3
BC	6.0	4.9	0.022	1.2	0.1	0.3	0.2	0.5	0.4	0.5	0.1	0.3
C	6.1	5.0	0.000	0.4	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.1
C (122)	5.6	4.6	0.030	1.1	0.3	0.9	0.3	0.8	0.4	0.9	0.3	0.4
C (230)	5.7	5.0	0.010	0.3	0.1	0.3	0.1	0.2	0.1	0.3	0.1	0.2
						FOR-8						
Oa	4.2	3.2	--	318.3	--	--	--	--	--	--	--	--
E	4.4	3.2	0.010	4.1	0.1	0.4	0.1	0.1	0.0	0.1	0.1	0.0
Bhsm	4.5	3.8	0.621	20.9	3.1	5.5	3.3	2.7	2.7	2.7	0.5	0.7
Bsm1	4.8	4.4	0.199	5.7	0.5	2.0	1.2	1.7	2.0	3.3	0.2	2.1
Bsm1*	5.1	4.4	0.380	10.1	0.9	2.5	1.6	3.1	2.9	4.3	0.3	2.2
Bsm2	5.3	4.6	0.067	2.1	0.2	0.6	0.4	1.2	0.6	1.6	0.2	0.9
2BC	5.4	4.8	0.020	1.1	0.1	0.5	0.2	0.7	0.3	0.9	0.1	0.5
3C	5.8	4.8	0.017	0.6	0.1	0.2	0.1	0.3	0.2	0.4	0.1	0.2
C (220)	5.9	4.8	0.000	0.0	0.1	0.2	0.1	0.2	0.0	0.1	0.1	0.0
						FOR-9						
Oi	3.8	3.1	--	192.7	--	--	--	--	--	--	--	-
E	4.4	3.2	0.005	4.7	0.1	0.8	0.1	0.1	0.1	0.2	0.2	0.0
Bhs	4.4	3.6	0.481	13.9	2.0	3.8	2.1	1.6	1.7	1.6	0.2	0.4
Bs1	4.7	4.5	0.160	6.0	0.5	1.9	1.1	2.1	2.0	4.1	0.3	2.6
Bs1*	4.6	3.9	0.560	13.6	1.4	3.1	2.3	1.8	2.1	3.5	0.2	1.2
Bs2	5.1	4.6	0.038	2.5	0.2	0.8	0.3	0.6	0.7	1.0	0.1	0.6
Bs2*	5.0	4.2	0.440	8.7	0.8	1.5	0.9	2.5	2.1	2.4	0.2	0.6
BC	5.4	4.8	0.021	0.7	0.2	0.4	0.1	0.5	0.4	0.6	0.1	0.3
C	5.6	4.9	0.010	0.6	0.1	0.3	0.1	0.3	0.3	0.4	0.1	0.2
C (270)	5.5	--	0.018	0.3	0.1	0.5	0.2	0.2	0.2	0.4	0.0	0.2
C (280)	5.6	4.3	0.031	0.5	0.0	4.8	0.6	0.8	1.3	1.4	0.1	0.6

*Indicates ortstein subsample.

Table 23 (Cont.)

Horizon	pH	pH	ODOE	OC	Fe_p	Fe_d	Fe_o	Al_p	Al_d	Al_o	Si_p	Si_o
	2:1 H_2O	2:1 KCl		----------------------------				$g\ kg^{-1}$				----------------------------
						SAV-1						
A	4.4	3.3	--	96.0	--	--	--	--	--	--	--	--
E	4.7	3.5	0.050	10.1	0.4	0.8	0.4	0.4	0.2	0.3	0.2	0.0
Bs1	5.3	4.7	0.060	1.8	0.3	1.1	0.6	1.3	1.1	2.0	0.3	1.2
Bs1*	5.2	4.4	0.272	6.3	0.9	1.8	1.3	2.1	1.9	2.6	0.3	1.1
Bs2	5.5	4.9	0.010	0.5	0.1	0.4	0.3	0.4	0.3	1.1	0.1	0.6
BC	5.6	5.0	0.000	0.3	0.1	0.2	0.1	0.3	0.1	0.5	0.0	0.3
C	5.6	4.6	0.020	0.1	0.3	0.5	0.2	0.5	0.3	0.3	0.2	0.1
						SAV-2						
A	4.4	3.4	--	40.0	--	--	--	--	--	--	--	--
E	4.7	3.6	0.015	5.2	0.1	0.4	0.1	0.2	0.1	0.1	0.2	0.0
Bs1	5.5	4.9	0.030	1.3	0.2	1.0	0.6	0.9	0.7	2.3	0.2	1.5
Bs1*	5.1	4.4	0.392	6.8	0.8	1.9	1.4	2.3	2.0	3.1	0.1	1.8
Bs2	5.6	5.0	0.010	0.4	0.1	0.2	0.2	0.4	0.2	0.7	0.1	0.5
BC	5.8	4.9	0.005	0.3	0.1	0.4	0.2	0.3	0.2	0.4	0.1	0.2
C	6.0	4.9	0.012	0.1	0.1	0.2	0.1	0.2	0.0	0.2	0.0	0.2
						SAV-3						
A	4.1	3.3	--	52.1	--	--	--	--	--	--	--	--
E	4.2	3.5	0.018	5.9	0.2	0.6	0.2	0.2	0.1	0.2	0.2	0.0
Bs1	4.9	4.6	0.171	7.6	0.6	2.8	1.3	2.2	2.5	4.0	0.4	2.6
Bs1*	5.0	4.4	0.430	11.4	1.3	4.1	2.8	4.3	4.0	5.7	0.2	2.7
Bs2	5.3	4.8	0.022	1.2	0.1	0.4	0.2	0.6	0.4	0.8	0.1	0.5
BC	5.7	4.9	0.012	0.6	0.1	0.3	0.1	0.4	0.3	0.5	0.1	0.3
C	5.8	4.9	0.000	0.1	0.0	0.2	0.1	0.2	0.1	0.4	0.0	0.3
						SAV-4						
A	4.6	3.4	--	42.6	--	--	--	--	--	--	--	--
E	4.5	3.7	0.012	5.0	0.0	0.7	0.1	0.0	0.1	0.1	0.0	0.0
Bs1	4.6	4.6	0.153	5.1	0.5	2.7	1.3	1.6	1.8	4.6	0.3	3.2
Bs1*	5.3	4.3	0.485	11.2	1.3	3.6	1.9	2.6	3.5	4.3	0.2	2.0
Bs2	4.6	4.9	0.023	1.3	0.1	0.7	0.4	0.5	0.4	1.4	0.1	1.0
BC	5.4	4.8	0.020	0.7	0.2	0.7	0.3	0.5	0.4	0.7	0.1	0.4
C	5.3	4.9	0.000	0.4	0.1	0.1	0.1	0.3	0.1	0.3	0.1	0.2
C (135)	5.3	4.9	0.005	0.4	0.1	0.3	0.1	0.3	0.2	0.4	0.1	0.2

*Indicates ortstein subsample.

Table 23 (Cont.)

Horizon	pH 2:1 H_2O	pH 2:1 KCl	ODOE	OC	Fe_p	Fe_d	Fe_o	Al_p	Al_d	Al_o	Si_p	Si_o
				$g\ kg^{-1}$								
						SAV-5						
A	4.5	3.0	--	55.0	--	--	--	--	--	--	--	--
E	4.6	3.5	0.018	4.5	0.2	0.7	0.1	0.2	0.1	0.2	0.2	0.0
Bs1	5.3	4.6	0.142	5.2	0.6	2.9	1.4	1.8	2.1	3.9	0.3	2.4
Bs1*	4.6	4.4	0.418	9.8	1.2	3.5	2.2	2.8	3.7	4.3	0.2	1.7
Bs2	5.4	4.9	0.020	0.8	0.2	1.0	0.4	0.7	0.5	1.6	0.2	1.1
BC	5.3	5.0	0.002	0.4	0.1	0.3	0.1	0.4	0.2	0.7	0.1	0.4
C	5.3	4.9	0.002	0.3	0.1	0.3	0.1	0.3	0.1	0.4	0.1	0.2
C (250)	5.7	5.0	0.001	-0.3	0.0	0.2	0.0	0.1	0.0	0.2	0.0	0.1
						SAV-6						
A	4.2	3.3	--	39.5	--	--	--	--	--	--	--	--
E	4.8	3.5	0.015	4.5	0.1	0.4	0.1	0.1	0.0	0.1	0.1	0.1
Bhs	4.8	3.9	0.237	7.3	1.1	2.1	1.1	0.7	0.7	0.9	0.1	0.3
Bs1	5.0	4.3	0.161	5.1	0.5	2.0	1.2	1.4	1.7	3.5	0.1	2.4
Bs1*	5.0	4.1	0.438	8.0	0.9	1.9	1.1	1.3	1.4	1.7	0.3	0.6
Bs2	5.2	4.6	0.098	1.5	0.1	0.7	0.5	0.6	0.5	2.3	0.1	2.1
Bs2*	5.2	4.4	0.250	5.7	0.8	1.7	1.1	1.7	2.1	2.6	0.2	1.1
BC	5.4	4.8	0.013	0.8	0.1	0.3	0.2	0.5	0.4	0.9	0.1	0.7
BC*	5.4	4.4	0.239	5.1	0.5	1.1	0.6	1.3	1.5	1.6	0.2	0.5
C	5.6	4.9	0.004	0.7	0.1	0.3	0.1	0.3	0.2	0.6	0.1	0.4
C (230)	5.7	4.9	0.000	0.3	0.0	0.2	0.0	0.2	0.1	0.3	0.0	0.2
						SAV-7						
A	4.1	3.4	--	33.1	--	--	--	--	--	--	--	--
E	4.7	3.5	0.016	4.5	0.1	0.5	0.1	0.1	0.0	0.2	0.2	0.1
Bs1	5.1	4.4	0.163	5.5	0.4	2.1	1.3	1.4	1.8	5.1	0.2	3.5
Bs1*	5.1	4.2	0.520	11.9	1.0	3.0	1.9	1.9	2.7	3.8	0.1	1.3
Bs2	5.3	4.7	0.041	1.8	0.2	0.7	0.3	0.7	0.6	1.6	0.1	1.0
Bs2*	5.2	4.3	0.250	4.8	0.5	1.1	0.6	1.1	1.3	1.8	0.1	0.7
BC	5.7	4.8	0.023	0.6	0.1	0.3	0.1	0.4	0.3	0.4	0.1	0.3
C	5.7	4.9	0.009	0.5	0.1	0.3	0.1	0.3	0.2	0.4	0.1	0.3
C (200)	5.9	4.9	0.010	0.3	0.0	0.3	0.0	0.2	0.1	0.3	0.1	0.2
C (300)	5.8	4.9	0.000	0.1	0.0	0.2	0.1	0.1	0.0	0.3	0.0	0.2

*Indicates ortstein subsample.

Table 23 (Cont.)

Horizon	pH 2:1 H_2O	pH 2:1 KCl	ODOE	OC	Fe_p	Fe_d	Fe_o	Al_p	Al_d	Al_o	Si_p	Si_o
				----------------------------				g kg^{-1}				----------------------------
							SAV-8					
A	4.4	3.3	--	29.0	--	--	--	--	--	--	--	--
E	5.1	3.8	0.020	3.5	0.2	0.5	0.1	0.2	0.1	0.2	0.1	0.1
Bs1	5.8	4.7	0.143	4.0	0.5	2.4	1.4	1.4	1.6	3.6	0.3	2.5
Bs1*	6.1	4.7	0.362	7.5	0.6	2.3	1.1	1.5	2.6	3.2	0.2	1.5
Bs2	6.1	5.1	0.032	1.4	0.1	0.7	0.3	0.4	0.4	1.3	0.1	0.9
Bs2*	6.0	4.9	0.150	3.7	0.3	0.7	0.4	1.3	1.1	1.8	0.2	0.9
BC	6.1	5.1	0.020	0.7	0.1	0.3	0.1	0.3	0.3	0.7	0.1	0.4
C	6.3	5.2	0.101	0.2	0.1	0.3	0.1	0.2	0.1	0.3	0.0	0.2
C (279)	5.9	4.9	0.000	0.6	0.0	0.3	0.0	0.1	0.0	0.2	0.0	0.1

*Indicates ortstein subsample.

Table 24. Fe and Al ratio data from the sampled pedons.

Horizon	$(Fe_o\text{-}Fe_p)/Fe_p$	Fe_o/Fe_d	$(Al_o\text{-}Al_p)/Al_p$	Al_o/Al_d	$Al_o\text{-}Al_p$	$(Al_o\text{-}Al_p)/Si_o$	Fe_p/Al_p
					$g\ kg^{-1}$		
			FOR-1				
E	-0.67	0.05	-0.59	0.83	0.0	3.39	0.46
Bhs	0.28	0.63	0.35	1.09	0.5	0.92	0.63
Bs1	1.61	0.57	1.25	1.77	1.7	1.07	0.12
Bs1*	0.48	0.64	0.53	1.26	0.7	1.00	0.25
Bs2	0.40	0.54	0.44	1.98	0.3	0.46	0.12
BC	0.51	0.43	0.29	1.73	0.1	0.40	0.12
C	0.25	0.27	0.31	2.28	0.1	0.67	0.13
			FOR-2				
E	-0.33	0.10	-0.31	1.14	0.0	2.06	0.41
Bhs	0.45	0.72	0.53	1.25	0.8	1.07	0.53
Bs1	2.04	0.62	1.28	1.68	2.0	0.90	0.13
Bs1*	0.42	0.71	0.40	1.24	0.6	0.66	0.48
Bs2	0.63	0.50	0.56	1.53	0.4	0.63	0.16
BC	0.21	0.52	0.13	1.60	0.1	0.25	0.11
C	0.25	0.67	0.14	1.54	0.1	0.28	0.20
C (200)[1]	-0.01	0.22	0.00	1.48	0.0	0.00	0.14
			FOR-3				
E	-0.25	0.17	0.00	1.49	0.0	0.02	0.45
Bhs	0.41	0.66	0.79	1.33	1.6	0.93	0.47
Bs1	0.74	0.52	0.87	1.59	1.3	1.03	0.16
Bs1*	0.23	0.72	0.35	1.26	0.6	1.58	0.39
Bs2	0.12	0.56	0.30	1.64	0.3	0.48	0.16
Bs2*	0.31	0.65	0.46	1.21	0.3	1.51	0.34
BC	-0.10	0.39	0.18	2.03	0.1	0.41	0.14
BC*	0.32	0.86	0.14	1.06	0.1	0.84	0.30
C	-0.04	0.32	0.28	2.48	0.1	0.56	0.13
C (200)	0.02	0.15	0.42	2.37	0.1	0.81	0.09
C (240)	0.54	0.22	0.16	2.44	0.0	0.40	0.23

[1]Indicates depth midpoint in cm for deep samples.

*Indicates ortstein subsample.

Table 24. (Cont.)

Horizon	$(Fe_o-Fe_p)/Fe_p$	Fe_o/Fe_d	$(Al_o-Al_p)/Al_p$	Al_o/Al_d	Al_o-Al_p	$(Al_o-Al_p)/Si_o$	Fe_p/Al_p
					$g\ kg^{-1}$		
			FOR-4				
E	-0.67	0.08	-0.19	3.33	0.0	-1.15	0.43
Bhs	0.63	0.76	1.06	1.38	1.2	1.88	0.84
Bs1	2.41	0.68	1.36	1.75	2.4	1.03	0.15
Bs1*	0.61	0.78	0.78	1.51	1.5	1.18	0.32
Bs2	2.10	0.65	2.24	3.00	1.3	1.11	0.14
Bs2*	0.25	0.69	0.32	1.24	0.5	0.87	0.22
BC	0.34	0.51	0.64	1.99	0.3	0.75	0.14
BC*	0.71	0.62	0.95	1.84	0.5	1.30	0.15
C	-0.03	0.41	0.15	1.86	0.1	0.26	0.15
C (220)	0.09	0.16	0.33	2.17	0.0	0.41	0.12
			FOR-5				
E	-0.07	0.33	-0.21	1.89	0.0	-1.08	0.67
Bs1	0.62	0.66	0.34	1.38	0.7	0.44	0.25
Bs1*	0.25	0.76	-0.04	1.06	-0.1	-0.12	0.25
Bs2	0.43	0.64	0.22	2.01	0.3	0.29	0.11
Bs2*	0.25	0.76	0.12	1.10	0.2	0.31	0.22
BC	0.15	0.60	0.06	1.57	0.0	0.11	0.12
C	0.84	0.59	0.13	2.18	0.1	0.23	0.12
C (230)	0.12	0.49	-0.07	2.62	0.0	-0.17	0.13
			FOR-6				
A	0.48	0.45	0.45	0.89	0.3	-108.47	0.49
E	-0.23	0.31	-0.30	1.30	-0.1	-3.85	0.69
Bs1	2.37	0.66	1.19	1.95	2.4	1.00	0.16
Bs1*	0.83	0.55	0.81	1.21	1.2	0.95	0.21
Bs2	1.48	0.52	0.51	2.07	0.4	0.59	0.11
Bs2*	1.22	0.63	0.39	1.63	0.5	0.55	0.11
BC	0.44	0.67	0.74	3.43	0.3	0.71	0.14
C	0.24	0.53	-0.05	2.68	0.0	-0.08	0.12
2C	0.19	0.37	0.18	1.07	0.1	0.46	0.25
3C	0.02	0.35	0.14	4.42	0.0	0.32	0.14

*Indicates ortstein subsample.

Table 24. (Cont.)

Horizon	$(Fe_o-Fe_p)/Fe_p$	Fe_o/Fe_d	$(Al_o-Al_p)/Al_p$	Al_o/Al_d	Al_o-Al_p	$(Al_o-Al_p)/Si_o$	Fe_p/Al_p
					$g\ kg^{-1}$		
			FOR-7				
E	-0.67	0.09	-0.48	-1.09	0.0	1.33	0.61
Bhs	0.13	0.57	0.17	0.93	0.3	0.51	0.83
Bs1	3.23	0.81	2.18	3.88	4.9	1.12	0.08
Bs1*	0.70	0.74	0.17	1.33	0.4	0.23	0.16
Bs2	0.61	0.59	0.51	2.61	0.4	0.54	0.09
Bs2*	0.60	0.83	0.74	2.00	1.1	0.87	0.13
BC	0.19	0.53	0.13	1.31	0.1	0.22	0.13
C	-0.11	0.42	-0.01	3.19	0.0	-0.02	0.13
C (122)	0.21	0.34	0.06	2.20	0.1	0.12	0.15
C (230)	0.62	0.46	0.37	4.14	0.1	0.45	0.21
			FOR-8				
E	-0.36	0.21	-0.21	2.60	0.0	1.79	0.56
Bhsm	0.05	0.59	0.01	1.03	0.0	0.04	0.56
Bsm1	1.57	0.60	0.91	1.70	1.6	0.80	0.13
Bsm1*	0.82	0.65	0.41	1.47	1.3	0.60	0.14
Bsm2	0.90	0.62	0.37	2.47	0.4	0.49	0.08
2BC	0.46	0.43	0.31	2.84	0.2	0.41	0.10
3C	0.21	0.60	0.23	1.88	0.1	0.35	0.16
C (220)	0.10	0.31	-0.31	5.45	-0.1	-2.27	0.17
			FOR-9				
E	-0.18	0.14	0.35	2.86	0.0	1.00	0.55
Bhs	0.03	0.55	0.01	0.93	0.0	0.04	0.63
Bs1	1.37	0.61	0.93	2.02	2.0	0.80	0.11
Bs1*	0.58	0.74	0.96	1.63	1.7	1.53	0.39
Bs2	0.67	0.34	0.67	1.47	0.4	0.66	0.13
Bs2*	0.18	0.62	-0.03	1.18	-0.1	-0.14	0.15
BC	-0.10	0.32	0.15	1.49	0.1	0.26	0.14
C	-0.19	0.26	0.22	1.51	0.1	0.35	0.17
C (270)	2.56	0.39	0.98	1.98	0.2	1.01	0.12
C (280)	10.89	0.12	0.73	1.08	0.6	1.01	0.03

*Indicates ortstein subsample.

Table 24. (Cont.)

Horizon	$(Fe_o-Fe_p)/Fe_p$	Fe_o/Fe_d	$(Al_o-Al_p)/Al_p$	Al_o/Al_d	Al_o-Al_p	$(Al_o-Al_p)/Si_o$	Fe_p/Al_p
					$g\ kg^{-1}$		
			SAV-1				
E	0.01	0.48	-0.17	1.83	-0.1	-1.92	0.50
Bs1	0.74	0.50	0.56	1.81	0.7	0.61	0.12
Bs1*	0.52	0.71	0.27	1.34	0.6	0.51	0.20
Bs2	1.32	0.74	1.46	3.94	0.7	1.07	0.16
BC	0.27	0.50	0.71	5.50	0.2	0.77	0.16
C	-0.20	0.48	-0.39	1.28	-0.2	-1.57	0.27
			SAV-2				
E	-0.35	0.17	-0.30	2.46	-0.1	-1.19	0.30
Bs1	2.35	0.57	1.45	3.06	1.3	0.91	0.09
Bs1*	0.78	0.76	0.33	1.55	0.8	0.45	0.17
Bs2	0.81	0.79	0.70	4.01	0.3	0.60	0.12
BC	0.21	0.44	0.26	1.77	0.1	0.39	0.22
C	0.53	0.53	0.24	6.19	0.0	0.26	0.15
			SAV-3				
E	0.02	0.26	0.09	2.38	0.0	0.42	0.39
Bs1	1.04	0.45	0.88	1.61	1.9	0.75	0.14
Bs1*	1.12	0.67	0.33	1.42	1.4	0.54	0.15
Bs2	0.30	0.43	0.28	1.87	0.2	0.36	0.11
BC	0.12	0.40	0.17	1.91	0.1	0.30	0.10
C	0.80	0.27	1.38	7.92	0.3	1.05	0.09
			SAV-4				
E	0.00	0.12	0.00	2.28	0.1	3.82	0.00
Bs1	1.85	0.50	1.89	2.58	3.0	1.00	0.14
Bs1*	0.44	0.52	0.69	1.23	1.8	0.90	0.25
Bs2	2.64	0.51	1.79	3.25	0.9	0.95	0.10
BC	0.46	0.36	0.46	1.82	0.2	0.60	0.18
C	-0.25	0.48	0.13	3.21	0.0	0.23	0.17
C (135)	-0.06	0.26	0.34	2.45	0.1	0.48	0.13

*Indicates ortstein subsample.

Table 24. (Cont.)

Horizon	$(Fe_o-Fe_p)/Fe_p$	Fe_o/Fe_d	$(Al_o-Al_p)/Al_p$	Al_o/Al_d	Al_o-Al_p	$(Al_o-Al_p)/Si_o$	Fe_p/Al_p
					$g\ kg^{-1}$		
			SAV-5				
E	-0.28	0.19	0.00	2.54	0.0	-0.03	0.38
Bs1	1.28	0.46	1.13	1.85	2.0	0.89	0.16
Bs1*	0.84	0.62	0.51	1.16	1.4	0.90	0.20
Bs2	1.23	0.35	1.49	3.57	1.0	0.94	0.12
BC	0.80	0.40	0.76	3.59	0.3	0.67	0.09
C	0.02	0.34	0.48	3.65	0.1	0.56	0.17
C (250)	1.37	0.24	0.61	6.23	0.1	0.58	0.07
			SAV-6				
E	-0.31	0.17	0.04	6.05	0.0	0.12	0.35
Bhs	0.04	0.52	0.26	1.18	0.2	0.55	0.75
Bs1	1.29	0.60	1.57	2.07	2.1	0.95	0.19
Bs1*	0.19	0.60	0.30	1.24	0.4	0.70	0.34
Bs2	3.01	0.67	2.74	4.57	1.7	0.80	0.09
Bs2*	0.45	0.63	0.48	1.24	0.8	0.83	0.21
BC	0.54	0.50	0.75	2.52	0.4	0.58	0.10
BC*	0.20	0.54	0.26	1.10	0.3	0.62	0.18
C	0.03	0.28	0.67	2.97	0.2	0.53	0.10
C (230)	-0.11	0.18	0.14	3.12	0.0	0.16	0.10
			SAV-7				
E	-0.33	0.18	0.40	3.27	0.0	0.55	0.62
Bs1	2.44	0.64	2.58	2.82	3.7	1.10	0.13
Bs1*	0.86	0.64	1.01	1.42	1.9	1.54	0.27
Bs2	0.82	0.45	1.46	2.82	1.0	1.00	0.13
Bs2*	0.37	0.56	0.58	1.40	0.6	0.99	0.20
BC	-0.03	0.36	0.09	1.45	0.0	0.12	0.13
C	-0.13	0.32	0.18	1.93	0.1	0.18	0.15
C (200)	0.13	0.14	0.92	3.05	0.2	0.71	0.11
C (300)	3.48	0.37	1.26	6.37	0.1	0.73	0.07
			SAV-8				
E	-0.57	0.19	-0.29	1.71	-0.1	-1.22	0.44
Bs1	1.96	0.58	1.62	2.25	2.2	0.94	0.16
Bs1*	0.96	0.50	1.11	1.23	1.7	1.12	0.18
Bs2	1.85	0.40	1.96	3.05	0.9	1.00	0.10
Bs2*	0.33	0.65	0.45	1.60	0.6	0.67	0.13
BC	0.71	0.39	1.26	2.21	0.4	0.97	0.10
C	0.77	0.31	0.92	3.37	0.2	0.83	0.14
C (279)	1.29	0.15	0.53	4.75	0.1	0.88	0.07

*Indicates ortstein subsample.

Table 25. Cations sorbed on cation exchange resins in the sampled pedons.

Pedon	Set	Horizon	Mg	Fe	Ca	Al
			------------------mg kg^{-1} dry resin------------------			
FOR-5	1	E	25	21	58	89
	2	E	38	13	112	15
	3	E	50	23	1758	39
	4	E	36	12	172	9
	1	B	14	17	18	47
	2	B	45	69	282	144
	4	B	28	58	81	206
	1	BC	173	14	708	100
	2	BC	14	10	46	22
	3	BC	28	24	67	71
	4	BC	17	10	78	15
FOR-7	1	E	178	13	503	8
	2	E	252	17	988	16
	3	E	280	27	941	76
	4	E	36	12	72	12
	1	B	119	29	385	67
	2	B	75	66	168	440
	3	B	135	54	315	146
	4	B	140	233	256	660
	1	BC	47	13	95	65
	2	BC	33	12	88	85
	3	BC	10	10	20	48
	4	BC	53	12	94	83
FOR-9	1	E	39	15	105	56
	2	E	28	14	25	49
	3	E	55	25	106	19
	4	E	38	15	132	25
	1	B	16	25	20	40
	2	B	59	41	79	90
	3	B	51	26	69	51
	4	B	37	51	36	326
	1	BC	4	11	-1	18
	2	BC	5	15	-3	21
	3	BC	14	17	7	61
	4	BC	20	32	37	70

Table 25. (Cont.)

Pedon	Set	Horizon	Mg	Fe	Ca	Al
			---------mg kg^{-1} dry resin---------			
SAV-6	1	E	25	11	25	10
	2	E	50	18	84	27
	3	E	43	13	80	9
	4	E	53	12	67	6
	1	B	23	31	292	53
	2	B	29	28	68	77
	3	B	37	16	94	18
	4	B	60	26	151	44
	1	BC	6	11	18	27
	2	BC	15	21	23	29
	3	BC	25	19	61	66
	4	BC	30	14	103	81
SAV-7	1	E	81	13	157	8
	2	E	47	12	92	14
	3	E	33	11	109	12
	4	E	35	11	54	8
	1	B	34	26	89	64
	2	B	66	42	244	97
	3	B	31	47	256	117
	4	B	51	26	182	129
	1	BC	8	11	24	22
	2	BC	26	14	72	57
	3	BC	27	17	69	73
SAV-8	1	E	17	12	41	9
	2	E	20	11	61	7
	3	E	24	13	58	10
	4	E	6	15	14	8
	1	B	43	19	125	26
	2	B	34	21	105	21
	3	B	7	33	23	53
	4	B	29	16	78	16
	1	BC	17	17	40	27
	2	BC	11	12	36	7
	3	BC	16	26	28	50
	4	BC	10	12	37	25

Table 26. Cations sorbed on chelating resins in the sampled pedons.

Pedon	Set	Horizon	Fe	Al
			-----mg kg^{-1} dry resin-----	
FOR-5	1	E	89	229
	2	E	164	410
	3	E	89	216
	4	E	125	389
	1	B	199	959
	4	B	42	107
	1	BC	34	796
	4	BC	29	154
FOR-7	1	E	62	130
	2	E	37	127
	3	E	145	347
	4	E	108	400
	1	B	311	876
	2	B	176	1677
	3	B	349	2039
	4	B	1005	2228
	1	BC	14	152
	2	BC	15	109
	3	BC	49	374
	4	BC	31	258
FOR-9	1	E	85	571
	2	E	46	200
	3	E	15	66
	4	E	29	177
	1	B	83	252
	2	B	265	753
	3	B	56	395
	4	B	69	304
	1	BC	0	106
	2	BC	7	107
	3	BC	19	137
	4	BC	7	105

Table 26. (Cont.)

Pedon	Set	Horizon	Fe	Al
			-----mg kg^{-1} dry resin-----	
SAV-6	1	E	36	129
	2	E	34	130
	3	E	40	110
	4	E	26	152
	1	B	159	1153
	2	B	103	735
	3	B	147	434
	4	B	242	596
	1	BC	6	130
	2	BC	6	69
	3	BC	12	178
	4	BC	18	147
SAV-7	1	E	137	215
	2	E	27	126
	3	E	47	172
	4	E	26	75
	1	B	116	1010
	2	B	165	715
	3	B	88	331
	4	B	125	540
	1	BC	16	178
	2	BC	21	201
	3	BC	38	193
	4	BC	27	275
SAV-8	1	E	44	238
	2	E	22	147
	3	E	10	80
	4	E	2	69
	1	B	97	314
	2	B	49	133
	3	B	190	454
	4	B	91	194
	1	BC	10	88
	2	BC	13	65
	3	BC	14	84
	4	BC	105	320

APPENDIX B: PEDON DESCRIPTIONS

Pedon: FOR-1
Location: SW 1/4 of SW 1/4 of NE 1/4 of section 19, T 48 N, R 15 W
Date of description: July 12, 1994
Series: Kalkaska
Subgroup classification: Typic Haplorthod
Parent material: Outwash sands
Physiography: Outwash plain
Slope: < 2 %
Comments: Forested area with mature trees, marked for logging.

Oa 0-3 cm. Very dark gray (10 YR 3/1) well decomposed hardwood leaf litter; abrupt smooth boundary.

E 3-18 cm. Grayish brown (10 YR 5/2) sand; single grain; loose; many medium and fine roots; abrupt wavy boundary.

Bhs 18-23 cm. Very dark gray (7.5 YR 3/2) sand; single grain; loose; many medium and fine roots; very dark gray (7.5 YR 3/2) weakly cemented ortstein occurs in chunks less than 1 cm diameter and occupies about 20 percent of exposed surface; clear wavy boundary.

Bs1 23-48 cm. Strong brown (7.5 YR 4/6) sand; single grain; loose; few fine roots; dark reddish brown (5 YR 3/4) very strongly cemented ortstein occurs in columns 10 cm wide and 50 cm long and occupies about 35 percent of exposed surface; gradual wavy boundary.

Bs2 48-78 cm. Yellowish brown (10 YR 5/6) slightly gravelly sand; single grain; loose; gradual wavy boundary.

BC 78-103 cm. Yellowish brown (10 YR 5/4) sand; single grain; loose; gradual smooth boundary.

C 103-150 cm. Yellowish brown (10 YR 6/4) sand; single grain; loose.

Pedon: FOR-2
Location: NW 1/4 of NE 1/4 of NW 1/4 of section 27, T 48 N R 15 W.
Date of description: July 24, 1994
Series: Deer Park
Subgroup classification: Spodic Udipsamment
Parent material: Outwash sand
Physiography: Outwash plain
Slope: < 2 %
Comments: Evidence of logging about 10 - 20 years ago.

Oa 0 - 3 cm. Black (N 2/0) well decomposed hardwood leaf litter; many fine roots.

E 3 - 18 cm. Grayish brown (10 YR 5/2) sand; weak fine subangular blocky; very friable; many fine and medium roots; clear wavy boundary.

Bhs 18 - 23 cm. Dark reddish brown (5 YR 2.5/2) sand; weak fine subangular blocky; friable; many fine and medium roots; dark reddish brown (5 YR 2.5/2) strongly cemented ortstein occurs in columns 14 cm wide and up to 70 cm long and occupies about 25 percent of exposed surface; clear irregular boundary.

Bs1 23 - 43 cm. Strong brown (7.5 YR 4/6) sand; weak medium subangular blocky; friable; common fine roots; dark reddish brown (5 YR 3/2) strongly cemented ortstein occurs in columns 20 cm wide and 70 cm long and occupies about 20 percent of exposed surface; gradual wavy boundary.

Bs2 43 - 78 cm. Dard yellowish brown (10 YR 4/6) sand; weak medium subangular blocky; very friable; few fine roots; dark brown (7.5 YR 4/4) medium cemented ortstein occurs in columns 5 to 10 cm wide and occupies about 15 percent of exposed surface; gradual wavy boundary.

BC 78 - 103 cm. Yellowish brown (10 YR 5/4) sand; weak medium subangular blocky; very friable; strong brown (7.5 YR 4/6) medium cemented ortstein occurs in columns 5 cm wide and occupies about 5 percent of exposed surface; gradual wavy boundary.

C 103 - 150 cm. Yellowish brown (10 YR 5/4) sand; massive.

C 190 - 210 cm.

Pedon: FOR-3

Location: NE 1/4 of SW 1/4, section 11, T 48 N, R 15 W

Date of description: July 25, 1994

Series: Kalkaska

Subgroup classification: Typic Haplorthod

Parent material: Outwash sand

Physiography: Outwash plain

Slope: < 2 %

Comments: Some logging has been done in the last 10-20 years.

Oa 0 - 4 cm. (7.5 YR 3/2) well-decomposed leaf litter.

E 4 - 16 cm. Grayish brown (10 YR 5/2) sand; weak medium subangular blocky structure; very firable; common medium roots; abrupt wavy boundary.

Bhs 16 - 19 cm. Dark brown (7.5 YR 3/2) sand; moderate medium subangular blocky structure; friable; common medium roots; black (5 YR 2.5/1) strongly cemented ortstein occurs in columns 15 - 20 cm wide which extend into the Bs1 horizon and occupies about 40 percent of the exposed surface; abrupt wavy boundary.

Bs1 19 - 39 cm. Dark yellowish brown (7.5 YR 4/6) sand; weak medium subangular blocky structure; very friable; common fine roots; black (5 YR 2.5/1) very strongly cemented orstein occurs in columns and chunks 15 - 20 cm wide which extend into lower horizons and occupies about 40 percent of the exposed surface; gradual wavy boundary.

Bs2 39 - 74 cm. Dark yellowish brown (10 YR 4/6) sand; weak coarse subangular blocky structure; very friable; few fine roots; dark brown (7.5 YR 3/4) very strongly cemented ortstein occurs in columns and chunks 15 - 20 cm wide which exted into lower horizons and occupies about 30 percent of the exposed surface; gradual wavy boundary.

BC 74 - 114 cm. Yellowish brown (10 YR 5/4) sand; massive; dark brown (7.5 YR 3/4) strongly cemented ortstein occurs in columns about 10 cm wide and occupies about 10 percent of the exposed surface; gradual wavy boundary.

C 114 - 150 cm. Light yellowish brown (10 YR 6/4) sand; massive.

C 190 - 210 cm.

C 230 - 250 cm.

Pedon: FOR-4

Location: NE 1/4 of SE 1/4 of SW 1/4 of SE 1/4, section 8, T 48 N, R 15 W.

Date of description: July 29, 1994

Series: Kalkaska

Subgroup classification: Typic Haplorthod

Parent material: Outwash sand

Physiography: Outwash plain

Slope: < 2 %

Comments: some logging about 40 years ago.

Oa 0 - 5 cm. Black (N 2/0) well-decomposed hardwood litter; many fine roots; abrupt wavy boundary.

E 5 - 15 cm. Grayish brown (10 YR 5/2) sand; weak medium subangular blocky structure; very friable; many fine and medium roots; abrupt wavy boundary.

Bhs 15 - 20 cm. Dark reddish brown (5 YR 2.5/2) sand; weak medium subangular blocky structure; very friable; common fine roots; dark reddish brown (5 YR 2.5/2) moderately cemented ortstein occurs in columns 10-15 cm wide which extend into lower horizons and occupies about 40 percent of the exposed surface; abrupt irregular boundary.

Bs1 20 - 45 cm. Strong brown (7.5 YR 4/6) sand; weak medium subangular blocky structure; friable; few fine roots; dark reddish brown (5 YR 2.5/2) very strongly cemented ortstein occurs in columns 10 - 15 cm wide which extend into lower horizons and occupies about 40 percent of the exposed surface; clear wavy boundary.

Bs2 45 - 75 cm. Strong brown (7.5 YR 5/6) sand; weak medium subangular blocky structure; very friable; few fine roots; dark reddish brown (5 YR 2.5/2) very strongly cemented ortstein occures in columns 10 - 15 cm wide which exted into lower horizons and occupies about 40 percent of the exposed surface; gradual wavy boundary.

BC 75 - 105 cm. Yellowish brown (10 YR 5/4) sand; massive; strong brown (7.5 YR 4/6) moderately cemented ortstein occurs in columns 5 - 10 cm wide and occupies about 10 percent of the exposed surface; gradual wavy boundary.

C 105 - 150 cm. Light yellowish brown (10 YR 6/4) sand; massive.

C 210 - 230 cm.

Pedon: FOR-5
Location: SE 1/4 of SW 1/4 of SE 1/4 of SW 1/4, section 4, T 48 N, R 15 W
Date of description: August 16, 1994
Series: Rubicon
Subgroup classification: Entic Haplorthod
Parent material: Outwash sand
Physiography: Outwash plain
Slope: < 2%
Comments: Surface soil very dry.

Oi 0 - 4 cm. Dark brown (10 YR 3/3) partially decompoed hardwood and conifer litter; many fine roots; abrupt wavy boundary.

E 4 - 19 cm. Grayish brown (10 YR 5/2) sand; single grain; loose; many fine and common medium roots; abrupt wavy boundary.

Bs1 19 - 39 cm. Dark brown (7.5 YR 4/4) sand; weak medium subangular blocky structure; very friable; common fine roots; dark reddish brown (5 YR 3/3) moderately to strongly cemented ortstein occurs in columns 10 - 20 cm wide which extend into lower horizons and occupies about 30 percent of the exposed surface; clear irregular boundary.

Bs2 39 - 69 cm. Strong brown (7.5 YR 4/6) sand; weak medium subangular blocky structure; very friable; dark reddish brown (5 YR 3/4) moderately to strongly cemented ortstein occurs in columns 10 - 20 cm wide which extend into lower horizons and occupies about 30 percent of the exposed surface; clear wavy boundary.

BC 69 - 89 cm. Yellowish brown (10 YR 5/4) sand; massive; strong brown (7.5 YR 4/6) moderately cemented ortstein occurs in columns 10 - 15 cm wide and occupies about 10 percent of the exposed surface; clear wavy boundary.

C 89 - 104 cm. Yellowish brown (10 YR 5/4) sand; massive.

C 240 - 250 cm.

Pedon: FOR-6
Location: NW 1/4 of NE 1/4 of NE 1/4 of SW 1/4, section 16, T 48 N, R 15 W
Date of description: August 12, 1994
Series: Deer Park
Subgroup classification: Spodic Udipsamment
Parent material: Outwash sand
Physiography: Outwash plain
Slope: < 2 %
Comments: Logging of large red and white pine about 10 - 20 years ago; charcoal chunks in E horizon.

Oi 0 - 3 cm. Dark brown (10 YR 3/3) decomposing pine litter; abrupt wavy boundary.

A 3 - 6 cm. Black (N 2/0) loamy sand; moderate medium granular structure; very friable; many fine roots; abrupt wavy boundary.

E 6 - 15 cm. Grayish brown (10 YR 5/2) sand; weak medium subangular blocky structure; very friable; many fine roots; abrupt wavy boundary.

Bs1 15 - 33 cm. Strong brown (7.5 YR 4/6) sand; weak medium subangular blocky structure; very friable; many fine and common medium roots; dark brown (7.5 YR 3/4) moderately cemented ortstein occurs in columns 10 - 20 cm wide which extend into lower horizons and occupies about 10 percent of the exposed surface; clear wavy boundary.

Bs2 33 - 58 cm. Yellowish brown (10 YR 5/6) slightly gravelly sand; weak coarse subangular blocky structure; very friable; few fine roots; strong brown (7.5 YR 4/6) weakly to moderately cemented ortstein occurs in columns 10 -20 cm wide and occupies about 10 percent of the exposed surface; clear wavy boundary.

BC 58 - 78 cm. Yellowish brown (10 YR 5/4) sand; massive; clear wavy boundary.

C 78 - 98 cm. Light yellowish brown (10 YR 6/4) slightly gravelly sand; massive; abrupt wavy boundary.

2C 98 - 108 cm. Brown (7.5 YR 5/4) loamy fine sand; massive; common medium roots; abrupt wavy boundary.

3C 108 - 130 cm. Light yellowish brown (10 YR 6/4) sand; massive.

Pedon: FOR-7
Location: NE 1/4 of SE 1/4 of SE 1/4 of SW 1/4, section 18, T 48 N, R 15 W
Date of description: August 11, 1994
Series: Wallace
Subgroup classification: Typic Haplorthod
Parent material: Outwash sand
Physiography: Side of kettle depression in outwash; a ledge on the shoulder slope.
Slope: 5%
Comments: Some pit/mound topography in vicinity.

Oa 0 - 4 cm. Black (10 YR 2/1) well decomposed hardwood and evergreen litter; many fine roots; abrupt wavy boundary.

E 4 - 24 cm. Light brownish gray (10 YR 6/2) sand; weak medium subangular blocky structure; very friable; many fine and common medium roots; abrupt irregular boundary.

Bhs 24 - 30 cm. Dark reddish brown (5 YR 2.5/2) sand; weak medium subangular blocky structure; friable; many fine roots; dark reddish brown (5 YR 2.5/2) moderately to very strongly cemented ortstein occurs in columns 10 - 20 cm wide which extend into lower horizons and occupies about 50 percent of the exposed surface; abrupt irregular boundary.

Bs1 30 - 49 cm. Strong brown (7.5 YR 4/6) sand; moderate medium subangular blocky structure; friable; common fine roots; dark reddish brown and strong brown (5 YR 3/2 and 7.5 YR 4/6) strongly to very strongly cemented ortstein occurs in columns 10 - 20 cm wide which extend into lower horizons and occupies about 60 percent of the exposed surface; clear irregular boundary.

Bs2 49 - 79 cm. Yellowish brown (10 YR 5/6) sand; weak medium subangular blocky structure; very friable; few fine roots; dark reddish brown (5 YR 3/3) moderately to strongly cemented ortstein occurs in columns 10 - 20 cm wide and occupies about 40 percent of the exposed surface; clear wavy boundary.

BC 79 - 119 cm. Yellowish brown (10 YR 5/4) sand; weak coarse subangular blocky structure; very friable; clear wavy boundary.

C 124 - 140 cm. Light yellowish brown (10 YR 6/4) sand; massive.

C 119 - 124 cm.

C 220 - 240 cm.

Pedon: FOR-8

Location:

Date of description: August 10, 1994

Series: Wallace

Subgroup classification: Typic Haplorthod

Parent material: Outwash sand

Physiography: Outwash plain

Slope: < 2 %

Comments: Hemlock logging occurred about 40 years ago.

Oa 0 - 3 cm. Black (N 2/0) well decomposed hardwood litter; abrupt wavy boundary.

E 3 - 14 cm. Grayish brown (10 YR 5/2) sand; weak medium subangular blocky structure; very friable; many fine and medium roots; abrupt wavy boundary.

Bhsm 14 - 19 cm. Dark brown (7.5 YR 3/2.5) sand; massive; few fine roots; very strongly cemented ortstein occupies about 100 percent of the exposed surface; abrupt irregular boundary.

Bsm1 19 - 43 cm. Strong brown (7.5 YR 4/6) sand; massive; few fine roots; very dark brown (5 YR 2.5/2) moderately to very strongly cemented ortstein occurs in columns 10 - 20 cm wide which extend to lower horizons and occupies about 80 percent of the exposed surface; clear wavy boundary.

Bsm2 43 - 65 cm. Strong brown (10 YR 4/6) sand; massive; dark brown (7.5 YR 3/4) moderately to strongly cemented ortstein occurs in columns 10 - 20 cm wide and occupies about 50 percent of the exposed surface; abrupt wavy boundary.

2BC 65 - 83 cm. Dark yellowish brown (10 YR 4/4) slightly gravelly coarse sand; single grain; loose; clear wavy boundary.

3C 83 - 103 cm. Yellowish brown (10 YR 5/4) sand; single grain; loose.

Pedon: FOR-9
Location:
Date of description: September 27, 1994
Series: Kalkaska
Subgroup classification: Typic Haplorthod
Parent material: Outwash sand
Physiography: Outwash plain
Slope: < 2%

Oi 0 - 5 cm. Black (N 2/0) partially decomposed hardwood litter; many very fine roots; abrupt wavy boundary.

E 5 - 15 cm. Grayish brown (10 YR 5/2) sand; weak medium subangular blocky structure; very friable; common fine roots; abrupt irregular boundary.

Bhs 15 - 20 cm. Dark reddish brown (5 YR 2.5/2) sand; weak fine subangular blocky structure; friable; many fine and medium roots; abrupt irregular boundary.

Bs1 20 - 35 cm. Dark brown (7.5 YR 4/4) sand; weak medium subangular blocky structure; very friable; common medium roots; dark reddish brown (5 YR 3/2) strongly cemented ortstein occures in columns 15 - 20 cm wide which extend into the horizons below and occupies about 40 percent of the exposed surface; clear irregular boundary.

Bs2 35 - 65 cm. Strong brown (7.5 YR 4/6) sand; weak medium subangular blocky structure; friable; dark brown (7.5 YR 3/6) moderately to strongly cemented ortstein occurs in columns 15 - 20 cm wide which extend into the horizon below and occupies about 30 percent of the exposed surface; clear wavy boundary.

BC 65 - 90 cm. Yellowish brown (10 YR 5/4) sand; weak medium subangular blocky structure; firable; dark brown (7.5 YR 4/4) moderately cemented ortstein occurs in columns 15 - 20 cm wide and occupies about 10 percent of the exposed surface; clear wavy boundary.

C 90 - 120 cm. Yellowish brown (10 YR 5/4) sand; single grain; massive.

C 265 - 275 cm.

C 275 - 285 cm.

Pedon: SAV-1
Location: NE 1/4 of SE 1/4 of NE 1/4, section 19, T 48 N, R 15 W
Date of description: July 14, 1994
Series: Rubicon
Subgroup classification: Entic Haplorthod
Parent material: Outwash sand
Physiography: Outwash plain
Slope: < 2 %
Comments: Scattered pit/mound pairs in this savanna. Stumps are plentiful.

A 0 - 2 cm. Very dark gray (10 YR 3/1) sand. Weak very fine granular structure; very friable; common fine roots; abrupt wavy boundary.

E 2 - 10 cm. Grayish brown (10 YR 5/2) sand. Single grain; loose; many fine roots; clear wavy boundary.

Bs1 10 - 45 cm. Dark brown (7.5 YR 4/4) gravelly sand. Weak fine subangular blocky structure; very friable; common fine roots; dark reddish brown (5 YR 3/3) strongly cemented ortstein occurs in columns about 7 cm extending into lower horizons and occupies about 20 percent of the exposed surface; gradual wavy boundary.

Bs2 45 - 80 cm. Dark yellowish brown (10 YR 4/4) slightly gravelly sand; single grain; loose; few fine roots; strong brown (7.5 YR 5/6) weakly cemented ortstein occurs in columns about 5 cm wide and occupies about 5 percent of the exposed surface; gradual wavy boundary.

BC 80 - 100 cm. Yellowish brown (10 YR 5/4) sand; single grain; loose; gradual wavy boundary.

C 100 - 180 cm. Light yellowish brown (10 YR 6/4) sand; single grain; loose.

Pedon: SAV-2

Location: SW 1/4 of SE 1/4 of NE 1/4, section 20, T 48 N, R 15 W

Date of description: July 16, 1994

Series: Deer Park

Subgroup classification: Spodic Udipsamment

Parent material: Outwash sand

Physiography: Near edge of kettle in outwash plain, on shoulder slope.

Slope: < 2 %

Comments: Center of slight depression is about 100 m to the ENE.

A 0 - 2 cm. Very dark grayish brown (10 YR 3/2) sand; single grain; loose; common fine roots; clear wavy boundary.

E 2 - 10 cm. Grayish brown (10 YR 5/2) sand; single grain; loose; common fine roots; abrupt wavy boundary.

Bs1 10 - 50 cm. Dark yellowish brown (7.5 YR 4/6) sand; weak medium subangular blocky structure; very friable; few fine roots; dark reddish brown (5 YR 3/2) strongly cemented ortstein occurs in columns 5 - 8 cm wide which extend into the horizon below and occupies about 20 percent of the exposed surface; gradual wavy boundary.

Bs2 50 - 85 cm. Dark yellowish brown (10 YR 4/6) slightly gravelly sand; weak medium subangular blocky structure; very friable; dark brown (7.5 YR 3/4) moderately cemented ortstein occurs in columns about 5 cm wide; gradual wavy boundary.

BC 85 - 100 cm. Yellowish brown (10 YR 5/4) sand; massive; loose; gradual wavy boundary.

C 100 - 170 cm. Pale brown (10 YR 6/3) sand; massive; loose.

Pedon: SAV-3
Location: NE 1/4 of SE 1/4 of NW 1/4, section 27, T 48 N, R 15 W
Date of description: July 20, 1994
Series: Deer Park
Subgroup classification: Spodic Udipsamment
Parent material: Outwash sand
Physiography: Outwash plain
Slope: < 2 %

A 0 - 3 cm. Very dark brown (10 YR 2/2) sand; weak fine granular structure; very friable; many fine roots; clear wavy boundary.

E 3 - 13 cm. Grayish brown (10 YR 5/2) sand; weak fine subangular blocky structure; very friable; many fine roots; clear wavy boundary.

Bs1 13 - 35 cm. Strong brown (7.5 YR 4/6) sand; weak fine subangular blocky structure; very friable; common fine roots; dark reddish brown (5 YR 3/3) moderately to strongly cemented ortstein occurs in columns 5 - 8 cm wide extending into lower horizons and occupies about 20 percent of the exposed surface; gradual irregular boundary.

Bs2 35 - 65 cm. Yellowish brown (10 YR 5/4) sand; weak moderate subangular blocky structure; very friable; few fine roots; strong brown (7.5 YR 5/6) weakly to moderately cemented ortstein occurs in columns 5 - 8 cm wide extending into lower horizons and occupies about 15 percent of the exposed surface; gradual wavy boundary.

BC 65 - 90 cm. Light yellowish brown (10 YR 6/4) sand; massive; loose; strong brown (7.5 YR 4/6) weakly to moderately cemented ortstein occurs in columns 5 cm wide and occupies about 5 percent of the exposed surface; gradual wavy boundary.

C 90 - 110 cm. Light yellowish brown (10 YR 6/4) sand; massive; loose.

Pedon: SAV-4
Location: SE 1/4 of NE 1/4 of SE 1/4, section 10, T 48 N, R 15 W
Date of description: July 26, 1994
Series: Rubicon
Subgroup classification: Entic Haplorthod
Parent material: Outwash sand
Physiography: Outwash plain
Slope: < 2 %
Comments: Recently burned stumps in area.

A 0 - 3 cm. Very dark gray (10 YR 3/1) sand; weak fine granular structure; very friable; many fine roots; abrupt wavy boundary.

E 3 - 11 cm. Grayish brown (10 YR 5/2) sand; weak medium subangular blocky structure; very friable; common fine roots; abrupt wavy boundary.

Bs1 11 - 30 cm. Dark brown (7.5 YR 4/4) slightly gravelly sand; weak medium subangular blocky structure; very friable; common fine roots; dark reddish brown (5 YR 3/2) moderately to strongly cemented ortstein occurs in columns 5 - 8 cm wide extending into the horizons below and occupying about 15 percent of the exposed surface; gradual irregular boundary.

Bs2 30 - 60 cm. Strong brown (7.5 YR 5/6) sand; weak medium subangular blocky structure; very friable; few fine roots; dark reddish brown (5 YR 3/4) moderately cemented ortstein occurs in columns 5 - 8 cm wide extending into the horizon below and occupies about 10 percent of the exposed surface; gradual irregular boundary.

BC 60 - 90 cm. Yellowish brown (10 YR 5/4) sand; massive; strong brown (7.5 YR 4/6) weakly to moderately cemented ortstein occurs in columns 5 cm wide and occupies abouto 5 percent of the exposed surface; gradual wavy boundary.

C 90 - 120 cm. Yellowish brown (10 YR 5/4) sand; massive.

C 120 - 150 cm.

Pedon: SAV-5

Location: NW 1/4 of SE 1/4 of NW 1/4 of NE 1/4, section 17, T 48 N, R 15 W

Date of description: July 29, 1994

Series: Rubicon

Subgroup classification: Entic Haplorthod

Parent material: Outwash sand

Physiography: Kettle depression; backslope

Slope: 12 %

A 0 - 3 cm. Very dark gray (10 YR 3/1) sand; weak fine granular structure; very friable; many fine and medium roots; abrupt wavy boundary.

E 3 - 15 cm. Grayish brown (10 YR 5/2) sand; weak fine subangular blocky structure; very friable; common fine and medium roots; abrupt wavy boundary.

Bs1 15 - 30 cm. Dark brown (7.5 YR 3/4) sand; weak fine subangular blocky structure; very friable; few fine roots; dark reddish brown (5 YR 2.5/2) weakly to moderately cemented ortstein occurs in columns 5 - 10 cm wide and extends into lower horizons and occupies about 15 percent of the exposed surface; clear wavy boundary.

Bs2 30 - 55 cm. Dark yellowish brown (10 YR 4/6) sand; single grain; loose; few fine roots; dark reddish brown (5 YR 3/3) weakly cemented ortstein occurs in columns 5 - 8 cm wide and occupies about 5 percent of the exposed surface; gradual wavy boundary.

BC 55 - 75 cm. Yellowish brown (10 YR 5/4) sand; single grain; loose; gradual wavy boundary.

C 75 - 120 cm. Light yellowish brown (10 YR 6/4) sand; massive.

C 240 - 260 cm.

Pedon: SAV-6
Location: NE 1/4 of NW 1/4 of NE 1/4 of NW 1/4, section 9, T 48 N, R 15 W
Date of description: August 15, 1994
Series: Kalkaska
Subgroup classification: Typic Haplorthod
Parent material: Outwash sand
Physiography: Outwash plain
Slope: < 2 %

A 0 - 2 cm. Very dark gray (10 YR 3/1) sand; weak fine grandual structure; very friable; many fine roots; abrupt wavy boundary.

E 2 - 12 cm. Grayish brown (10 YR 5/2) sand; weak fine subangular blocky structure; very friable; many fine roots; abrupt irregular boundary.

Bhs 12 - 17 cm. Dark brown (7.5 YR 3/2) sand; weak fine subangular blocky structure; very friable; many fine roots; abrupt irregular boundary.

Bs1 17 - 35 cm. Strong brown (7.5 YR 4/6) sand; weak medium subangular blocky structure; very friable; common fine roots; dark reddish brown (5 YR 3/2) moderately to very strongly cemented ortstein occurs in columns 15 - 20 cm wide extending into the horizon below and occupies about 30 percent of the exposed surface; clear wavy boundary.

Bs2 35 - 65 cm. Dark yellowish brown (10 YR 4/6) sand; weak medium subangular blocky structure; very friable; few fine roots; dark reddish brown (5 YR 3/4) very strongly cemented ortstein occurs in columns 20 - 25 cm wide extending into the horizon below and occupies about 40 percent of the exposed surface; clear wavy boundary.

BC 65 - 95 cm. Yellowish brown (10 YR 5/4) sand; massive; dark reddish brown (5 YR 3/4) moderately to strongly cemented ortstein occurs in columns 15 - 20 cm wide and occupies about 20 percent of the exposed surface; clear wavy boundary.

C 95 - 110 cm. Yellowish brown (10 YR 5/4) sand; massive.

C 220 - 240 cm.

Pedon: SAV-7
Location: NE 1/4 of NW 1/4 of SE 1/4 of SW 1/4, section 18,T 48 N, R 15 W
Date of description: August 9, 1994
Series: Rubicon
Subgroup classification: Entic Haplorthod
Parent material: Outwash sand.
Physiography: Outwash plain
Slope: < 2 %

A 0 - 6 cm. Very dark gray (10 YR 3/1) sand; weak medium granular structure; friable; common fine roots; abrupt wavy boundary.

E 6 - 17 cm. Grayish brown (10 YR 5/2) sand; weak fine subangular blocky structure; very friable; common fine roots; abrupt wavy boundary.

Bs1 17 - 35 cm. Reddish brown (7.5 YR 4/4) sand; weak fine subangular blocky structure; very friable; common fine roots; dark reddish brown (5 YR 2.5/2) strongly cemented ortstein occurs in columns 8 - 12 cm wide extending into the horizon below and occupies about 30 percent of the exposed surface; clear irregular boundary.

Bs2 35 - 70 cm. Yellowish brown (10 YR 5/6) sand; weak fine subangular blocky structure; very friable; dark brown (7.5 YR 3/4) moderately to strongly cemented ortstein occurs in columns 5 - 10 cm wide extending into the horizon below and occupies about 25 percent of the exposed surface; gradual wavy boundary.

BC 70 - 110 cm. Yellowish brown (10 YR 5/4) sand; structureless; loose; strog brown (7.5 YR 4/6) weakly cemented ortstein occurs in columns 5 - 10 cm wide and occupies about 10 percent of the exposed surface; gradual wavy boundary.

C 110 - 150 cm. Yellowish brown (10 YR 5/4) sand; structureless; loose.

C 190 - 210 cm.

C 290 - 310 cm.

Pedon: SAV-8
Location: NE 1/4 of SE 1/4 of NW 1/4, section 10, T 48 N, R 15 W
Date of description: September 26, 1994
Series: Rubicon
Subgroup classification: Entic Haplorthod
Parent material: Outwash sand
Physiography: Outwash plain
Slope: < 2 %

A 0 - 8 cm. Very dark gray (10 YR 3/1) sand; weak fine subangular blocky structure; very friable; many fine and very fine roots; abrupt wavy boundary.

E 8 - 23 cm. Grayish brown (10 YR 5/2) sand; weak fine subangular blocky structure; very friable; many fine roots; abrupt irregular boundary.

Bs1 23 - 40 cm. Dark brown (7.5 YR 4/4) sand; weak medium subangular blocky structure; very friable; common fine roots; dark reddish brown (5 YR 3/2) moderately to strongly cemented ortstein occurs in columns 10 - 15 cm wide extending into the horizon below and occupies about 30 percent of the exposed surface; clear irregular boundary.

Bs2 40 - 60 cm. Strong brown (7.5 YR 5/6) sand; weak medium subangular blocky structure; friable; few fine roots; dark brown (7.5 YR 4/4) moderately to strongly cemented ortstein occurs in columns 10 - 15 cm wide extending into the horizon below and occupies about 20 percent of the exposed surface; clear wavy boundary.

BC 60 - 90 cm. Yellowish brown (10 YR 5/4) sand; single grain; massive; dark brown (7.5 YR 4/4) moderately cemented ortstein occurs in columns 15 cm wide and occupies about 10 percent of the exposed surface; clear wavy boundary.

C 90 - 120 cm. Yellowish brown (10 YR 5/4) sand; single grain; massive.

C 275 - 282 cm.

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