Nutrient distribution in sandy soils along a forest productivity gradient in the Athabasca Oil Sands Region, Alberta, Canada

by

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Abstract

Brunisolic soils developed on coarse textured (sandy loam to sand) deposits comprise a significant portion of the land currently being disturbed by surface mining in the Athabasca Oil Sands Region of Alberta, Canada. The goals of this study were to determine (i) how the physical properties of these sandy soils influence the accumulation of different forms of nutrients in the soil profile, (ii) the processes at work that govern the amounts and availability of soil nutrients, (iii) how nutrient cycling processes differ between aspen and jack pine dominated stands, which are the two most common canopy species associated with these soils in the AOSR, and (iv) how differences in their associated productivity levels relate to soil physical properties and nutrient levels. To accomplish this, I measured total nutrient stocks contained in the forest floor, available soil nutrients as measured using Plant Root Simulator (PRS) probes, which are ion exchange membranes buried in the soil for a 35 to 38 day field incubation, and select B horizon nutrients. I used correlation analysis and non-metric multidimensional scaling to quantify relationships between these nutrients and soil texture and vegetation productivity. When all sites were considered together, differences in forest floor total and available nutrients were found to largely be influenced by the texture of the upper soil profile, most likely through its influence on canopy type and vegetation productivity levels and therefore the quantity and quality of litter nutrient inputs to the forest floor. However, soil textural controls on nutrient forms are likely different between jack pine and aspen stands. In soils under jack pine, relatively small increases in silt and clay content (≤ 8 %) were associated with a greater site index, greater total nutrient stocks in the forest floor, as well as a higher forest floor quality (lower C:N and C:Ca ratios), potentially linked to more optimal moisture conditions in finer textured jack pine stands. Interestingly, most PRS nutrients showed little relationship with soil texture under jack pine, while available NH_4, P and K actually increased with coarser textures, potentially due to low tree nutrient uptake associated with coarser sites. Forest floor nutrient stocks under aspen related most strongly to B horizon texture, with finer B horizon texture (silt + clay) being associated with larger forest floor nutrient stocks (C, N, P, S, Ca, Mg, K), although availability of Ca and Mg was lower with finer B horizon textures (clay; silt + clay). However, only soils with fine lower soil profile textures were associated with higher forest floor quality (lower C:N and C:Ca ratios). These results indicate that B horizon texture may control the quantity of forest floor nutrients while lower profile texture may control the quality of litter nutrient inputs under aspen. Therefore, while upper profile silt + clay may correlate best with differences in nutrient amounts and availability in sandy soils of the AOSR overall, and correlate strongly with soil nutrients under jack pine, more complex interactions between the relative textures of the B horizon and lower soil profile regulate soil nutrient stocks and forms under aspen.

“Do not sleep under a roof. Carry no money or food. Go alone to places frightening to the common brand of men. Become a criminal of purpose. Be put in jail, and extricate yourself by your own wisdom.”

Miyamoto Musashi

To Caroline

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List of symbols and abbreviations

ρ	Spearman's correlation coefficient
AOSR	Athabasca Oil Sands Region
$CaCl_2$	Calcium chloride
C:nutrient	Carbon divided by nutrient ratio
CSSC	Canadian System of Soil Classification
C_{total}	Total carbon
EC	Electrical conductivity
H_2O_2	Hydrogen peroxide
KM	Modified Kelowna
MRPP	Multi-response permutation procedure
NMDS	Nonmetric multidimensional scaling
N_{total}	Total nitrogen
ODF	Oven dry fraction
PGM	Parent geologic material
pH_{CaCl2}	pH measured in a 1 to 2 soil to $CaCl_2$ solution (0.01M)
pH_{water}	pH measured in a 1 to 1, soil to water solution
PRS	Plant Root Simulator ion exchange membrane

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Chapter 1. Introduction

1.1. Forest nutrient cycling

Nutrient cycling is fundamental to all forest ecosystems because it governs the availability of nutrients to vegetation. Nutrient availability in forest ecosystems may largely control vegetation productivity (Vitousek et al., 1995), and our understanding of these nutrient cycles is vital to ensuring the continued productivity of forest ecosystems and the ecosystem services that are associated with them (Doran, 2002; Nambiar, 1996). While vegetation characteristics may in large part influence nutrient cycles in forest ecosystems, abiotic factors may exert greater control on these nutrient cycles in undisturbed systems overall through their relationship with vegetation distribution and forest productivity levels and their influence on the rates of nutrient additions to and losses from the system.

The primary abiotic factor controlling nutrient cycling in forest ecosystems is climate, largely due to the strong influence of temperature and moisture on forest productivity levels, decomposition and mineralization rates (Swift et al., 1979). Climate also greatly influences soil chemical weathering rates which in turn alter rates of nutrient release and leaching from soils (Ollier, 1975). Therefore, nutrient cycling processes in forests will depend on the major climatic region they inhabit. For example, slow organic matter decomposition rates associated with cold temperatures in boreal forest ecosystems lead to the storage of large quantities of nutrients in the forest floor organic layer, making the chemical composition of organic matter in boreal forest soils highly important to the release of nutrients and nutrient availability to vegetation in these systems (Bonan & Shugart, 1989; Flanagan & Van Cleve, 1983). Conversely, the warm and humid conditions associated with tropical regions lead to rapid rates of decomposition and nutrient turnover in tropical systems in general which leads to the storage of the majority of nutrient capital in biomass of living plants and animals, which helps to counteract the rapid leaching of nutrients from tropical systems (Swift et al., 1979). Organic matter chemical composition may therefore be less important to the release of nutrients from organic matter in tropical forests than total ecosystem nutrient capital overall.

While climate may be the primary overarching factor influencing forest nutrient cycling, within a given climatic region the chemical and physical characteristics of the soil, which are in large part inherited from the soil parent material, may largely control nutrient cycles in the forests that develop on them. The influence of parent material on forest nutrient cycling may result both directly through the chemical and physical composition of the parent material, and indirectly through its influence on vegetation properties and organic matter dynamics. For example, increased immobilization of nutrients has been shown to occur in less fertile tropical soils as a result of greater competition for nutrients (Vitousek & Sanford, 1986), and so even in tropical forests where decomposition rates are high, soil fertility may exert a strong influence on the availability of nutrients from organic matter. Therefore parent material physical and chemical properties may lead to high variation in forest nutrient cycling patterns within major climatic regions.

1.2. Direct effects of parent material on forest nutrient cycles

Soil parent material can directly influence the availability of many nutrients to forest ecosystems. The chemistry of the parent material will largely control the capital of many nutrients in forests and is considered to be a significant source of inputs for many nutrients essential to biogeochemical cycling (Anderson, 1988). For example, the P present in constituent minerals of the soil parent material is for the most part the only source of P to natural ecosystems because atmospheric inputs of P are extremely low compared to other major elements necessary for plant nutrition, such as N (Schlesinger & Bernhardt, 2013). The soil parent material can also supply large quantities of K to soils due to the relatively abundant nature of K in rock-forming minerals at the earth’s surface that soil parent materials are derived from, although the relatively large uptake of K by vegetation generally causes available soil K levels to be very small (Black, 1984). The parent material is an important source of base cations (Ca, Mg, K) that play important roles in vegetation growth and functioning, and their gradual release from the parent material minerals can provide an important continuous supply of these nutrients to vegetation in many systems that helps to counteract their susceptibility to leaching from the soil (Black, 1984).

The susceptibility of different soil parent material minerals to weathering is another important factor to ecosystem nutrient cycling. The minerals making up the soil parent material weather chemically at different rates, with some weathering relatively rapidly and some being highly resistant to weathering (Birkeland, 1999; Ollier, 1975). Because many of these minerals contain nutrients of biological significance, the relative susceptibility of these minerals to weathering is important depending on the soil environment and age of the soils that these minerals are found in. For example, more easily weathered minerals will play a more important role in supplying nutrients in younger soils or soils limited in moisture where chemical weathering rates are low, whereas in older soils or more highly weathered soils, such as those in tropical regions, more resistant minerals will play a more important role in nutrient supply because easily weathered minerals are removed from the system relatively quickly (Anderson, 1988).

The physical makeup of soil parent material greatly influences nutrient availability to biological cycling through its strong connection with soil moisture dynamics. In areas of similar climate and relief, parent material texture largely controls the movement and residence time of water within the soil profile through its direct connection with soil reactive surface area (Anderson, 1988), and therefore controls many soil processes that are associated with water movement, such as the rates of chemical weathering and therefore nutrient release. The greater residence time of water associated with finer textured soils, in combination with greater reactive surface area of soil particles, leads to increased chemical weathering rates in these soils compared to those derived from coarser materials (Birkeland, 1999). Therefore finer textured soils are associated with greater rates of nutrient release due to increased chemical weathering of minerals. The reactive surface area of the soil profile also directly controls the amount of nutrients that can be stored in soils, with soils derived from coarse textured materials generally being very limited in the amounts of nutrients stored in the soil profile due to their relatively low cation exchange capacities (Brady & Weil, 2010). Leaching rates and depths are also controlled largely by soil texture, once again with coarse textured soils being much more susceptible to leaching compared to their finer textured counterparts (Anderson, 1988; Birkeland, 1999), making coarse textured soils more prone to nutrient loss from the soil profile.

The physical makeup of soil parent material can alter nutrient cycling in less obvious ways, one being through the layered nature of many parent materials derived from sedimentary deposits. Many studies have shown that layering of different textured materials in the soil profile can drastically affect the flow paths and residence time of water through the soil, especially in sandy materials (Kung, 1990a, 1990b; Zettl et al., 2011), and therefore influence forest productivity levels (Hannah & Zahner, 1970; McFadden et al., 1994) and species distribution (Host & Pregitzer, 1992). However, relatively little has been studied on how these layers can influence site nutrient dynamics. These layers are known to restrict water flow in some cases, potentially changing the redox conditions of the soil (Anderson, 1988) and theoretically nutrient availability to vegetation and chemical weathering rates, although research on this topic is scarce. Because water dynamics are tied so closely with nutrient movement and availability in the soil profile, one would assume that physical soil profile layering could greatly influence nutrient dynamics in soils, especially in those with coarse textures which are otherwise very nutrient limited. White and Wood (1958) did find that K deficiency in red pine (*Pinus resinosa Ait*) trees located on a sandy soil in New York is reduced in sites with fine texture bands present within 6 ft of the soil surface. These bands were demonstrated to increase the amount of available K in the sandy soils of their study which are otherwise deficient in K. White and Woods' study supports the hypothesis that fine texture layers in otherwise sandy soils will influence nutrient dynamics, although a lack of other studies into this topic makes it difficult to conclude the importance of textural layering to nutrient dynamics in other systems.

1.3. Indirect effects of parent material on forest nutrient cycles

Parent material can influence nutrient cycling in many indirect ways, mainly through its influence on vegetation. Development of vegetation within a given climatic region is largely controlled by soil parent material characteristics (Jenny, 1994). In undisturbed ecosystems, vegetation is likely to develop on sites where moisture and nutrient conditions are most suited to its development (G. G. Whitney, 1991), so in a natural setting, the vegetation community inhabiting a soil may in large part be controlled by the physical and chemical characteristics inherited from the soil parent material. van Breemen et al. (1997) found that the distribution of various tree species in northwestern Connecticut is related to soil texture, although they attributed this to greater Ca and Mg associated with the coarser textured parent materials than to the direct influence of soil texture. The relationships between soil parent material and vegetation species distribution have been documented in many studies (Binkley et al., 1995; Host & Pregitzer, 1992) as well as the influence of parent material on forest productivity (Host et al., 1988; McFadden et al., 1994). This relationship between vegetation and soil parent material brings about its own changes to soil development through the influence of vegetation on soil chemical weathering and nutrient cycling, although the effect of site properties and the effect of vegetation is often difficult to separate because they are typically highly interrelated (Stone & Gibson, 1975).

By influencing vegetation distribution, parent material can indirectly influence nutrient redistribution in the soil profile due to the differing rates of nutrient uptake from and input to the soil by different species. This redistribution of nutrients, particularly the base cations, directly alters the chemical weathering environment in the soil profile by altering soil pH, which has been shown to relate to the rates of removal of these base cations by vegetation (Kelly et al., 1998). A companion study to van Breemen et al. (1997), showed that different tree species, whose distribution was influenced by parent material characteristics, were associated with different pH levels in the forest floor and upper soil profile (0 – 7.5 cm), which was attributed to differences in additions of organic acids and uptake of Ca by the different species (Finzi et al., 1998a). Alban (1982) found similar relationships in soils under different tree species in Minnesota, with aspen (*Populus tremuloides Michx.*) and white spruce (*(Picea glauca Moench Voss*) stands being associated with lower Ca in the shallow mineral soil (0 – 10 cm) than adjacent pine stands (*Pinus resinosa Ait.; Pinus banksiana Lamb*), which resulted in greater soil pH and cation exchange capacity in the pine stands when compared to aspen and spruce.

In addition to altering nutrient distribution in the soil profile, vegetation can directly influence nutrient release from soil minerals through its effect on chemical weathering that results from biologically associated acidity. Chemical weathering rates are affected by CO_2 levels in the soil system (Ollier, 1975), which can vary greatly with plant and microbial activity when climatic factors are kept constant (Amundson & Davidson, 1990). CO_2 concentration influences the pH of the soil environment, which is strongly related to the chemical weathering rates of many minerals (Drever, 1994; Kelly et al., 1998) in addition to the solubility of many ions in the soil solution (Ollier, 1975). Plants and the microbes associated with them also produce organic acids that are emitted into the soil system (Jongmans et al., 1997) which can further influence pH, as well as organic chelating agents that can increase the dissolution rates of some minerals (Drever, 1994).

Soil organic matter dynamics, which are closely tied with nutrient cycles in forest ecosystems can be influenced indirectly by soil parent material through its close relationship with vegetation. The surface organic layer of forest soils is highly important to nutrient cycling largely due to its ability to increase soil moisture storage and nutrient capital, thereby improving overall soil quality and functioning (Gosz et al., 1976; Schoenholtz et al., 2000). The composition of organic matter can influence microbial activity and therefore decomposition and mineralization rates of soil organic matter, which are important processes to the efficient recycling of nutrients in forest ecosystems (Prescott, 2002). The concentration of nutrients in soil organic matter has been shown to relate to the amount of those nutrients released from the organic matter in many studies (McClaugherty et al., 1985; Melillo et al., 1982; Thomas & Prescott, 2000). In systems that are stressed for nutrients, such as those that are highly susceptible to leaching, the organic cycling of nutrients is an important mechanism that helps preserve the amount of nutrients within the system (Fortescue, 1980; Nikiforoff, 1959), although in some cases the buildup of undecomposed organic layers may lead to a reduction in the availability of large amounts of nutrients in the system (Everett & Brown, 1982).

The quantity of nutrients in the forest floor layer and availability of those nutrients can be greatly influenced by vegetation. Tree species are characterized by different litter input rates as well as litter chemical composition and quality (Ovington, 1954; Prescott, 2002). The physical characteristics of the canopy associated with different vegetation species, as well as different forest productivity levels, can also influence nutrient cycling. For example, by controlling the amount of solar radiation reaching the soil surface, the canopy can alter the moisture and temperature conditions of the soils beneath them and therefore directly influence rates of decomposition and nutrient mineralization from soil organic matter, which are highly temperature and moisture sensitive (Prescott, 2002). Because the forest floor layer is a result of the balances between litter input rates, decomposition and nutrient output rates, which are greatly influenced by the quality of the organic matter (Attiwill & Adams, 1993; Flanagan & Van Cleve, 1983; Van Cleve, 1974), vegetation species composition can largely influence the amounts of nutrients that are stored at the soil surface as well as the ease with which nutrients in that organic matter can be recycled by the microbial and plant populations. For example, a second companion study to van Breemen et al. (1997) found that different tree species, whose distribution related to parent material characteristics, differed in C:N ratios in the forest floor, with lower C:N ratios being associated with greater N mineralization from the forest floor (Finzi et al., 1998b). Many organic matter quality predictors have been found to relate to organic matter decomposition and mineralization rates, such as C:N ratio, lignin content, tannin content and N content. However, the organic matter qualities that are associated with greater nutrient mineralization in one ecosystem do not always apply to others. Many studies have shown relationships between N mineralization and the lignin to N ratio of leaf litter inputs (Harmon et al., 1990; Scott & Binkley, 1997; Stump & Binkley, 1993), whereas in other studies lignin to N ratio is a poor predictor of mineralization rates (Prescott and Vesterdal et al., 2000; Thomas & Prescott, 2000) and Staaf (1987) found that forest floor pH and base cation concentrations (Ca and Mg) explained differences in litter decomposition better than lignin or N concentrations in beech (*Fagus sylvatica*) forests of Sweden. Therefore the quality characteristics of the forest floor that lead to greater decomposition may be quite variable and site specific.

Soil characteristics inherited from the parent material have been shown to influence concentrations of nutrients and organic matter quality in the forest floor irrespective of stand type (Reich et al., 1997). Studies have illustrated positive feedback cycles leading to increased nutrient cycling and availability in the forest floors of sites with higher inherited soil fertility. For example, Prescott and Chappell et al. (2000) found that litter N content increased in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands as soil N capital increased, resulting from increased mass and N concentration of litter inputs. They also found that forest floor decomposition and N cycling was also greater in the more N rich soils. Increased concentrations of other nutrients in the forest floor have also been shown to relate to soil fertility. Vesterdal and Raulund-Rasmussen (1998) found that carbon to nutrient ratios (C:P, C:Ca, C:K) in the forest floors along a soil fertility gradient in Denmark are negatively correlated to the concentrations of those nutrients in the mineral soil, which they attributed to greater concentrations of those nutrients in litter inputs on more fertile sites. Similarly, negative feedback cycles involving nutrient availability in the forest floors of nutrient poor sites may also occur, either through poor litter quality associated with infertile sites (Florence & Lamb, 1974; Raulund-Rasmussen & Vejre, 1995) or the increased concentrations of plant compounds that hinder decomposition in nutrient deficient sites (Davies et al., 1964; Lamb, 1975). Therefore litter quality may reflect soil fertility conditions and serve to intensify differences in soil fertility, with less fertile soils being characterized by reduced organic nutrient cycling and more fertile soils leading to greater organic nutrient cycling.

1.4. Alberta's oil sands region

The Athabasca Oil Sands Region (AOSR) of NE Alberta, Canada is an area characterized by high levels of ecosystem disturbance due to the mining of bitumen rich deposits that are abundant throughout the region. A significant amount of this disturbance is in the form of surface mining, which as of 2013 has affected roughly 895 km^2 of land within the AOSR (Alberta Government, 2016). Surface mining leads to the complete disruption of the ecosystems that it affects resulting from the complete removal of soil and vegetation to access the bitumen rich deposits below. If soils destroyed during the surface mining process are to be recreated and their functional nature restored, which largely entails restoring equivalent forest communities and productivity levels native to this landscape, an understanding of the functional relationships between these soils and their associated forest communities is necessary. To ensure reclamation is successful, different vegetative communities must be able to be successfully targeted that are self-sustaining and resilient to environmental stresses. Because proper nutrient cycling is essential to the sustainability of forest ecosystems, and because nutrient cycles are unique to their respective systems, an understanding of how nutrient cycles vary with respect to the specific forest community and the original soil materials is necessary to ensure the successful restoration of target ecosystems throughout this region.

Because the AOSR is part of the boreal forest region of Alberta, the surface organic layer will play an important role in forest nutrient cycling in the different ecosystem types associated with this region. With the slow decomposition rates characteristic of the boreal forest, large amounts of nutrients may accumulate in the forest floor layer, which can comprise a significant amount of the site nutrient capital (Prescott and Maynard et al., 2000; Van Cleve et al., 1983). Over 80 percent of roots were found to reside in the surface organic layer and top 10 cm of mineral material in boreal soils of Quebec, Canada (Finér et al., 1997), further illustrating the potential importance of this layer to vegetation functioning in the boreal region. Decomposition of the forest floor layer is often limited due to the relatively cold temperatures associated with the boreal forest (Van Cleve et al., 1981), therefore the chemical composition and quality of litter inputs to the forest floor is highly important to organic matter decomposition and nutrient release (Bonan & Shugart, 1989). For reasons stated previously, soil parent material characteristics often play an important role in influencing organic matter quality, decomposition and nutrient release, and an understanding of how these properties are related is essential to ensuring the successful reclamation of soils in this sensitive region. Some studies have found that parent material type significantly correlates with forest floor properties of fine textured boreal forest soils of Quebec, Canada, including base cation concentrations, pH and N cycling (Lamarche et al., 2004) and C and N mineralization (Côté et al., 2000). However, no studies have focused on the relationship between parent material and forest floor properties of coarse textured boreal forest soils independently of tree species to the best of my knowledge.

Soil parent materials throughout the AOSR, which generally consist of unconsolidated sediments, vary greatly in their textures and depositional particle sorting due to the complexity of the glacial environment that they formed in (Turchenek & Lindsay, 1982). The nature of the effects of soil texture and depositional layering on site vegetation characteristics and nutrient cycling is of interest because the initial stages of reclamation following surface mining involves the layering of stockpiled soil material of varying depths and textures. An understanding of how the depositional complexity of soil parent materials throughout this region relates to forest productivity and nutrient cycling may allow reclamation specialists to better target specific forest species and productivity levels by altering the way soil materials are placed during the initial stages of reclamation, in addition to which species are chosen for planting on materials of differing physical composition. With the assumptions of a consistent climate and similar time of deposition of parent materials throughout the region, variation in species distribution and productivity levels of vegetation and their associated differences in nutrient cycling throughout this region can be assumed to result from soil parent material differences, provided that topographic factors and disturbance effects are minimized.

Brunisolic soils developed on coarse textured parent material (sandy loam to sand) are a common upland forest soil of the AOSR. While these soils are relatively moisture and nutrient limited, they support unique forest communities ranging from the most limiting sites consisting of jack pine (*Pinus banksiana*) overstory and lichen (*Cladina spp.*) understory communities to more productive aspen (*Populus tremuloides*) and white spruce (*Picea glauca*) communities with a more diverse array of understory species (Natural Regions Committee, 2006). However, the processes governing this range of forest community types and their accompanying site productivities are not fully understood. Zettl et al. (2011) found that variation in particle size distribution of coarse textured soils of the AOSR relates to differences in forest communities and productivity levels mentioned above, with more texturally heterogeneous profiles being associated with more productive vegetation communities. They illustrated that more texturally heterogeneous soils had significantly greater moisture storage at field capacity, and attributed the greater productivity levels associated with these soils to result from this greater moisture availability. However, the ways in which textural differences may influence nutrient cycling in sandy soils of this region has not been studied.

1.5. Research objectives

This study aims to examine the ways in which differences in soil parent material, largely soil textural properties, of coarse textured soils of the AOSR influence nutrient cycling. Nutrients at the soil surface are emphasized due to the previously stated importance of the surface organic layer to nutrient cycling in boreal forests. Total amounts of many nutrients important to plant growth were measured in the forest floor, and carbon to nutrient ratios of some of these nutrients were used to assess differences in organic matter quality. Plant available nutrients were also measured near the soil surface to assess the availability of many of these nutrients to vegetation during part of the summer growing season. Different forms of C, N and P were measured in the soil B horizons in an attempt to understand how mineral soil nutrient concentrations may relate to these forest nutrient cycles. Properties relating to productivity of the canopy and understory vegetation were also measured to assess how vegetation productivity levels relate to the properties mentioned above. Therefore the main objectives of this thesis are to:

1. determine how soil physical properties influence the accumulation of different forms of nutrients in the soil profile and the processes at work that govern the amounts and availability of soil nutrients in sandy soils of the AOSR.
2. determine how nutrient cycling processes differ between aspen and jack pine dominated sites, which are the two most common canopy species associated with sandy soils of the

AOSR, and how differences in their associated productivity levels relate to soil physical properties and nutrient levels.

These objectives will be explored in the second chapter of this thesis, which will be followed by a brief third chapter synthesizing the findings and discussing the limitations of the data, opportunities for further research and some brief recommendations for the reclamation of sandy soils in the AOSR. The effect of the different types of textural layering commonly associated with these soils on nutrient cycling will also be discussed briefly in the final chapter, as well as the difficulties associated with quantifying the effect of these layers.

Chapter 2. Nutrient distribution in sandy soils along a forest productivity gradient in the Athabasca Oil Sands Region, Alberta, Canada

2.1. Introduction

Surface mining in the Athabasca Oil Sands Region (AOSR) of northeastern Alberta, Canada leads to the disruption of entire ecosystems due to the complete removal of soil and vegetation during mine development. The successful reclamation of these disturbed ecosystems is hinged upon the restoration of self-sustaining ecosystem functioning to the landscape, which depends upon the identification of landscape scale environmental factors that influence a wide range of ecosystem functions that are being targeted in the reclamation process (Ehrenfeld, 2000). In the AOSR, the target ecosystem function of reclamation largely entails the re-establishment of upland forest species diversity and productivity levels that are comparable to the pre-mined landscape that are self-sustaining and resilient to disturbance (Alberta Environment, 2010), which in large part depends upon the restoration of similar forest nutrient cycles to these disturbed ecosystems compared to their natural counterparts.

As part of the boreal forest region of Alberta, forest nutrient cycles in the AOSR are unique compared to other forest ecosystems. Slow decomposition rates due to the relatively cold temperatures associated with the boreal region lead to the buildup of large quantities of organic matter at the soil surface, which may lead to the storage of significant site nutrient capital in the surface organic layer of boreal forest soils (Prescott and Maynard et al., 2000; Van Cleve et al., 1981, 1983). Due to these slow decomposition rates, and therefore slow rates of nutrient cycling from organic matter in boreal forests, organic matter quality is considered to be highly important to the cycling of nutrients in these systems (Bonan & Shugart, 1989). Differences in organic matter composition has been associated with differences in microbial activity and composition in the boreal forests of Alberta (Hannam, 2006) and may therefore greatly influence the rates of decomposition and nutrient release from the surface organic layer (McClaugherty et al., 1985; Pastor et al., 1984; Scott & Binkley, 1997; Stump & Binkley, 1993). Similarly, because organic matter is closely tied with many properties that are important to soil functioning (Gosz et al., 1976; Schoenholtz et al., 2000) and total amounts of nutrients in organic matter may influence the quantity of nutrients made available to vegetation (Thomas & Prescott, 2000), the restoration of processes that drive the accumulation and quality of soil organic matter in boreal forest soils of the AOSR is important to ensuring the proper functioning of reclaimed boreal ecosystems following surface mining.

Because the majority of soil forming materials in the AOSR were deposited at similar times during the retreat of the continental ice sheet (Turchenek & Lindsay, 1982) and climate is relatively consistent throughout the AOSR, forest nutrient cycles in this region may in large part be controlled by the physical and chemical characteristics of the soil parent material. Soil parent material is closely tied to forest nutrient cycling because it may largely control the capital of many essential biogeochemical elements (Anderson, 1988), soil moisture dynamics and chemical weathering rates (Birkeland, 1999; Ollier, 1975), leaching of nutrients (Anderson, 1988; Birkeland, 1999) and vegetation species distribution and productivity levels which further influence soil chemical weathering rates (Drever, 1994; Kelly et al., 1998) and composition and quantity of organic matter inputs (Alban, 1982; Florence & Lamb, 1974; Prescott, Chappell, et al., 2000; Raulund-Rasmussen & Vejre, 1995). However, little is known about how soil parent material differences influence forest nutrient cycling in the AOSR, especially in soils derived from coarse textured deposits.

Brunisolic soils are a common upland soil in the AOSR that are typically derived from deposits that are too coarse (sandy loam to sand textures) to form well developed soil profiles. Due to their coarse textures, these soils are generally nutrient and moisture limited (Smith et al., 2011). Because sandy deposits of this region are predominantly composed of quartz (Spiers et al., 1989), which is highly resistant to weathering (Birkeland, 1999; Ollier, 1975), rates of nutrient input from chemical weathering will be very slow. One advantage of sandy textures is generally good water infiltration and drainage, which may reduce the erodibility of these soils (Brady & Weil, 2010), although for this reason sandy soils are highly susceptible to leaching (Anderson, 1988; Birkeland, 1999), which further contributes to their nutrient poor status. Therefore sandy soils of the AOSR are likely to be heavily reliant on organic cycling of nutrients to maintain forest productivity levels and prevent leaching losses of nutrients from the soil profile, while the quality of the organic layer may play an essential role in controlling the availability of nutrients in these soils.

Despite moisture and nutrient limitations, sandy soils of the AOSR support a relatively wide range of forest productivity levels and species types. These productivity levels typically range from the most nutrient limited, low productivity jack pine (*Pinus banksiana*) dominated stands with a predominantly lichen (*Cladina spp.*) understory to trembling aspen (*Populus tremuloides*) dominated stands with a blueberry (*Vaccinium myrtilloides*) dominated understory and may even range up to more productive trembling aspen and white spruce (*Picea glauca*) ecosystems with a low bush cranberry (*Viburnum edule*) dominated understory, which are typically associated with finer textured soils in this region (Beckingham & Archibald, 1996).

Variation in forest productivity levels associated with sandy soils in the AOSR has generally been attributed to differences in moisture status, which may in large part relate to variation in the textural characteristics of the soil parent material. Parent materials of sandy soils in the AOSR, the majority of which are derived from glaciofluvial outwash sediments, can vary greatly in their physical properties (Turchenek & Lindsay, 1982). This physical variation is expressed by differences in physical layering, sorting of particles and subtle textural differences of soil forming deposits. Therefore, despite average textures of these coarse deposits being relatively similar, drainage patterns and residence time of moisture in these sandy soils may be relatively variable (Kung, 1990a, 1990b; Zettl et al., 2011). Differences in the physical morphology and texture of sedimentary deposits has been shown to relate to forest productivity levels in the AOSR (Zettl et al., 2011) and other areas derived from different types of glacial sediments (Farrish et al., 1990; Hannah & Zahner, 1970; Host & Pregitzer, 1992; McFadden et al., 1994), which has been shown to influence the organic cycling of nutrients in other regions (Finzi et al., 1998a, 1998b; van Breemen et al., 1997). However, little is known about how nutrient cycling in coarse textured soils of the AOSR relates to variation in soil physical properties and forest productivity.

A better understanding of how the physical properties of soil parent materials influence nutrient cycling in sandy soils of the AOSR is important to ensuring that soil function may be restored following surface mining. In this study, we looked at how soil physical properties and total amounts and availability of nutrients vary along a gradient in forest productivity of jack pine and aspen dominated sites, which are the two most common canopy species associated with sandy soils of the AOSR. My main objectives, therefore, are to determine (i) how soil physical properties influence the accumulation of different forms of nutrients in the soil profile, (ii) the processes at work that govern the amounts and availability of these nutrients in sandy soils of the AOSR, (iii) how nutrient cycling processes differ between aspen and jack pine dominated sites, and (iv) how differences in their associated productivity levels relate to soil physical properties and nutrient levels. An emphasis was placed on nutrients at the soil surface due to the previously stated importance of the surface organic layer to nutrient cycling in these soils. Select nutrients in the soil B horizons were also measured to assess the role of mineral soil nutrients in forest nutrient cycles of these sandy soils.

2.2. Materials and methods

2.2.1. Study area

The study area is located in the Athabasca Oil Sands Region (AOSR) of northeastern Alberta (Figure 2.1), which is part of the Central Mixedwood Natural Subregion of the Boreal Forest Region of Alberta (Natural Regions Committee, 2006). The Central Mixedwood Natural Subregion is characterized by short, warm summers and long, cold winters with a mean annual temperature (MAT) of 0.2 °C and a mean annual precipitation (MAP) of 478 mm, with 70 % of precipitation occurring as rain during the summer growing season (Natural Regions Committee, 2006).

The most common soil types developed on coarse textured parent materials in this region consist of Eutric and Dystric Brunisols following the Canadian System of Soil Classification (Soil Classification Working Group, 1998), while Gray Luvisols are the most common mineral soils on finer textured deposits (Natural Regions Committee, 2006). Parent materials of Brunisolic soils typically consist of glaciofluvial outwash or ice contact deposits formed during the retreat of the continental ice sheet roughly 10,000 years ago, some of which have been modified by eolian activity following deposition (Turchenek & Lindsay, 1982). Glaciofluvial outwash deposits generally consist of sands with very low silt and clay contents and in some cases occur as a veneer overlying a finer textured glaciolacustrine or morainal second parent material (Turchenek & Lindsay, 1982). Glaciofluvial ice contact deposits typically consist of sands with varying quantities of gravels, stones and boulder sized rock fragments and commonly contain lenses of finer textured material and naturally occurring oil sand deposits (Turchenek & Lindsay, 1982). Eolian deposits occur in the form of sand sheets and dunes with very low coarse fragment contents and are generally found in the northeast portion of the AOSR (Turchenek & Lindsay, 1982).

Jack pine (*Pinus banksiana*) and trembling aspen (*Populus tremuloides*) are the predominant canopy species found on coarse textured deposits in the region, with jack pine typically occurring on drier coarse textured sites and jack pine, trembling aspen and white spruce (*Picea glauca*) generally occurring on wetter coarse textured sites (Natural Regions Committee, 2006). Understories of bearberry (*Arcostaphylos uva-ursi Kinnikinnick*) and lichen (*Cladina* spp.) typically occur on the driest jack pine sites while bearberry, green alder (*Alnus crispa*), common blueberry (*Vaccinium myrtilloides*), prickly rose (*Rosa acicularis*), hairy wild rye (*Elymus innovatus*) and wild lily-of-the-valley (*Maianthemum canadense*) are associated with wetter sites (Natural Regions Committee, 2006). Sites of greater moisture and nutrient content are associated with low bush cranberry (*Viburnum edule*), green alder, rose (*Rosa woodsia*), buffaloberry (*Shepherdia canadensis*), hairy wild rye, wild sarsaparilla (*Aralia nudicaulis*), bunchberry (*Cornus canadensis*) and dewberry (*Rubus pubescens*) and an aspen and white spruce canopy (Natural Regions Committee, 2006).

2.2.2. Study sites and sample collection

Sixteen sites with coarse textured parent materials (Table 2.1) were selected within a roughly 60 km by 20 km area to the north of Fort McMurray in northeastern Alberta, Canada (Figure 2.1). Sites were selected to capture representative stands of trembling aspen and jack pine and the range of forest productivity exhibited within each of these stand types. Initially, forest productivity level was estimated visually to aid in site selection and then quantified later. Whenever possible, level sites were chosen and differences in anthropogenic disturbance, ground water table influence, and texture of the primary soil parent material was minimized.

The soil great groups of this study consist of Eutric and Dystric Brunisols (Table 2.1) following the Canadian System of Soil Classification (Soil Classification Working Group, 1998), with nine sites developed under jack pine dominant stands and seven sites developed under aspen dominant stands (Table 2.1). Fifteen of the seventeen sites contained some form of physical layering within the soil profile (Appendix 1). All soils developed from glaciofluvial ice contact deposits were found to contain naturally occurring oil sand inclusions of varying quantities within the soil profile. Specific sites that contained oil sand inclusions can be found in Appendix 1 and field descriptions of oil sand deposits can be found in Appendix 2. Three sites developed on glaciofluvial outwash sands and three of the four sites derived from eolian deposits contained fine texture bands (≤ 1 cm thickness) within the sandy matrix, while one glaciofluvial outwash site (M178) contained fine texture bands of greater thickness (1 – 4 cm). These bands typically occurred at varying intervals from roughly 50 to 175 cm or greater depth and contoured roughly parallel to the soil surface. Five of the glaciofluvial outwash sites occurred as veneers (20 – 130 cm thick) overlying a fine textured second parent material; either poorly sorted and rocky, loamy sand to loam glacial till or loamy sand to sandy clay loam glaciolacustrine material, which often contained lenses of coarser material (Table 2.1).

Sample plot establishment and soil sampling

Soil properties and metrics for aboveground forest productivity were measured within a 5.64 m radius (100 m^2) circular sample plot at each site (Figure 2.2a) following the detailed plot layout of the Alberta Regeneration Standards for the Mineable Oil Sands (Alberta Environment and Sustainable Resource Development, 2013). Soil sampling occurred over the summers of 2013 and 2014. One soil pit was excavated at the center of each sample plot by shovel to a depth of roughly 1.5 m, and then augered to 2 m. However, pits at some sites were shallower if restricting layers were encountered. A full soil characterization was done morphologically as per (Watson, 2014) including description of morphological horizons, structure, color, rooting, effervescence, mottling, rock fragments, oil sand inclusions and textural layering where applicable. Site and soil field descriptions can be found in Appendix 2.

One composite soil sample of at least 3 L volume was taken from each morphologic horizon within the soil profile including the forest floor layer, stored in a plastic bag, and then air dried within 2 weeks of being sampled. However, in a few cases soil samples were less than 3 L volume if the horizon was too thin to obtain a sufficient sample size, although this was not a problem for the major laboratory analyses. Mineral samples were passed through a 2 mm sieve and the fine earth fraction (<2 mm) was retained for laboratory analysis. Adjustments for coarse fragments (>2 mm) were taken into account in calculations when they exceeded 5 percent. In addition to the bulk forest floor sample taken at the soil pit location, two additional forest floor samples were collected from undisturbed locations within the sample plot boundary to be used for forest floor bulk density and field moisture content as well as chemical analyses. After removing all live vegetation, forest floor samples were obtained by excavating a 10 cm by 10 cm square to the mineral soil interface. The depth of each corner of the square was recorded and the samples were stored in sealed Ziploc bags and refrigerated until time of analysis. Incorporation of mineral material into the forest floor bulk density samples was minimized as much as possible. However, in the case of sites with very thin organic horizons, it was difficult to separate mineral soil from forest floor while still retaining a sufficient forest floor sample. In these cases, one extra sample was taken in an attempt to minimize error in the bulk density calculation caused by the additional weight of mineral material and samples with excessive mineral material were excluded from calculations. Forest floor samples were dried at 65 °C for 48 hours and passed through a 4 mm sieve and the <4 mm fraction was retained for laboratory analyses. Values from the organic samples were averaged for each site.

Plant root simulator (PRS) probes

Plant Root Simulator (PRS) probes (Western Ag Innovations, Inc., Saskatoon, Canada), which are buried ion exchange membranes used to estimate plant available nutrients, were placed at each site using the typical field burial protocol described by Western Ag (Western Ag, 2014). Two pairs of cation and anion probes were placed at four locations within the sample plot boundary 4 m to the north, south, east and west of the plot center, for a total of 8 cation probes and 8 anion probes per site. Refer to Figure 2.2 (a) and (b) for the PRS probe placement locations and configuration at each point. Probes were buried at a 45° angle so that the probe membrane was located at a depth of approximately 4 to 8 cm beneath the surface of the forest floor layer. Probes were collected 35 to 38 days after burial, placed in Ziploc bags and refrigerated until they could be cleaned and shipped to Western Ag for analysis of NO_3^-, NH_4^+, Ca, Mg, K, P, Fe, Mn, Cu, Zn, B, S, Pb, Al and Cd. PRS probe results are reported in units of $\mu g/10cm^2$/burial length.

Cu, Zn, B, Pb and Cd were removed from subsequent statistical analyses because they were for the most part below detection limits.

Forest productivity measurements

All forest productivity metrics were measured during the first two weeks of August, 2014 and included both understory and overstory properties within the 5.64 m radius sample plot. Total shrub biomass was measured on two square, 4 m^2 subplots within the main plot boundary, located 4 m to the north and to the south of the plot center (Figure 2.2a), following the direct method for biomass harvesting of (Bonham, 2013). Shrubs were clipped at ground level, collected in garbage bags, returned to the lab, separated by species and weighed fresh. A subsample of each shrub species from each plot was then oven dried at 60 ºC and the ratio of oven dry to fresh weight was used to calculate the oven dry equivalent value for each sample. Only vegetation that were present vertically within the subplot boundary were retained for weighing. Raw understory biomass data by species can be found in Appendix 5.

Overstory data was collected on trees that were alive and healthy with at least part of the stem falling within the plot boundary and two or fewer stems originating from the tree base for coniferous species following the guidelines for acceptable trees from the Alberta Regeneration Standards for the Mineable Oil Sands (Alberta Environment and Sustainable Resource Development, 2013). However, trees 1.3 m or taller were measured rather than trees 0.3 m or taller. All tree species present within the main plot boundary were recorded and dominant species was estimated visually by which species dominated the total canopy area within the plot boundary. Diameter at breast height (DBH) and height were measured using diameter measuring tape and a Haglöf Vertex IV Hypsometer (Haglöf Inc., Madison, Mississippi, USA) respectively, on all acceptable trees. Whole tree, aboveground biomass for each plot was estimated using Formula 7 from Miao and Li (2007) for oven dry biomass of total stemwood, total stem bark and total crown biomass, which were summed to give a total aboveground tree biomass estimate (kg * 100m^{-2}) for all eligible jack pine and aspen trees within the plot boundary. In one site (M177), that white spruce was present, the equations for white spruce were also used. These equations are a national equation system developed by Evert (1985) for major tree species of the prairie provinces of Canada, and it should be noted that these biomass estimates were simply used in comparing relative overstory biomass levels between plots of this study and should not be used as true estimates of stand biomass because they were not developed specifically for use in the AOSR. Cores from the three tallest trees were taken from the dominant canopy species at 1.3 m height with a Haglöf 16” increment borer (Haglöf Inc., Madison, Mississippi, USA). Age of the core was determined in the lab using a dissecting microscope (Jena Scientific Instruments, Toronto, Ontario, CA). Tree age was used in combination with tree height to calculate an average site index for the dominant species at each site using algorithm 2 presented in Huang et al., (1997) with Statistical Analysis Software (SAS) version 9.3 (copyright SAS Institute Inc., Cary, NC, USA). In six sites where three satisfactory cores could not be taken, site index was calculated based on the number of satisfactory cores available. The age of each core was also averaged for each site and used to estimate stand age for each plot (Table 2.1). In addition, DBH of all eligible trees was used to calculate basal area at breast height (m^2 tree cross sectional area at breast height * 100 m^{-2} ground area) for each site as per (West, 2009).

2.2.3. Laboratory analyses

Soil physical analyses

Soil particle size analysis was done by the hydrometer method of the Soil Survey Staff (2009). Due to the sandy nature of the samples, however, a larger 80 g sample was used. The sample was dispersed overnight using a 5 % sodium hexametaphosphate solution, agitated for five minutes using a Hamilton Beach mixer and transferred to a 1 L sedimentation cylinder. Once in the cylinder, samples were mixed using a plunger and measured after 7 hours of settling with a standard ASTM 152h hydrometer for the clay (< 2 µm) fraction. After measurement samples were thoroughly washed through a 54 µm sieve and the sand fraction was collected, oven dried and weighed. The silt fraction was determined after calculating the clay and sand fractions.

Pretreatments for organic matter and carbonates were done when necessary following the procedure of the Soil Survey Staff (2009). Briefly, for organic matter, 10 mL additions of 35 % H_2O_2 were made at room temperature until the reaction subsided. Samples were then heated to 90 ºC and additional treatments were made until all organic matter was oxidized. Excess peroxide was destroyed through heating for an additional 45 minutes and the samples were washed twice with deionized water. For carbonates, 100 ml of deionized water and 10 mL of 1M sodium acetate (pH 5.0) were added to the sample, mechanically shaken with a vortex mixer, centrifuged and the solution was decanted. Additional washing was done until the supernatant was clear.

For forest floor sample bulk density and field moisture measurements, samples were weighed field moist, dried in the oven at 65 ºC overnight and then re-weighed. Field moisture content was calculated based on the weight lost after drying, and bulk density was calculated by dividing the oven dry soil weight by the volume of the 10 cm by 10 cm square. An oven dry fraction (ODF) was calculated for all mineral soil samples following the protocol of the Soil Survey Staff (2009), where 10 g of air dry soil was weighed, oven dried at 105 ºC and then re-weighed. ODF was calculated as the ratio of oven dry to air dry soil weight. The values from analyses done using air dry soil could then be multiplied by the ODF to calculate an oven dry equivalent value. All analyses of forest floor samples were done using oven-dry samples.

Soil chemical analyses

Total carbon and nitrogen contents (% wt) were measured on forest floor and B horizon samples by dry combustion at the Natural Resources Analytical Laboratory (University of Alberta). Samples were finely ground in a Brinkmann ball grinder, oven dried overnight, flash combusted and analyzed using a Costech 4010 Elemental Analyzer System (Costech Analytical Technologies Inc., Valencia, CA, USA). Only nutrient concentration in the first B horizon (closest to the soil surface) was used in subsequent analyses. Carbon and nitrogen isotopic composition, $\delta^{13}C$ and $\delta^{15}N$ (‰), were determined on a Finnigan Deltaplus Advantage Isotopic Ratio Mass Spectrometer (ThermoFinnigan, Bremen, Germany). Results are expressed against the international reference scale, Vienna Pee Dee Belemnite (vPDB) and air (vAIR) for ^{13}C and ^{15}N respectively (De Groot, 2004). This data was not used in the study but can be found in Appendix 4.

Total amounts of Al, Ca, Fe, Mg, Mn, K, Na, P, and S in forest floor samples were extracted by microwave digestion following the method of (USEPA, 2007). The sample was dissolved in concentrated nitric acid with microwave heating using an Xpress Mars Microwave Digestion

System (CEM Corp, Mathews, NC, USA). The sample and acid was placed in a microwave vessel, sealed and heated in the microwave unit for 10 minutes. After cooling, the sample was allowed to settle and then decanted for analysis by an iCap6000 ICP-OES (Thermo Fisher Scientific, Waltham, MA, USA).

Extractable NO_3^-, NH_4^+ and PO_4^{3+} (ppm) were measured on the B horizons of all sites with the assumption that the B horizon was the mineral horizon of greatest nutrient accumulation. Extractable nutrients in both B horizons were measured for soils with two B horizons. For soils with one B horizon, the underlying BC horizon was also measured. In one case the parent material changed directly below the B horizon and so the overlying AB horizon was used instead. Only nutrient concentration in the first B horizon (closest to the soil surface) was used in subsequent statistical analyses. NO_3^- and NH_4^+ were extracted by the method of Maynard et al. (2006) using 2.0 M KCl and a 1:10 soil to extractant ratio, while PO_4^{3+} was extracted following the Modified Kelowna procedure of (Ashworth & Mrazek, 1995) using a Modified Kelowna (KM) solution consisting of 0.015 M ammonium fluoride, 1.0 M ammonium acetate and O.5 M acetic acid as the extractant in a 1:10 soil to extractant ratio. The extracts were analyzed as soon as possible by colorimetry using a Microplate Spectrophotometer (Synergy HT, BioTek, Winooski, VT, USA) following the Aridlands Ecology Laboratory Protocol (Castle, 2010) for NO_3^- (Doane & Horwath, 2003), NH_4^+ (Weatherburn, 1967) and PO_4^{3+} (Lajtha et al., 1999). Low concentration calibration curves (0, 0.02, 0.05, 0.1, 0.5, 1 ppm) and (0, 0.1, 0.5, 1 ppm) were used for NO_3^- and NH_4^+ respectively and a high concentration curve (0, 0.5, 1, 2.5, 4, 5 ppm) was used for PO_4^{3+}. Plates were measured at a wavelength of 540, 650 and 630 nm for NO_3^-, NH_4^+ and PO_4^{3+} respectively. A separate calibration curve was created for each microplate and two blanks were carried throughout the procedure and their values subtracted from the sample values.

Soil pH and electrical conductivity (EC) was done sequentially using an Accumet XL200 combination pH and EC meter as per the Soil Survey Staff (2009). First, active pH and EC were measured after 30 minutes in a 1:1 soil to water solution which was stirred for 1 minute at 10 minute intervals. Following this measurement, 0.02 M $CaCl_2$ was added to the same sample which was stirred again for 1 minute and pH was measured a second time to give the 1:2 $CaCl_2$ exchangeable pH after a 30 second settling time.

2.2.4. Statistical analyses

All statistical analyses and graphing was performed using R version 3.1.1 (R Core Team, 2014). Comparison of site and soil properties between aspen and jack pine canopies was done using the Wilcoxon Rank Sum Test due to potential violations of the assumption of normality with such a small sample size. The Spearman's Rank Order Correlation was used to examine monotonic relationships between continuous variables because it is much more robust against outliers, which could have a strong influence on correlations once again due to the small sample size. Spearman's correlations were calculated using the rcorr function of the Hmisc package (Harrell Jr & Dupont, 2016) in R, which uses mid-rank values when data points are tied and calculates an approximated p value using a t distribution. Spearman's correlation returns a correlation coefficient ρ, where $-1 \leq \rho \leq 1$ in which positive correlations closer to 1 indicate stronger positive relationships and negative correlations closer to -1 indicate stronger negative correlations. All of the environmental variables assessed in these correlations can be found in Table 2.5. Due to the layered nature of some of the soils, the B horizon texture, upper profile average texture and lower profile average texture were used in the correlations to assess how the texture of different soil layers may influence nutrient cycling. Upper profile texture was calculated as the average texture of the soil horizons from the mineral soil surface down to the bottom of the IBC horizon, although the depth of the mineral soil surface to the bottom of the IB horizon was used when no IBC horizon was present. Lower profile texture was calculated as the average texture of all horizons below the bottom of the IBC horizon, although all horizons below the bottom of the IB horizon were used when no IBC horizon was present. Environmental parameters that were co-linear based on linear regression analysis were removed from subsequent correlation analyses to reduce the number of variables assessed and can be found in Table 2.2.

Nonmetric Multidimensional Scaling (NMDS) ordination was used to explore how the environmental parameters assessed relate to nutrient profiles of all sites. NMDS is a nonparametric technique in which the species composition of sites are organized in ordination space based on the rank of the dissimilarity of the data points, so that sites farther apart are more dissimilar in their species composition (Jongman et al., 1995). Ordinations were done separately using the data sets of forest floor nutrient stocks, forest floor carbon to nutrient ratios and PRS probe available nutrients as the ordination species. When the ordination finds a solution after numerous iterations it outputs a stress value (%) indicating how well the distances between points in the ordination actually correspond to their dissimilarities, with lower stress values indicating a better representation. In all cases, the NMDS was performed using a Sorenson (Bray-Curtis) distance measure and a Wisconsin double standardization in which species values are divided by their maximum values, as well as a square root transformation to minimize the spread in values. The envfit function of the vegan package in R (Oksanen et al., 2015) was used to assess how well environmental parameters correlate with site nutrient distributions in ordination space for the continuous variables found in Table 2.5. This function outputs an R^2 and a p value for each environmental parameter assessed, which corresponds to the strength of the correlation between continuous environmental parameters with the ordination, or the goodness of fit of categorical variables with the ordination, while the p values are based on how likely it is that random permutations of the data, in this case 999 permutations, give a better R^2 value (J. Oksanen, 2015). A non-parametric, multi-response permutation procedure (MRPP) was used to test for differences in nutrient species composition between aspen and jack pine sites using the mrpp function of the vegan package in R (Oksanen et al., 2015). This function outputs an A value, which corresponds to the similarity within groups, and a p value, which indicates how likely the difference between groups is due to chance (McCune & Grace, 2002), while groups were weighted by the number of samples within each group. The soil physical properties and vegetation properties that had the strongest relationship with the ordination were then plotted in the ordination diagram. A specific p value cutoff was not used due to the high variation in p values between ordinations, therefore the environmental parameters shown in the ordination diagrams are those with the lowest p values relative to that specific ordination, although the canopy grouping was shown regardless of the strength of the MRPP. Continuous environmental parameters are represented by an arrow, which points in the direction of most rapid change of that variable while the length of the arrow corresponds to the strength of the correlation between that variable and the ordination, with longer arrows having stronger correlations, and ellipses represent the 95 % confidence interval for the canopy type groupings (Oksanen, 2015).

Due to the small sample size of the groups examined in this study, I used the framework proposed by Hurlbert and Lombardi (2009), in which a critical p value is not used to assess whether a significant effect has been detected. Instead, different p value levels were used as indicators of the likelihood of a difference between groups in the case of Wilcox tests or as an estimate of the strength of the correlation between the explanatory variable and the dependent variable in the Spearman's correlations.

2.3. Results

2.3.1. General site properties

Physical and chemical soil properties of aspen and jack pine sites are shown in Table 2.3. Average texture of the upper soil profile (above the IBC or IC horizon) of both pine and aspen dominated sites was sand, although aspen sites were slightly finer textured on average (88% sand) than pine sites (94% sand) and varied more greatly in texture between sites when compared to pine. Lower profile texture (below the IB or IBC horizon) of pine sites was sand on average also. The aspen sites averaged a sandy loam texture in the lower soil profile and showed high variation between sites due to the prevalence of depositional layers of varying but generally finer textures (Table 2.1) in the lower soil profile of most aspen sites. The Wilcoxon tests showed good evidence of a difference in upper profile and lower profile texture (sand, silt and clay) between canopy groups ($p \leq 0.06$). Soil chemical properties were similar between pine and aspen sites. pH (water and $CaCl_2$) were both slightly higher in aspen sites than pine, although the difference was very small in both cases. EC was also higher in aspen sites than pine although variation was very high within both groups. All chemical properties showed little evidence for a significant difference between canopy types ($p > 0.3$).

On average, all of the site vegetation properties measured were roughly 1.5 to 2 times greater in aspen sites compared to pine, although variation was high within groups (Table 2.4). Basal area showed weak evidence of a difference between canopy groups ($p = 0.15$) but shrub biomass showed good evidence of a difference between groups ($p = 0.05$). Site index and overstory biomass were not compared.

Correlation results between site environmental parameters can be found in Table 2.5. In jack pine sites, lower % clay showed a moderately good ($p = 0.07$), negative relationship with EC while B horizon % clay showed a moderately good ($p = 0.07$), positive relationship with pH. Shrub biomass also showed a good ($p = 0.02$), positive relationship with EC in jack pine sites and very good ($p = 0.01$), negative relationship with lower % clay. Overstory biomass only showed a very weak ($p = 0.3$) relationship with lower % sand while site index showed a very strong ($p < 0.001$), negative relationship with upper % sand in the pine sites. The aspen sites showed relatively weak correlations between environmental variables when compared with pine. EC in aspen sites showed a weak ($p = 0.11$), positive relationship with upper % clay and pH was weakly ($p = 0.18$) related to B horizon % clay. Shrub biomass was weakly ($p = 0.18$) related to B horizon % clay in aspen sites but showed good ($0.01 < p \leq 0.05$) relationships with lower soil profile texture parameters, site index showed a good ($p = 0.04$), negative relationship with B horizon % clay and overstory biomass showed a moderately good ($p = 0.09$), negative relationship with upper % sand.

2.3.2. Forest floor total nutrient stocks

The NMDS ordination of all nutrient stocks in the forest floor found a two dimensional solution with a stress of 8.5 % after one try and good correlations were found with both soil and vegetation properties relating to forest floor nutrient stock profiles. The strongest relationships were found with upper profile texture parameters: upper % clay ($R^2 = 0.42$, $p = 0.037$) and upper % sand ($R^2 = 0.52$, $p = 0.010$). Of the vegetation properties, overstory biomass showed the strongest correlation ($R^2 = 0.53$, $p = 0.021$) followed by site index ($R^2 = 0.45$, $p = 0.026$) and only a weak correlation was found with shrub biomass ($R^2 = 0.26$, $p = 0.145$). The MRPP indicated a moderately good chance of a significant difference between canopy types ($A = 0.09$, $p = 0.055$). Looking at graphical trends in the NMDS ordination of forest floor nutrient stocks (Figure 2.3), the canopy groups showed relatively good separation between ellipses, indicating different forest floor total nutrient profiles between canopy groups. Jack pine sites were associated with coarser textures, indicated by the upper profile % sand vector pointing in roughly the same direction, while aspen sites were associated with decreased upper profile % sand and greater overstory biomass and site index (Figure 2.3).

Comparisons of total nutrient stocks in the forest floor between canopy groups can be found in Table 2.6. All of the nutrient stocks measured in the forest floor samples were greater on average in aspen sites than pine, and the Wilcoxon tests showed moderately good to good evidence that differences between the two groups likely exist for C, N, P, S, Ca, Mg, and K ($0.01 < p \leq 0.1$), which is consistent with the ordination results that indicated a difference in forest floor nutrient stock profiles between pine and aspen sites. Na, Mn, Fe, and Al showed little evidence for a difference between groups ($p > 0.35$), however.

Correlations between environmental parameters and forest floor total nutrient stocks in pine sites (Tables 2.7 and 2.8) were generally consistent with the findings from the ordination stated previously. Upper soil profile % sand showed good to very good ($p \leq 0.05$) relationships with all of the nutrient species in the pine sites and in almost all cases the strongest correlations, which were always negative. Site index showed moderately good to good ($p < 0.1$), positive correlations with all nutrient species in jack pine sites with the exception of S, Fe and Al. EC showed good ($0.01 < p \leq 0.05$), positive relationships with S, Fe, Al, Mg, K and Na, despite being poorly related to the ordination.

Correlations in aspen sites (Tables 2.7 and 2.8) were much less consistent compared to pine. Of the soil texture parameters assessed, B horizon % sand generally showed the strongest relationships in aspen sites with individual nutrient stocks (C, N, P, S, Fe, Al, Ca, Mg, K, Mn), and was always negatively correlated. However, this relationship was weak or very weak in many cases (C, P, Fe, Al, K, Mn; $0.15 < p \leq 0.25$). The vegetation parameters were in almost all cases very weakly or weakly related to nutrient stocks of aspen sites although shrub biomass typically showed the strongest correlations (C, N, P, Mg, K) compared to other vegetation properties. No consistent trends were found with soil chemical properties in aspen sites, which were for the most part weakly or very weakly related.

2.3.3. Forest floor nutrient ratios

The NMDS ordination with forest floor nutrient ratios found a two dimensional solution after 2 tries with a stress of 9.5 %. Upper % sand showed the strongest correlation with the data ($R^2 = 0.63$, $p = 0.005$) while weaker but still good relationships were found with B horizon % sand and

EC. Overstory biomass was the most correlated of the vegetation properties ($R^2 = 0.49$, $p = 0.020$) followed by shrub biomass ($R^2 = 0.44$, $p = 0.029$) and only a weak relationship was found with site index ($R^2 = 0.27$, $p = 0.133$). The MRPP indicated little evidence for a significant difference between canopy types ($A = 0.0004$, $p = 0.384$). Graphically, the NMDS ordination of forest floor nutrient ratios (Figure 2.4) showed generally similar trends to forest floor nutrient stocks. Jack pine grouped towards greater % sand in the upper soil profile, while aspen sites grouped towards decreased upper profile % sand and greater overstory biomass or shrub biomass. Overlap was much greater between the canopy groups in this case when compared to the forest floor nutrient stocks ordination, which is reflected in the low R^2 value of the canopy grouping.

Carbon to nutrient ratios of the selected total nutrients in the forest floor were lower in aspen sites on average in all cases except for C:K, which was lower in the pine group (Table 2.9). However, only the C:N ($p < 0.001$) ratio showed evidence of a significant difference between groups.

Correlations between nutrient ratios in the forest floor are found in Table 2.10. In pine sites, EC showed good ($0.01 \leq p \leq 0.05$) relationships with many of the ratios (C:S, C:Ca, C:Mg, C:K) and in all cases this was a negative correlation. Texture parameters also generally showed relatively good correlations which is consistent with the ordination results. Upper profile % sand showed a moderately good ($0.05 < p \leq 0.1$), positive relationship with C:N and C:Ca, while C:S and C:K were best related to lower profile % clay (positive correlation; $p < 0.1$). Overstory biomass showed a good ($0.01 < p \leq 0.05$), positive relationship with C:Mg and C:K, while site index showed a good ($p = 0.05$), negative relationship with C:Ca. C:P was most strongly related to overstory biomass although this relationship was very weak ($p = 0.21$).

Aspen correlations (Table 2.10) were once again quite mixed. Of the texture parameters, lower profile texture (% clay or % sand) showed the strongest relationships with C:N and C:Ca ($0.05 \leq p < 0.1$). C:P was most strongly correlated with upper profile % clay (positive correlation; $p = 0.09$), while C:K was most strongly related to upper profile % sand (negative correlation; $p = 0.03$). Vegetation parameters were generally very weakly related to ratios in the aspen sites with the exception of shrub biomass, which showed a good ($p = 0.04$), positive relationship with C:N ratio and overstory biomass which showed a moderately good ($p = 0.07$) relationship with C:K.

2.3.4. PRS probe available nutrients

The NMDS ordination of PRS probe available nutrients found a solution after 1 try with a stress of 10%. EC showed the strongest correlation with the data ($R^2 = 0.84$, $p = 0.001$) as well as upper % sand ($R^2 = 0.53$, $p = 0.006$), while B horizon % sand showed a weaker but still good relationship. The remaining soil variables were only weakly or very weakly related. The continuous vegetation parameters were more weakly related to PRS probe nutrients than the soil parameters, with overstory biomass being most strongly correlated ($R^2 = 0.35$, $p = 0.055$) followed by site index ($R^2 = 0.35$, $p = 0.084$) and shrub biomass showed only a weak relationship ($R^2 = 0.31$, $p = 0.117$). The MRPP indicated moderately good evidence for a difference between canopy types ($A = 0.05$, $p = 0.10$). Graphically, the PRS probe NMDS ordination shows similar trends to forest floor nutrient stocks, with jack pine sites plotting with increasing upper profile % sand while aspen sites plotted in roughly the opposite direction and were associated with increasing levels of site index and overstory biomass (Figure 2.5).

PRS probe available nutrient comparisons between canopy groups are shown in Table 2.11. Differences in PRS probe N_{total} and NO_3 were minimal between the canopy groups but NH_4 showed good ($0.01 \leq p \leq 0.05$) evidence of being significantly different between the groups along with P, K and Fe, with aspen sites containing greater amounts of all these nutrients except for Fe. Al was also lower in aspen sites and showed moderately good evidence ($p = 0.06$) of a difference between groups. Ca and Mg were both higher on average in aspen sites although evidence of a significant difference was very weak ($p = 0.25$), with very high variation in Ca and Mg amounts within the groups. S and Mn levels were very similar in aspen and pine sites.

Correlations for PRS probe nutrients are shown in Tables 2.12 and 2.13. In pine sites, all of the environmental parameters were generally weakly or very weakly related with PRS probe nutrients. NO_3, S, Mg, Mn and Al were all very weakly ($p > 0.2$) related to all texture parameters. NH_4, P and K showed weak to moderately good ($0.05 < P < 0.2$), positive relationships with upper % sand in pine sites. Soil chemical properties and site vegetation parameters in the pine sites were generally weakly or very weakly ($p > 0.1$) related to PRS probe nutrients.

In Aspen sites, PRS probe nutrients were generally related relatively well to either soil texture or vegetation properties. Overstory biomass showed a good ($p = 0.02$), negative relationship with NO_3 while shrub biomass showed good ($0.01 < p \leq 0.05$), positive relationships with NH_4 and Mn; moderately good ($0.05 < p \leq 0.1$), negative relationships with S and Ca; and a weak, negative relationship with Mg ($p = 0.18$). Lower % clay showed a very strong ($p < 0.0001$), negative relationship with NH_4; a good ($p = 0.05$), positive correlation with S; and a good ($p = 0.05$), negative relationship with Mn. Upper % clay and B horizon % clay both showed good to moderately good ($0.05 \leq p \leq 0.1$) correlations with Ca and Mg. The remaining nutrients showed weak ($p > 0.1$) correlations with environmental variables.

2.3.5. B horizon nutrients

B horizon nutrient results are found in Table 2.14. Total C was higher on average in pine sites than aspen, although there was no evidence for a significant difference ($p = 0.92$) due to high variation within groups. Total N was higher in aspen sites with moderate evidence ($p = 0.1$) of a difference between the two groups. Extractable PO_4 and NH_4 concentrations were both greater in pine sites and showed weak ($0.1 < p \leq 0.2$) evidence of a difference between the groups. Extractable NO_3 was below detection limits at most sites and was therefore not included in subsequent statistical analyses. B horizon nutrients were in almost all cases poorly correlated with the environmental variables assessed in both jack pine and aspen sites (Table 2.15).

2.4. Discussion

2.4.1. Forest floor nutrient stocks

The forest floor nutrient stock ordination (Figure 2.3) indicates that forest floor total nutrient profiles of these soils are different between aspen and jack pine sites with changes in soil texture (% silt and clay) and overstory productivity levels also explaining differences in nutrient profiles well. Aspen is associated generally with either finer textures in the upper soil profile or lower profile whereas jack pine is, in almost all cases, associated with consistent, sandy upper and lower soil profile textures (Table 2.3), likely due to the importance of soil moisture to aspen development (Fralish, 1972; Peterson & Peterson, 1992). Finer textured sites have been shown to be associated with greater litter nutrient inputs for the same tree species in Minnesota (Perala & Alban, 1982) likely resulting from the greater water and nutrient availability associated with more optimal moisture and nutrient conditions in soils higher in silt and clay contents. Therefore, nutrient stock profiles in sandy soils of the AOSR are likely related indirectly to soil texture, which probably affects litter inputs of nutrients by influencing canopy type and productivity levels. Soil texture is considered to be a relatively stable site factor, largely unaffected by vegetation (van Breemen et al., 1997) and is therefore hypothesized to be the predominant factor controlling these nutrient stocks, albeit indirectly through its effect on vegetation.

The strong relationships between forest floor thickness and individual nutrient stocks in both aspen and jack pine sites (Appendix 1) suggest that litter input volume is largely controlling nutrient stocks in the forest floors of both canopy types. However, the correlations within canopy types suggest that mechanisms influencing these litter nutrient inputs are likely different for jack pine and aspen, although both are proposed to relate to textural influence. The strong relationships of upper soil profile texture and site index with the majority of individual forest floor nutrient stocks in jack pine sites (Tables 2.7 and 2.8) indicate that litter nutrient inputs in these sites largely relate to the productivity of the trees, as suggested by the nutrient stock ordination, although interestingly tree biomass showed very little evidence of a relationship with forest floor nutrient stocks individually. Greater litter nutrient inputs likely result from more productive trees on finer textured soils, resulting in either greater amounts of litter and therefore nutrients, or more nutrient rich litter inputs. Understory biomass levels likely contribute relatively little amounts of litter nutrient inputs due to their unproductive nature in these jack pine stands, which is often dominated by lichens. Site index also showed a relatively strong relationship with forest floor thickness at the jack pine sites ($\rho = 0.58$, $p = 0.10$), which was the strongest of all the vegetation variables measured (Appendix 1), further indicating a direct relationship between tree productivity and the amount of nutrients in the forest floor. Silt and clay content has shown strong correlations with jack pine site index in other studies through its association with soil water and nutrient storage (Pawluk & Arneman, 1961), which is consistent with my findings (Table 2.5). This relationship between site index and texture therefore appears to further result in increased nutrient capital contained in the forest floor.

However, factors controlling nutrient stocks in the aspen stands are more complex. Aspen are typically associated with more diverse understory species and greater understory biomass levels compared to coniferous species of the same region (Gordon, 1981; Peterson & Peterson, 1992) which can result in complex interactions influencing litter nutrient inputs, decomposition rates and nutrient cycling (Taylor et al., 1989). Despite being less well defined when compared to the pine sites, the generally stronger relationship of individual forest floor nutrient stocks with shrub biomass when compared to other environmental variables (Tables 2.7 and 2.8), in addition to the relatively strong relationship between shrub biomass and forest floor thickness in aspen sites ($\rho = 0.64$, $p = 0.12$) compared to other vegetation properties (Appendix 1), indicate that nutrient inputs to the forest floor of these aspen sites are largely via shrub litter. Ground cover species have been shown to contribute greatly to forest floor nutrient contents in Minnesota on soils of similar textures to this study in jack pine and aspen stands (Perala & Alban, 1982) possibly due to their more nutrient rich nature when compared to tree litter (Bernier & Frison, 1984) which supports my findings. Greater silt and clay contents in the more shallow soil profile (B horizon) show stronger relationships with nutrient stocks likely through its influence on understory biomass levels, which have more shallow rooting depths compared to aspen (Sucoff, 1982). However, the relatively weak correlations between these variables indicate overstory and non-shrub understory litter inputs are likely also important to nutrient inputs in these sites, so a more comprehensive characterization of litter inputs may help to improve these relationships.

2.4.2. Forest floor nutrient ratios

The carbon to nutrient ratio ordination (Figure 2.4) showed little evidence for a difference between aspen and jack pine sites and suggests that differences occur more due to interactions between soil texture, overstory biomass and shrub biomass levels, indicating that litter quality is more greatly influenced by texture differences and its influence on biomass levels than by the type of tree species.

The C:N ratio follows roughly the same pattern as forest floor nutrient stocks in both aspen and jack pine sites. In the jack pine sites, C:N relates most strongly to upper profile % sand and site index of the soil and vegetation properties examined (Table 2.10), which is similar to forest floor nutrient stocks although the relationship was negative in this case. C:N also directly related to all forest floor nutrient stocks in the jack pine sites ($\rho \leq -0.73$, $p \leq 0.02$). These relationships indicate that finer textured jack pine sites with greater litter nutrient inputs also show greater forest floor quality, at least in terms of C:N. C:N ratio also shows a strong relationship with field moisture content in the forest floor ($\rho = -0.86$, $p = 0.003$), which illustrates a potential positive feedback loop leading to improved moisture conditions, decomposition, nutrient cycling and likely further increasing site index in the finer textured jack pine sites, even though the difference in average texture was generally very small (≤ 8% silt + clay).

The C:N ratio in aspen sites related positively with shrub biomass (Table 2.10), which may indicate litter quality is lower on sites with high shrub biomass. Furthermore the C:N ratio also related positively with C:S and C:Mg in aspen sites, indicating lower concentrations of other nutrients may relate to lower C:N ratios as well. The positive relationship with lower profile % sand with C:N and C:Ca (Table 2.10) potentially indicates that aspen sites with more silt and clay in the lower soil profile may lead to improved litter quality, possibly by improving water residence time in the soil profile, reducing leaching and making nutrients more plant available, which has been observed in at least one other study (White & Wood, 1958), although site index and overstory biomass showed little evidence of a relationship with these nutrient ratios. Conversely, sites of high shrub biomass, which are associated with greater % sand in the lower soil profile (Table 2.5), are more indicative of poor forest floor quality despite greater total amounts of forest floor nutrients, possibly resulting from less optimal soil moisture and nutrient conditions. These relationships could indicate that slow decomposition rates associated with poor organic matter quality (McClaugherty et al., 1985) of aspen sites with high shrub biomass could also be a factor in the relatively high amounts of nutrient stocks in these sites.

Carbon to nutrient ratios of the other nutrients are more difficult to interpret. In other studies, carbon to nutrient ratios in the forest floor have been shown to decrease with increasing concentrations of those nutrients in the mineral soil (0-50 cm) through increased litter inputs of those nutrients on the more fertile sites (Vesterdal & Raulund-Rasmussen, 1998). Possible evidence for this relationship can be seen with the negative relationships between soil EC and C:S, C:Ca, C:Mg and C:K (Table 2.10). EC is an indicator of the amount of soluble salts in the soil solution, and therefore higher EC could indicate higher amounts of soluble forms of the above nutrients in the mineral soil. EC was also found to relate positively with forest floor nutrient stocks of S, Mg, K, Na and weakly with Ca in jack pine sites (Tables 2.7 and 2.8) which further supports this hypothesis. However, no such relationships were found in the aspen sites. EC also showed a negative relationship with upper soil profile % sand (Table 2.5), indicating greater leaching or lower chemical weathering may result in lower availability of these nutrients to plants in the coarser jack pine sites as well as lower forest floor quality. Spiers et al. (1989) found that concentrations of many elements in different major parent material types in the AOSR relate to the texture of the parent material, with greater clay content being associated with greater elemental concentrations for all major elements except Ca, which related more strongly to the presence of carbonates. Therefore it is possible that the availability of many of these elements is also related to the texture of the soil profile, although this cannot be concluded for certain because the actual concentrations of these nutrients were not measured in the mineral soils of this study. Interestingly, no relationship was found between extractable PO_4 concentration in the soil B horizon and forest floor C:P ratios in either the pine or aspen sites of this study, although P solubility in soils is influenced by a multitude of factors (Black, 1984) and will be discussed in further detail later in the paper.

2.4.3. PRS probe available nutrients

The PRS probe nutrient ordination (Figure 2.5) indicates that available nutrient profiles are likely different between aspen and jack pine sites. Similar to forest floor nutrient stocks, differences also correlate well with upper soil profile % sand and overstory productivity metrics. Similar processes to those governing site nutrient stocks are likely at work, with upper profile soil texture possibly changing the availability of nutrients indirectly through its influence on vegetation species and productivity levels and the balance between nutrient release and uptake.

In jack pine sites, individual PRS probe nutrients correlate poorly with most of the environmental variables considered, including the vegetation productivity measures (Table 2.12 and 2.13). Interestingly, PRS probe NH_4, P, Ca, Mg and K all correlate negatively with jack pine site index and positively with upper profile percent sand, which is opposite to forest floor nutrient stocks, although the correlations with NH_4, Ca and Mg are very weak. This relationship potentially indicates that the drier sites are more limited by moisture than nutrient availability, with coarser textured, low productivity sites unable to utilize these available nutrients, or that PRS nutrients in sandy sites are leached from the rooting zone too quickly to be utilized by plants, possibly due to the very thin forest floor layers associated with sites of lower site index, which were always less than 2 cm thick. However, atmospheric deposition of nutrients resulting from the high industrial activity in the AOSR could be influencing PRS probe nutrient concentrations as well. Amounts of atmospherically deposited NH_4-N, S, Ca, Mg and Na were found to decrease greatly a distance of 20 km from the major industrial center in the AOSR (Fenn et al., 2015). The most southerly jack pine sites in this study (M57-1 and M57-2) are roughly 4 km away from the industrial center and could therefore be affecting these relationships. Fenn et al. also found that NO_3-N, NH_4-N and SO_4 deposition also increased during a large forest fire in 2011. During the time of PRS probe incubation for this study in the late summer of 2014, a large forest fire was occurring to the north of the study area and similarly could have influenced PRS probe nutrient concentrations, especially in the more northerly sites. Therefore complex environmental factors are likely contributing to the poor relationships between site environmental factors and PRS probe nutrients at Jack pine sites, some of which are relatively far apart (Figure 2.1b) and therefore may be subject to different amounts of atmospherically deposited nutrients.

Industrially driven atmospheric inputs of nutrients are likely of less significance with the aspen sites, which are located in relatively close proximity to one another compared to the pine sites (Figure 2.1b), although it is possible that the more southerly aspen sites are affected. PRS probe P, Ca and Mg under aspen show relatively strong relationships with B horizon texture (clay; silt + clay) (Tables 2.12 and 2.13), with the amounts of these nutrients decreasing in sites with finer B horizons. Greater nutrient quantities in the forest floor, possibly resulting from increased shrub biomass associated with fine B horizon textures, therefore, do not result in greater available Ca, Mg and P. However, some PRS nutrients also relate to decomposition of the forest floor. C:N relates negatively to PRS probe S, Ca and Mg ($\rho \leq -0.75$, $p \leq 0.05$), indicating greater litter quality and decomposition could lead to increased availability of S, Ca and Mg possibly from lower competition and uptake from understory species (Ovington, 1965) or increased nutrient release from the forest floor. As stated earlier, this positive feedback loop likely relates back to the texture of the lower soil profile in these aspen sites, with finer lower soil profile textures associated with increased litter quality and availability of some nutrients at the soil surface.

2.4.4. B horizon nutrients

The B horizon soil nutrients measured proved to be difficult to interpret. The presence of naturally occurring oil sand inclusions in some sites (M152-1, M152-2, M175 and M182) no doubt contribute to the high C levels of those sites and cannot be distinguished from soil C in the B horizon with the available data. Additionally, the positive relationship between total N and total C in jack pine ($\rho = 0.72$, $p = 0.02$) and aspen sites ($\rho = 0.72$, $p = 0.06$) could indicate that the presence of oil sand inclusions may influence soil N levels as well, although it should be noted that mineral soil total N levels were very low in all cases (<0.02%). Nagy and Gagnon (1961) found that the petroleum deposits commonly found in sedimentary bedrock deposits of the AOSR do contain N compounds in some cases. With the small amounts of N found in sandy soils of this region, it is possible that the presence of oil sand inclusions could significantly affect total N contents in the mineral soil as well, even if the N content of oil sand inclusions is very small. Therefore we did not attempt to interpret these nutrients in terms of environmental variables due to the possibility of making false conclusions that are skewed by the presence of oil sand deposits.

Extractable P and N in the B horizons of both jack pine and aspen sites were generally very weakly related with all of the environmental variables assessed. In jack pine sites, extractable B horizon NH_4 showed the same trend as forest floor nutrient stocks, with upper soil profile sand relating negatively and site index relating positively (Table 2.15). Therefore greater litter nutrient inputs on finer textured jack pine sites may also lead to greater extractable NH_4 in the mineral soil, potentially through the greater litter decomposition associated with these sites and increased cation exchange capacity. In the aspen sites, however, extractable B horizon NH_4 showed poor relationships with all environmental variables except EC (Table 2.15), although the relationship between these two variables is unknown.

Extractable B horizon P related poorly to all of the environmental variables assessed for both canopy species. However, relationships between B horizon P and PRS probe nutrients may shed some light onto the factors influencing mineral soil P in these sandy soils. In both canopy types, B horizon extractable P was found to relate negatively with PRS probe Ca and positively with Fe, as well as positively with Al in the aspen sites (Table 2.16), all of which are known to influence P solubility in soils (Brady & Weil, 2010). Therefore, the relative amounts of mobile forms of Ca, Fe and Al may influence the availability of P to vegetation in these soils, with greater Fe or Al leading to greater accumulation of extractable mineral soil P, while greater Ca may lead to more optimal conditions for the solubility of P. Liming of acidic soils has been shown to increase P uptake by plants in some cases, either directly by increasing the availability of Al or Fe bound P in the soil or indirectly by reducing Al toxicity in plants, which results in greater plant uptake of P (Haynes, 1982). Although the soils of this study are not extremely acidic (Table 2.3), they are in the range where low P solubility would be expected due to Fe and Al complexing (Brady & Weil, 2010) and therefore it is logical that increased Ca in the soil solution may increase the solubility of P and availability to vegetation leading to lower extractable P levels in the B horizon. The accumulation of P in the sandy soils of the AOSR may also relate to the degree of podzolic development, which is known to lead to the accumulation of different forms of P in the B horizons of podzolic soils (Väänänen et al., 2008). While different forms of P have not been studied in great detail in the AOSR, one study found that a soil in northern Alberta derived from eolian material had an accumulation of Fe and Al bound P and occluded P in the B horizon (Alexander & Robertson, 1968). Alexander and Robertson also found that plant available P correlated well with Fe and Al bound P in the soils of their study whereas there was no correlation with Ca bound P and plant available P. This finding may account for the high amounts of extractable P in some of the B horizons of this study. They also found that the distribution of inorganic forms of P in Alberta was related to the degree of soil development but more strongly with soil parent material type. The degree of accumulation of extractable P in sandy soils of the AOSR may, therefore, reflect the degree of accumulation of Fe and Al in the soil profile relative to Ca, with soils higher in Ca potentially having lower extractable P levels than soils higher in Fe and Al. In my study sites, this relationship may reflect the degree of chemical weathering and development of these sandy soils because the mineralogy of the sand fraction in soil parent materials of this region is relatively uniform within and between different soil parent materials (Spiers et al., 1989).

2.5. Conclusions

The primary goals of this study were to determine (i) how soil physical properties influence the accumulation of different forms of nutrients in the soil profile, (ii) the processes at work that govern the amounts and availability of these nutrients in sandy soils of the AOSR, (iii) how nutrient cycling processes differ between aspen and jack pine dominated sites, and (iv) how differences in their associated productivity levels relate to soil physical properties and nutrient levels. Upper soil profile texture (silt + clay) was found to show the strongest relationships with differences in forest floor total stocks of nutrients, forest floor quality and nutrient availability at the soil surface, likely through interactions between soil texture and site vegetation properties. Forest floor nutrient stocks and nutrient availability were most strongly influenced by interactions between upper soil texture, canopy type and tree productivity (site index and overstory biomass), while differences in forest floor quality result more due to interactions between upper soil profile texture and shrub and overstory biomass levels.

However, the processes influencing nutrient forms within aspen and jack pine stands are likely different. Under jack pine stands, greater forest floor nutrient stocks (all nutrients) were associated with increased silt + clay content in the upper soil profile, likely due to increased litter nutrient inputs associated with more productive trees (greater site index) on finer textured sites. Increased forest floor quality (lower C:N and C:Ca ratio) was also related to higher silt and clay content in the upper profile, indicating that greater amounts of nutrients in the forest floor may also relate to higher forest floor quality, possibly resulting from greater nutrient availability in the mineral soil. However, nutrient availability (PRS) showed little relationship with soil texture under jack pine, and some PRS nutrients (NH_4, S, K), interestingly, decreased with greater silt and clay content under jack pine, possibly resulting from higher nutrient uptake associated with greater tree productivity or more rapid leaching of these nutrients from less productive sites with thin forest floor layers.

Correlations between nutrients and environmental variables in aspen stands were generally poor, which likely results from much higher variation in soil textural properties and understory and tree productivity levels when compared to jack pine stands. Forest floor nutrient stocks (C, N, P, S, Ca, Mg, K) under aspen related most strongly to B horizon texture (silt + clay), with finer B horizon textures having greater nutrient stocks, although availability of P, Ca and Mg were lower in sites with finer B horizons (clay; silt + clay), possibly due to higher shrub biomass and therefore greater competition associated with finer B horizon textures. However, only soils with fine lower soil profile textures (clay; silt + clay) were associated with higher forest floor quality (lower C:N and C:Ca ratios), potentially due to low shrub biomass levels associated with fine lower soil profile textures. Higher availability of PRS S, Ca and Mg associated with lower C:N ratios under aspen stands could also indicate that availability of some nutrients may also increase indirectly due to finer lower soil profile textures and lower shrub biomass levels. Therefore, while B horizon texture may influence nutrient quantity and availability, lower soil texture may more strongly influence the quality of litter nutrient inputs to the forest floor under aspen, potentially due interactions between B horizon and lower soil profile texture on shrub biomass levels. Therefore, soil nutrients under jack pine are most likely controlled by relatively simple interactions between upper profile soil texture and tree productivity, while more complex interactions between the relative textures of the B horizon and lower soil profile and understory and tree productivity levels are most likely the cause of the relatively variable nutrient profiles of sandy soils under aspen.

Chapter 2 tables and figures

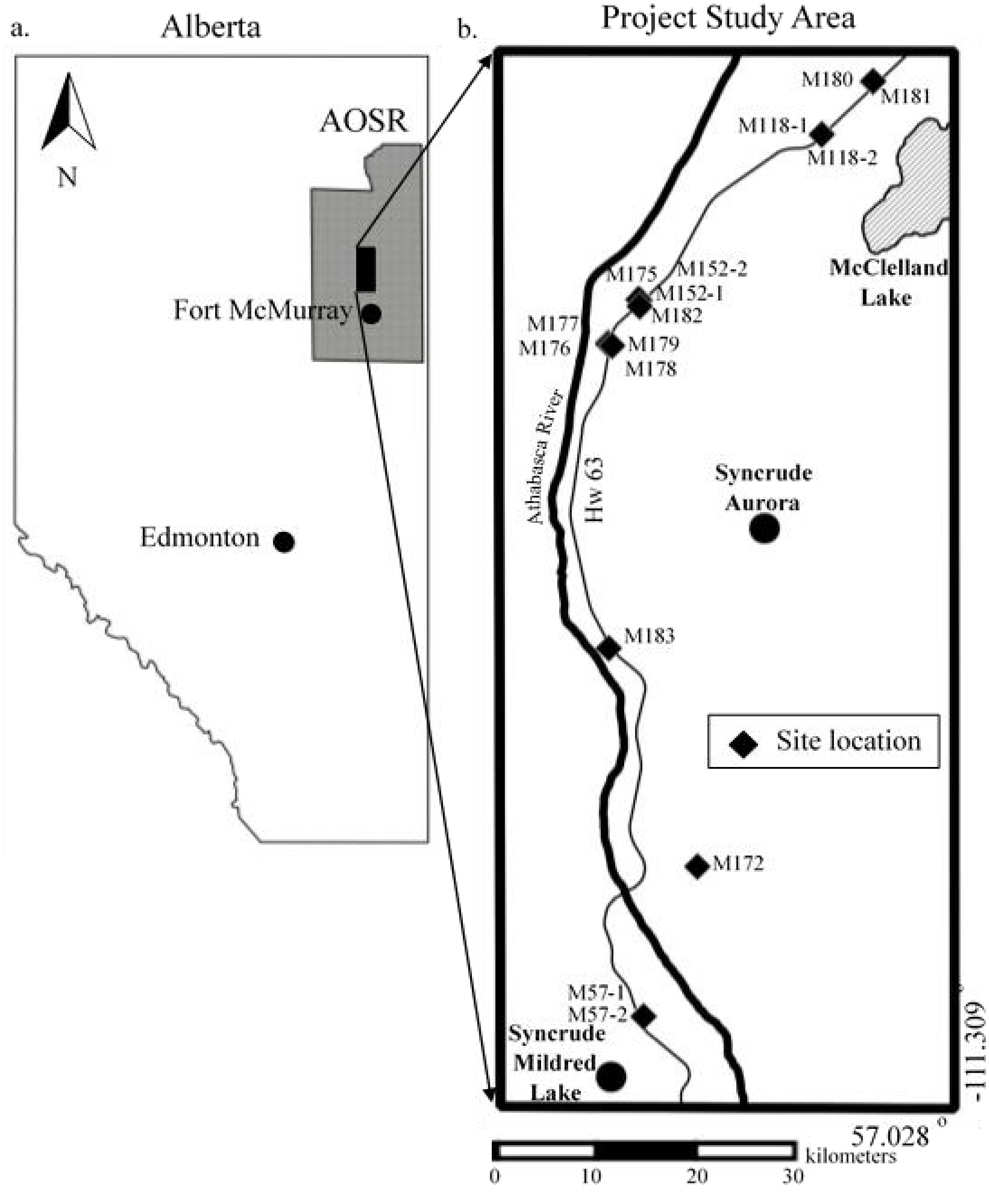

Figure 2.1. Study area maps of the province of Alberta, Canada with the location of the AOSR and the project study area within the AOSR highlighted (a); and a map of the study area showing site locations (b).

Table 2.1. Site locations with soil and overstory vegetation information. PGM is the soil parent geologic material while Classification (CSSC) is the Canadian soil classification to the subgroup level.

	Location		**Soil**			**Overstory vegetation**		
			PGM		**Classification (CSSC)**		**Site index ***	
Site ID	**Lat**	**Long**	**Type (1, 2)**	**Texture (1, 2)**		**Species (1, 2)**	**SI50**	**Age**
M57-1	57.0733889	-111.5936667	GLFL	S	EDB	Pj	12	60
M57-2	57.0730833	-111.5935833	GLFL	S	EDB	Pj	14	56
M118-1	57.5110278	-111.4299722	EOLI	S	EDB	Pj	12	80
M118-2	57.5105278	-111.4301111	EOLI	S	EDB	Pj	15	46
M152-1	57.4289167	-111.5961111	GLFL-IC	S	EDB	Pj, Aw	16	59
M152-2	57.4285278	-111.5969444	GLFL-IC	S	EEB	Pj, Aw	17	58
M172	57.1476944	-111.5438333	GLFL, TILL	S, LS	OEB	Aw	22	71
M175	57.42919	-111.59782	GLFL-IC	S	EDB	Aw	11	78
M176	57.40796	-111.62553	GLFL, GLLC	S, LS	EEB	Aw	15	66
M177	57.40708	-111.62531	GLFL, GLLC	S, SCL	EDB	Aw, Sw	17	72
M178	57.4064	-111.62176	GLFL	S	EDB	Pj	18	59
M179	57.4064	-111.62176	GLFL, GLLC	LS, LS	EDB	Aw	20	75
M180	57.53645	-111.38319	EOLI	S	EDB	Pj	10	118
M181	57.53689	-111.38303	EOLI	S	EDB	Pj	11	109
M182	57.42589	-111.59673	GLFL-IC	S	EDB	Aw	NA	NA
M183	57.25635	-111.62487	GLFL, TILL	LS, L	ODB	Aw	19	68

(1, 2) = (Primary, secondary)

* Analyses done on primary overstory species only, NA indicates analyses not obtained

SI50 Site index at 50 years

PGM: GLFL = glaciofluvial outwash sands; GLFL-IC = glaciofluvial ice contact deposits; EOLI = eolian; GLLC = glaciolacustrine; TILL = morainal

CSSC: ODB = Orthic Dystric Brunisol; EDB = Eluviated Dystric Brunisol; OEB = Orthic Eutric Brunisol; EEB = Eluviated Eutric Brunisol;

Species: Pj = jack pine (*Pinus banksiana*); Aw = trembling aspen (*Populus tremuloides*); Sw = white spruce (*Picea glauca*)

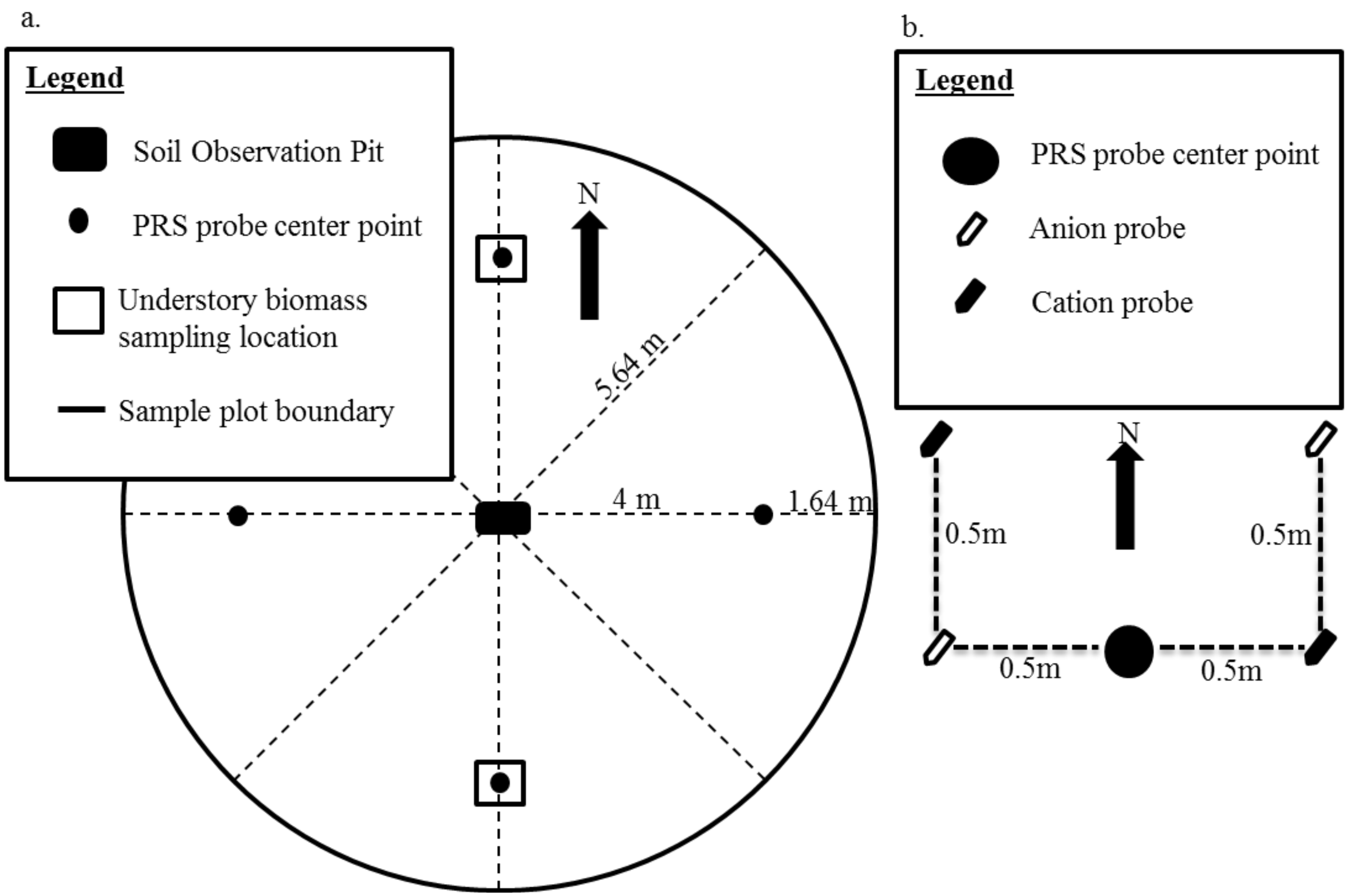

Figure 2.2. Diagram of the sample plot layout within which soil and vegetation properties were measured (a). The soil pit was located at the center of the sample plot and PRS probes were placed at four locations 4 m to the N, E, S, and W of the soil pit. Understory biomass was sampled in 2 m by 2 m plots corresponding with the N and S PRS probe locations. The PRS probe placement configuration at each subplot location is shown in (b). Two cation and two anion PRS probes were placed at each PRS probe center point location for a total of 8 cation and 8 anion probes per site.

Table 2.2. Relevant linear regressions illustrating co-linearity of soil chemical properties with other soil chemical properties and soil physical properties with other soil physical properties.

Soil property	**Soil property ***	**r**	**R^2**	**p**
	Jack pine (n = 9)			
B horizon % sand	B horizon % silt	-0.87	0.76	0.002
Upper sand %	Upper % silt	-0.94	0.88	<0.0001
Lower sand %	Lower % silt	-0.93	0.87	0.0002
pH_{CaCl2}	B horizon pH_{water}	0.83	0.69	0.005
	pH_{water}	0.96	0.92	<0.0001
	Aspen (n = 7)			
B horizon % sand	B horizon % silt	-0.94	0.88	0.001
Upper sand %	Upper silt %	-1.00	1.00	<0.0001
Lower sand %	Lower silt %	-0.92	0.84	0.004
pH_{CaCl2}	B horizon pH_{water}	0.95	0.90	<0.001
	pH_{water}	0.99	0.98	<0.0001

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* Soil property removed from subsequent statistical analyses

Table 2.3. Soil texture, pH and EC of all sites grouped by dominant canopy type. Upper texture values are averages calculated from the mineral soil surface to the BC or C horizon of the primary parent material and lower texture values are averages of the horizons below the B or BC horizons of the primary parent material.

	General soil properties								
	Upper profile texture			**Lower profile texture**			**Upper profile**		
	Sand	**Silt**	**Clay**	**Sand**	**Silt**	**Clay**	**pH_{water}**	**pH_{CaCl2}**	**EC**
Site	**%**			**%**					**$dS\ m^{-1}$**
Jack pine*									
M57-1	95	4	1	99	0	1	5.72	5.10	0.57
M57-2	94	5	1	98	1	1	5.50	4.70	0.67
M118-1	96	3	1	96	1	2	5.71	4.74	0.44
M118-2	95	2	3	96	1	3	6.08	5.13	0.46
M152-1	94	4	2	95	4	1	6.47	5.52	0.55
M152-2	93	4	3	93	5	2	6.75	5.90	0.60
M178	88	9	3	89	6	5	5.72	4.76	0.33
M180	97	1	2	98	0	2	5.79	4.87	0.17
M181	96	1	2	95	2	3	6.16	5.15	0.21
$\bar{X}$	94	4	2	95	2	2	5.99	5.09	0.44
s_e	0.9	0.8	0.3	1.0	0.7	0.4	0.1	0.1	0.1
Aspen*									
M172	86	11	3	76	19	5	6.06	5.32	0.78
M175	89	7	4	90	7	2	7.10	6.26	0.88
M176	94	3	3	82	8	10	6.56	5.63	0.46
M177	93	4	3	48	21	31	6.23	5.31	0.42
M179	83	13	4	81	10	9	5.36	4.42	0.56
M182	94	4	2	95	3	2	5.98	5.00	0.22
M183	76	21	3	42	41	17	5.75	4.91	0.71
$\bar{X}$	88	9	3	73	16	11	6.15	5.26	0.57
s_e	2.5	2.5	0.3	7.8	4.9	3.8	0.2	0.2	0.1
p	0.02	0.06	0.02	0.004	0.001	0.02	0.53	0.47	0.30

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* Site dominant canopy

$\bar{X}$ = mean of the sample, s_e = standard error of the sample group

p = p value from Wilcoxon test comparing soil property values of that column between the two canopy types

Table 2.4. All measured vegetation properties of each site grouped by dominant canopy type.

Site	Site vegetation properties			
	Basal area	Overstory biomass	Shrub biomass	Site index
	$m^2 * 100\ m^{-2}$	$kg * 100\ m^{-2}$	$kg * 100\ m^{-2}$	
Jack pine*				
M57-1	13	193	49	12
M57-2	20	807	40	14
M118-1	29	862	4	12
M118-2	13	93	3	15
M152-1	40	1416	10	16
M152-2	33	703	6	17
M178	30	1232	1	18
M180	28	921	1	10
M181	23	843	4	11
$\bar{X}$	26	786	13	14
s_e	3	142	6	1
Aspen*				
M172	52	1847	20	22
M175	29	758	43	11
M176	47	884	25	15
M177	27	689	18	17
M179	71	3967	33	20
M182	19	758	29	NA
M183	31	1397	19	19
$\bar{X}$	39	1472	27	17
s_e	7	446	3	3
p	0.15	-	0.05	-

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* Site dominant canopy

$\bar{X}$ = mean of the sample, s_e = standard error of the sample group

p = p value from Wilcoxon test comparing vegetation measurements of that column between the two canopy types

Table 2.5. Spearman's correlation table of all assessed environmental parameters. **ρ** is the Spearman's correlation coefficient and correlations with a p value of ≤ 0.1 are highlighted in light grey.

Environmental parameter	**Environmental parameter**																			
	EC		**pH$_{CaCl2}$**		**B % clay**		**B % sand**		**Upper % clay**		**Upper % sand**		**Lower % clay**		**Lower % sand**		**Shrub biomass**		**Overstory biomass**	
	ρ	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**
Jack pine (n = 9)																				
pH$_{CaCl2}$	0.07	0.86																		
B % clay	-0.12	0.76	0.63	0.07																
B % sand	0.13	0.75	0.01	0.98	-0.46	0.21														
Upper % clay	-0.21	0.59	0.53	0.14	0.83	0.01	-0.53	0.14												
Upper % sand	-0.57	0.11	-0.14	0.71	-0.62	0.08	0.44	0.24	-0.43	0.25										
Lower % clay	-0.63	0.07	0.04	0.91	0.46	0.21	-0.61	0.08	0.68	0.04	-0.02	0.96								
Lower % sand	0.16	0.68	-0.42	0.26	-0.82	0.01	0.77	0.02	-0.72	0.03	0.57	0.11	-0.59	0.10						
Shrub biomass	0.77	0.02	0.17	0.67	-0.31	0.42	0.56	0.12	-0.58	0.10	-0.14	0.73	-0.83	0.01	0.41	0.27				
Overstory biomass	-0.45	0.22	-0.12	0.77	0.28	0.47	-0.23	0.54	0.00	1.00	-0.06	0.88	0.03	0.93	-0.39	0.30	-0.33	0.38		
Site index	0.42	0.26	0.20	0.61	0.68	0.04	-0.70	0.03	0.58	0.10	-0.92	<0.001	0.19	0.62	-0.70	0.04	-0.10	0.80	0.12	0.77
Aspen (n = 7)																				
pH$_{CaCl2}$	0.36	0.43																		
B % clay	-0.09	0.84	0.57	0.18																
B % sand	-0.18	0.70	0.54	0.22	0.09	0.84														
Upper % clay	0.66	0.11	0.10	0.83	0.32	0.49	-0.46	0.30												
Upper % sand	-0.61	0.14	0.49	0.27	0.62	0.14	0.63	0.13	-0.49	0.26										
Lower % clay	-0.25	0.59	-0.29	0.53	-0.24	0.61	-0.25	0.59	-0.05	0.91	-0.21	0.65								
Lower % sand	-0.18	0.70	0.36	0.43	0.66	0.11	0.32	0.48	-0.06	0.90	0.65	0.12	-0.81	0.03						
Shrub biomass	0.29	0.53	0.18	0.70	0.57	0.18	-0.11	0.82	0.50	0.26	0.09	0.85	-0.79	0.03	0.79	0.04				
Overstory biomass	0.50	0.25	-0.36	0.43	-0.38	0.40	-0.14	0.76	0.44	0.33	-0.68	0.09	-0.05	0.91	-0.25	0.59	0.21	0.64		
Site index (n = 6)*	0.03	0.96	-0.66	0.16	-0.84	0.04	0.09	0.87	-0.21	0.69	-0.60	0.21	0.03	0.96	-0.54	0.27	-0.31	0.54	0.77	0.07

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* Only six values used in the calculation

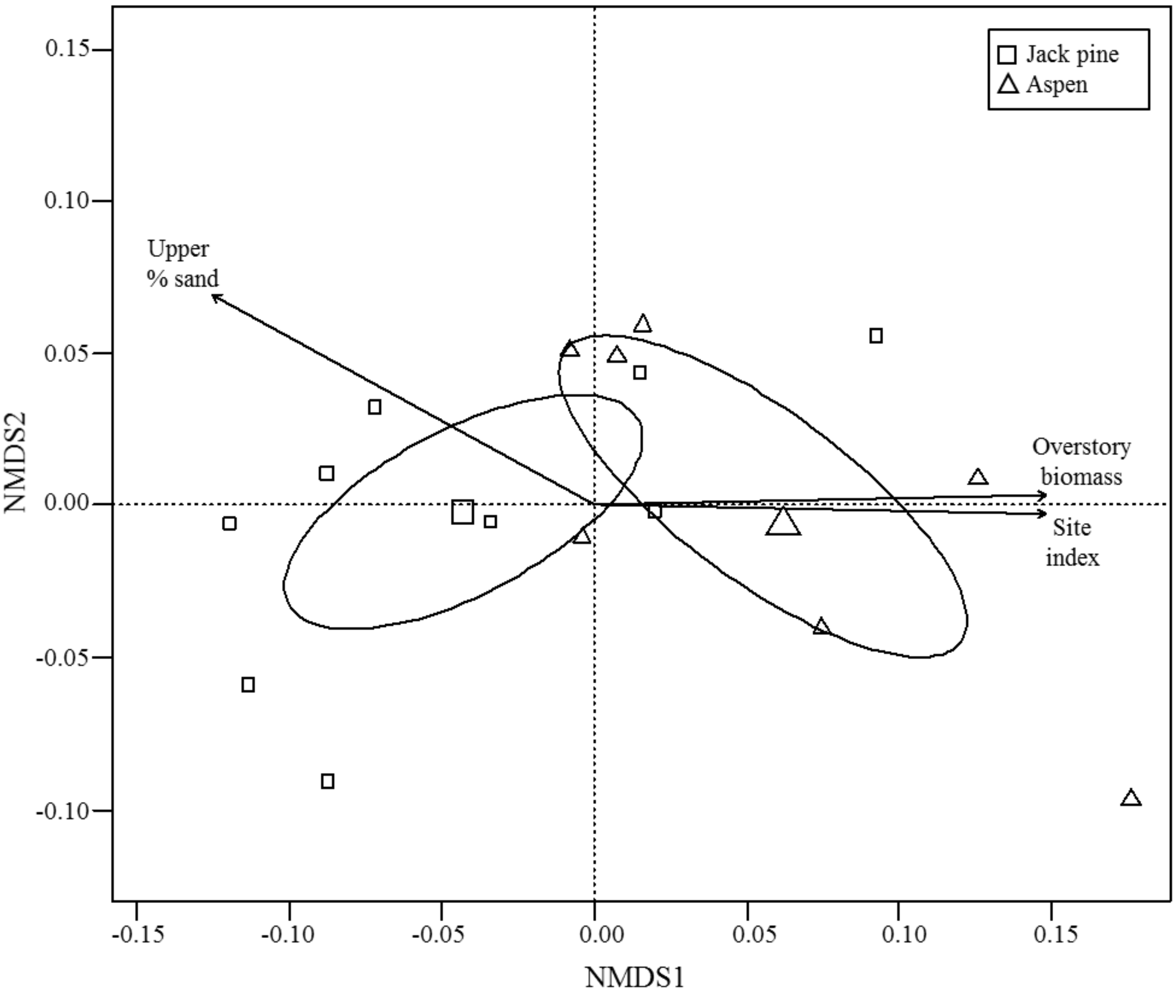

Figure 2.3. NMDS ordination (stress = 8.5 %) of forest floor nutrient stocks (C, N, P, S, Ca, Mg, K, Na, Mn, Fe, Al). Vectors show the direction of greatest positive change of the most strongly correlated continuous environmental variables. Ellipses show the 95% confidence interval for the canopy groups and large symbols show the group centroid location.

Table 2.6. Average forest floor total nutrient stocks and bulk densities for each site grouped by dominant canopy species.

Site	Forest floor total nutrient stocks											Bulk density
	C	N	P	S	Ca	Mg	K	Na	Mn	Fe	Al	
	Mg ha^{-1}	kg ha^{-1}										kg m^{-3}
Jack pine*												
M57-1	3.6	132.5	5.1	21.0	68.3	12.2	16.8	2.3	8.1	341.4	54.1	266
M57-2	10.1	402.9	18.0	55.0	198.2	42.3	48.4	9.6	37.6	1189.0	194.8	275
M118-1	3.5	131.7	5.8	6.7	57.5	9.4	12.9	3.0	13.1	290.6	47.6	280
M118-2	1.5	53.1	2.9	3.0	36.0	6.3	6.1	1.5	4.0	145.5	26.7	280
M152-1	9.6	408.8	15.1	20.7	247.2	25.4	27.2	5.6	55.4	474.6	77.3	179
M152-2	13.1	563.6	24.5	27.9	288.4	44.5	49.1	11.8	80.6	1227.4	176.8	218
M178	14.0	533.9	20.0	25.0	257.0	29.7	29.3	3.7	80.0	292.2	75.1	217
M180	3.3	122.4	4.9	6.6	41.1	5.9	7.8	1.8	8.5	182.9	31.6	280
M181	4.9	191.2	7.8	7.2	65.6	7.9	10.1	1.9	11.8	180.1	39.5	280
$\bar{X}$	7.1	282.2	11.6	19.2	139.9	20.4	23.1	4.6	33.2	480.4	80.4	253
s_e	1.6	65.0	2.6	5.4	35.1	5.2	5.5	1.2	10.5	141.5	20.8	12.6
Aspen*												
M172	8.7	476.7	14.1	33.1	185.2	23.5	23.7	1.5	8.5	157.8	32.6	115
M175	16.5	796.6	27.2	43.1	353.6	53.8	57.6	8.3	49.4	1007.5	160.3	146
M176	5.0	243.4	10.9	12.5	120.1	14.4	22.6	3.2	31.7	328.8	40.9	172
M177	9.6	484.3	16.7	22.2	211.8	22.6	38.4	6.0	54.0	465.7	77.1	183
M179	21.9	950.9	33.4	45.1	428.9	38.5	45.6	5.1	50.5	327.8	103.0	153
M182	18.3	848.2	35.3	38.0	325.8	43.1	51.7	10.8	127.6	846.3	156.0	229
M183	14.9	853.7	26.2	48.5	496.3	59.9	39.2	5.1	71.4	851.7	97.4	163
$\bar{X}$	13.6	664.8	23.4	34.6	303.1	36.5	39.8	5.7	56.2	569.3	95.3	166
s_e	2.3	99.3	3.6	4.9	51.6	6.4	5.0	1.2	14.1	123.9	19.0	13.3
p	0.04	0.01	0.03	0.05	0.03	0.09	0.07	0.41	0.35	0.54	0.47	0.004

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* Dominant canopy species; p = p value from Wilcoxon test comparing soil property values of that column between the two canopy types
$\bar{X}$ = mean of the sample, s_e = standard error of the mean of the sample

Table 2.7. Spearman's correlation coefficient (ρ) between forest floor total nutrient stocks and environmental parameters. Correlations with a p value of ≤ 0.1 are highlighted in light grey.

Environmental parameter	**Forest floor total nutrient stock**											
	C		**N**		**P**		**S**		**Fe**		**Al**	
	ρ	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**
Jack pine (n = 9)												
EC	0.37	0.33	0.40	0.29	0.40	0.29	0.67	0.05	0.77	0.02	0.73	0.02
pH_{CaCl2}	0.07	0.86	0.28	0.46	0.12	0.77	-0.08	0.83	0.08	0.83	-0.03	0.93
B % clay	0.51	0.16	0.58	0.10	0.45	0.23	0.15	0.70	0.10	0.79	0.13	0.74
B % sand	-0.29	0.44	-0.28	0.46	-0.37	0.33	0.03	0.95	0.07	0.86	-0.04	0.91
Upper % clay	0.21	0.59	0.26	0.49	0.21	0.59	-0.11	0.79	-0.16	0.68	-0.16	0.68
Upper % sand	-0.83	0.01	-0.81	0.01	-0.78	0.01	-0.74	0.02	-0.66	0.05	-0.73	0.02
Lower % clay	0.00	1.00	-0.07	0.86	-0.02	0.96	-0.34	0.37	-0.62	0.08	-0.50	0.17
Lower % sand	-0.61	0.08	-0.66	0.05	-0.65	0.06	-0.20	0.60	-0.11	0.78	-0.22	0.57
Shrub biomass	0.17	0.67	0.23	0.55	0.17	0.67	0.50	0.17	0.60	0.09	0.55	0.13
Overstory biomass	0.32	0.41	0.32	0.41	0.30	0.43	0.02	0.97	0.08	0.83	0.17	0.67
Site index	0.65	0.06	0.67	0.05	0.65	0.06	0.47	0.21	0.47	0.21	0.53	0.14
Aspen (n = 7)												
EC	-0.07	0.88	0.00	1.00	-0.18	0.70	0.39	0.38	0.11	0.82	0.04	0.94
pH_{CaCl2}	-0.57	0.18	-0.79	0.04	-0.50	0.25	-0.57	0.18	0.18	0.70	-0.11	0.82
B % clay	0.00	1.00	-0.28	0.54	0.00	1.00	-0.38	0.40	0.28	0.54	0.38	0.40
B % sand	-0.61	0.15	-0.82	0.02	-0.50	0.25	-0.82	0.02	-0.54	0.22	-0.57	0.18
Upper % clay	0.28	0.54	0.26	0.58	0.06	0.90	0.36	0.43	0.02	0.97	0.28	0.54
Upper % sand	-0.27	0.56	-0.58	0.18	-0.11	0.82	-0.77	0.04	0.04	0.94	0.00	1.00
Lower % clay	-0.41	0.36	-0.09	0.85	-0.50	0.25	-0.16	0.73	-0.14	0.76	-0.52	0.23
Lower % sand	0.32	0.48	-0.07	0.88	0.43	0.34	-0.18	0.70	0.18	0.70	0.54	0.22
Shrub biomass	0.57	0.18	0.29	0.53	0.54	0.22	0.29	0.53	0.18	0.70	0.68	0.09
Overstory biomass	0.11	0.82	0.29	0.53	-0.07	0.88	0.43	0.34	-0.54	0.22	-0.25	0.59
Site index (n = 6)*	0.03	0.96	0.20	0.70	0.03	0.96	0.31	0.54	-0.77	0.07	-0.43	0.40

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* Only six values used in the calculation

Table 2.8. Spearman's correlation coefficient (ρ) between forest floor total nutrient stocks and environmental parameters. Correlations with a p value of ≤ 0.1 are highlighted in light grey.

Environmental parameter	**Forest floor total nutrient stock**									
	Ca		**Mg**		**K**		**Na**		**Mn**	
	ρ	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**
Jack pine (n = 9)										
EC	0.48	0.19	0.73	0.02	0.67	0.05	0.67	0.05	0.28	0.46
pH$_{CaCl2}$	0.25	0.52	0.05	0.90	0.02	0.97	0.05	0.90	0.13	0.73
B % clay	0.55	0.12	0.29	0.45	0.25	0.51	0.19	0.62	0.48	0.19
B % sand	-0.23	0.54	-0.24	0.53	-0.17	0.67	-0.22	0.57	-0.49	0.19
Upper % clay	0.21	0.59	0.05	0.89	0.00	1.00	-0.05	0.89	0.26	0.49
Upper % sand	-0.84	0.004	-0.86	0.003	-0.80	0.01	-0.73	0.03	-0.72	0.03
Lower % clay	-0.16	0.67	-0.29	0.46	-0.33	0.39	-0.40	0.29	-0.01	0.98
Lower % sand	-0.57	0.11	-0.39	0.30	-0.35	0.35	-0.37	0.33	-0.71	0.03
Shrub biomass	0.30	0.43	0.43	0.24	0.42	0.26	0.43	0.24	0.02	0.97
Overstory biomass	0.27	0.49	0.03	0.93	0.13	0.73	0.22	0.58	0.48	0.19
Site index	0.68	0.04	0.70	0.04	0.62	0.08	0.60	0.09	0.68	0.04
Aspen (n = 7)										
EC	0.25	0.59	0.39	0.38	0.14	0.76	-0.36	0.43	-0.57	0.18
pH$_{CaCl2}$	-0.61	0.15	-0.29	0.53	-0.14	0.76	-0.07	0.88	-0.61	0.15
B % clay	-0.28	0.54	-0.28	0.54	0.19	0.68	0.38	0.40	-0.19	0.68
B % sand	-0.93	0.003	-0.68	0.09	-0.54	0.22	-0.32	0.48	-0.54	0.22
Upper % clay	0.36	0.43	0.14	0.77	0.28	0.54	-0.06	0.90	-0.42	0.35
Upper % sand	-0.70	0.08	-0.54	0.21	-0.13	0.79	0.34	0.45	0.02	0.97
Lower % clay	-0.02	0.97	-0.34	0.45	-0.59	0.16	-0.38	0.40	0.11	0.82
Lower % sand	-0.21	0.64	0.00	1.00	0.46	0.29	0.54	0.22	0.00	1.00
Shrub biomass	0.21	0.64	0.29	0.53	0.64	0.12	0.39	0.38	-0.14	0.76
Overstory biomass	0.25	0.59	0.11	0.82	-0.18	0.70	-0.64	0.12	-0.43	0.34
Site index (n = 6)*	0.14	0.79	0.09	0.87	-0.20	0.70	-0.60	0.21	-0.09	0.87

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* Only six values used in the calculation

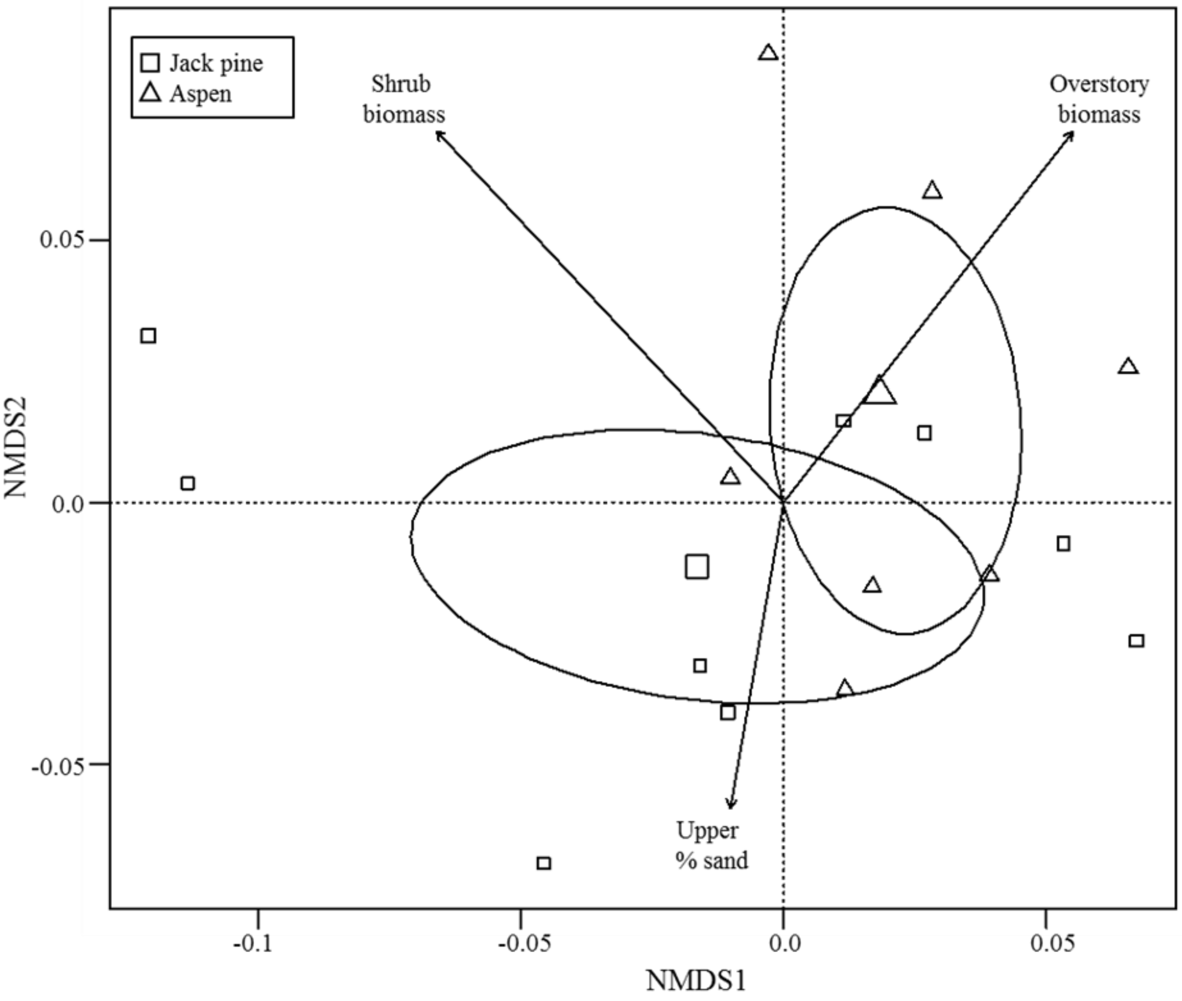

Figure 2.4. NMDS ordination (stress = 9.5 %) of forest floor nutrient ratios (C:N, C:P, C:S, C:Ca, C:Mg, C:K). Vectors represent the direction of greatest positive change of the most strongly correlated continuous environmental variables. Ellipses show the 95% confidence interval for the canopy groups and large symbols show the group centroid location.

Table 2.9. Average nutrient ratios (g carbon / g nutrient) in the forest floors at all study sites grouped by dominant canopy.

Site	Forest floor carbon to nutrient ratios					
	C:N	**C:P**	**C:S**	**C:Ca**	**C:Mg**	**C:K**
Jack pine*						
M57-1	26.9	706.2	169.8	52.2	292.2	212.0
M57-2	25.0	559.3	182.9	50.7	237.6	207.8
M118-1	26.7	611.7	525.3	61.1	374.6	273.1
M118-2	28.1	520.4	498.3	41.5	238.3	243.2
M152-1	23.6	636.3	465.2	39.0	379.6	353.6
M152-2	23.2	531.7	468.1	45.2	293.1	265.9
M178	26.3	699.7	559.9	54.5	472.4	478.5
M180	27.3	680.9	505.8	81.3	570.0	426.5
M181	25.6	623.8	679.9	74.6	619.7	482.4
$\bar{X}$	25.8	618.9	450.6	55.6	386.4	327.0
s_e	0.6	23.3	56.1	4.8	46.8	37.0
Aspen*						
M172	18.4	618.9	264.2	47.2	373.0	369.7
M175	20.7	607.5	383.4	46.7	306.9	286.8
M176	20.6	460.0	400.4	41.8	347.2	221.9
M177	19.8	574.1	432.1	45.4	424.8	250.5
M179	23.1	656.8	486.2	51.1	569.9	480.4
M182	21.5	516.8	480.5	56.0	424.0	353.1
M183	17.4	566.2	306.6	29.9	248.0	378.7
$\bar{X}$	20.2	571.5	393.3	45.5	384.8	334.4
s_e	0.7	25.0	31.6	3.1	39.0	33.4
p	<0.001	0.21	0.17	0.30	0.92	0.76

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* Site dominant canopy
$\bar{X}$ = mean of the sample, s_e = standard error of the sample group
p = p value from Wilcoxon test comparing soil property values of that column between the two canopy types

Table 2.10. Spearman's correlation coefficient (ρ) between forest floor carbon to nutrient ratios and environmental parameters. Correlations with a p value of ≤ 0.1 are highlighted in light grey.

Environmental parameter	Forest floor Carbon to nutrient ratio											
	C:N		C:P		C:S		C:Ca		C:Mg		C:K	
	ρ	p-value	ρ	p-value	ρ	p-value	ρ	p-value	ρ	p-value	ρ	p-value
Jack pine (n = 9)												
EC	-0.48	0.19	-0.35	0.36	-0.82	0.01	-0.72	0.03	-0.83	0.01	-0.83	0.01
pH_{CaCl2}	-0.35	0.36	-0.17	0.67	-0.05	0.90	-0.42	0.26	0.22	0.58	0.22	0.58
B % clay	-0.34	0.37	0.11	0.78	0.25	0.52	-0.35	0.36	0.36	0.35	0.48	0.19
B % sand	0.15	0.70	0.33	0.39	-0.53	0.14	0.18	0.65	-0.08	0.83	-0.29	0.44
Upper % clay	-0.05	0.89	-0.26	0.49	0.37	0.33	-0.26	0.49	0.21	0.59	0.37	0.33
Upper % sand	0.58	0.10	0.07	0.86	0.26	0.50	0.62	0.08	0.32	0.40	0.19	0.63
Lower % clay	0.29	0.46	-0.12	0.76	0.85	0.004	0.33	0.39	0.44	0.23	0.61	0.08
Lower % sand	0.52	0.15	0.15	0.70	-0.54	0.13	0.18	0.65	-0.41	0.27	-0.58	0.10
Shrub biomass	-0.43	0.24	0.00	1.00	-0.78	0.01	-0.42	0.26	-0.50	0.17	-0.62	0.08
Overstory biomass	-0.28	0.46	0.47	0.21	0.37	0.33	0.23	0.55	0.67	0.05	0.67	0.05
Site index	-0.47	0.21	-0.23	0.55	-0.08	0.83	-0.67	0.05	-0.27	0.49	-0.08	0.83
Aspen (n = 7)												
EC	-0.29	0.53	0.54	0.22	-0.68	0.09	-0.21	0.64	-0.54	0.22	0.29	0.53
pH_{CaCl2}	-0.14	0.76	-0.21	0.64	-0.46	0.29	-0.21	0.64	-0.43	0.34	-0.75	0.05
B % clay	0.57	0.18	-0.28	0.54	0.38	0.40	0.00	1.00	0.00	1.00	-0.66	0.11
B % sand	-0.07	0.88	-0.21	0.64	-0.21	0.64	0.25	0.59	0.14	0.76	-0.50	0.25
Upper % clay	0.28	0.54	0.68	0.09	0.04	0.93	-0.06	0.90	0.02	0.97	0.24	0.61
Upper % sand	0.32	0.48	-0.63	0.13	0.32	0.48	0.20	0.67	0.18	0.70	-0.81	0.03
Lower % clay	-0.52	0.23	-0.16	0.73	-0.02	0.97	-0.70	0.08	0.05	0.91	-0.13	0.79
Lower % sand	0.75	0.05	-0.21	0.64	0.39	0.38	0.61	0.15	0.11	0.82	-0.29	0.53
Shrub biomass	0.79	0.04	0.25	0.59	0.32	0.48	0.54	0.22	0.04	0.94	0.14	0.76
Overstory biomass	0.00	1.00	0.54	0.22	-0.18	0.70	0.07	0.88	0.00	1.00	0.71	0.07
Site index (n = 6)*	-0.31	0.54	0.54	0.27	-0.20	0.70	0.43	0.40	0.43	0.40	0.66	0.16

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* Only six values used in the calculation

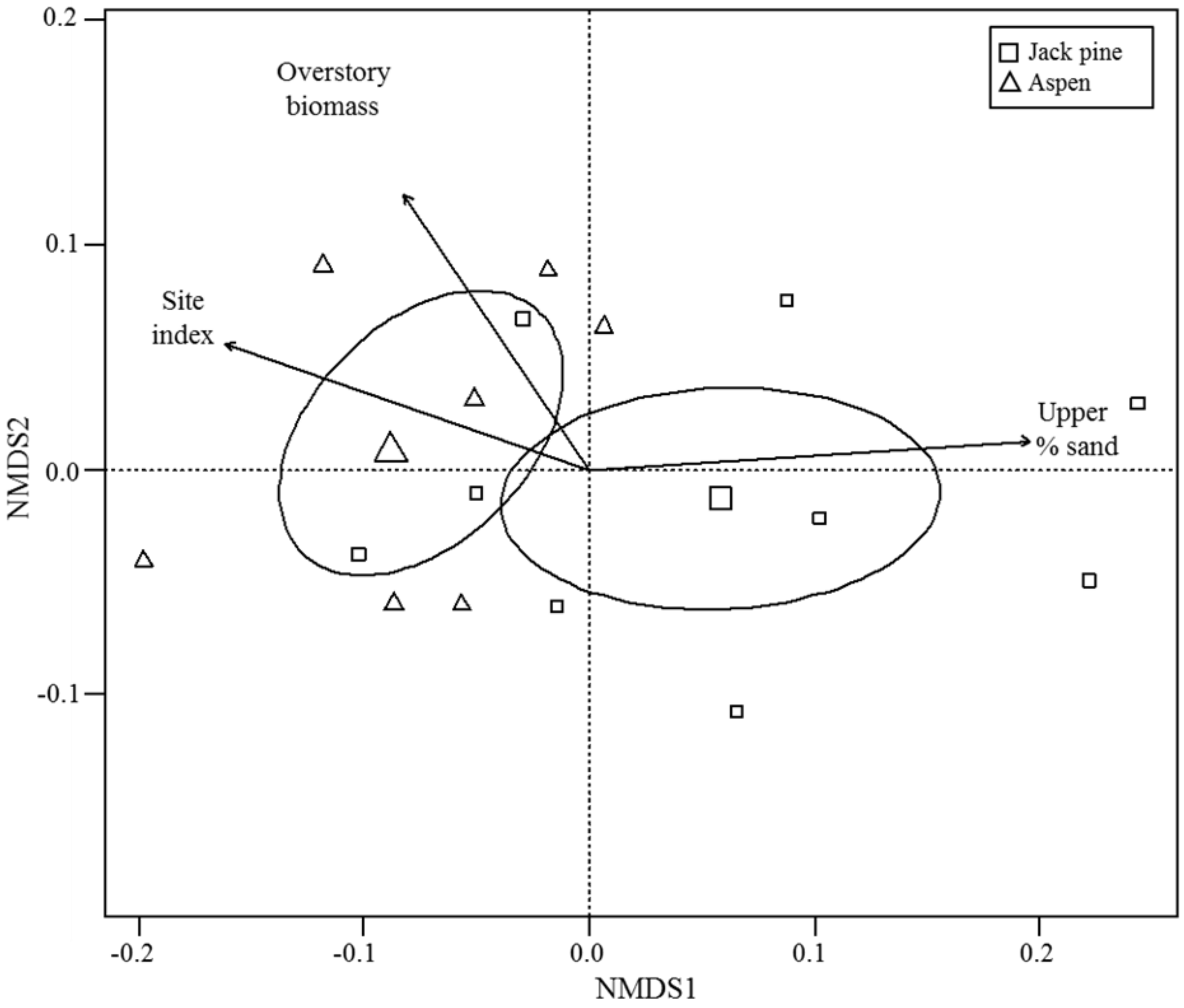

Figure 2.5. NMDS ordination (stress = 10 %) of PRS probe available nutrients (N_{total}, NO_3, NH_4, P, S, Ca, Mg, K, Mn, Fe, Al). Vectors show the direction of greatest positive change of the most strongly correlated continuous environmental variables. Ellipses show the 95% confidence interval for the canopy groups and large symbols show the group centroid location.

Table 2.11. Average PRS probe nutrients (µg 10cm^{-2} burial length^{-1}) for each site grouped by dominant canopy species.

Site	**PRS probe available nutrients**										
	N_{total} †	**NO_3**	**NH_4**	**P**	**S**	**Ca**	**Mg**	**K**	**Mn**	**Fe**	**Al**
Jack pine*											
M57-1	4.0	1.6	2.4	1.8	39.0	612.4	138.5	121.2	10.8	4.0	6.0
M57-2	7.0	5.3	1.7	1.8	57.2	401.6	100.9	117.6	6.8	4.8	4.3
M118-1	3.5	1.6	1.9	0.5	22.7	238.9	36.3	92.7	4.0	4.0	4.0
M118-2	3.7	1.6	2.1	1.0	19.0	190.5	27.4	59.0	3.5	6.3	12.5
M152-1	4.7	1.5	3.2	5.0	31.3	847.5	133.2	193.6	14.3	4.3	4.8
M152-2	4.4	1.9	2.4	3.8	33.8	904.8	182.7	303.7	10.0	2.3	5.0
M178	4.0	1.8	2.3	7.0	31.4	219.5	47.6	166.4	13.3	2.8	3.3
M180	6.7	1.8	4.9	1.0	24.8	112.9	19.6	73.7	6.0	5.5	8.8
M181	9.3	7.1	2.2	6.0	34.7	363.2	57.7	154.5	17.0	5.3	7.3
$\bar{X}$	5.2	2.7	2.6	3.1	32.7	432.4	82.7	142.5	9.5	4.3	6.2
s_e	0.7	0.7	0.3	0.8	3.7	97.0	19.4	24.9	1.6	0.4	1.0
Aspen*											
M172	4.3	1.8	2.6	2.0	37.9	461.2	120.5	171.4	5.3	2.0	3.5
M175	5.1	1.3	3.8	2.0	26.0	776.4	148.5	199.6	9.8	2.3	2.5
M176	4.6	2.3	2.3	7.3	26.3	489.7	84.0	315.5	6.5	3.3	4.8
M177	4.6	1.4	3.3	4.8	25.1	250.6	47.6	251.1	18.5	3.0	4.0
M179	11.9	4.0	7.9	8.0	21.5	726.8	145.2	255.8	14.3	2.0	3.8
M182	6.5	2.0	4.5	6.5	25.3	382.6	79.5	171.6	19.0	3.3	6.5
M183	4.6	2.2	2.4	8.8	41.9	873.2	178.1	222.6	2.0	1.3	3.0
$\bar{X}$	6.0	2.1	3.8	5.6	29.1	565.8	114.8	226.8	10.8	2.4	4.0
s_e	1.0	0.3	0.7	1.0	2.9	86.5	17.5	19.6	2.5	0.3	0.5
p	0.41	1.00	0.03	0.04	0.76	0.25	0.25	0.01	0.79	0.01	0.06

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* Dominant canopy species, p = p value from Wilcoxon test comparing soil property values of that column between the two canopy types
$\bar{X}$ = Mean of the sample, s_e = standard error of the mean of the sample
† Sum of NO_3-N and NH_4-N

Table 2.12. Spearman’s correlation coefficient (ρ) between PRS probe available nutrients and environmental parameters. Correlations with a p value of ≤ 0.1 are highlighted in light grey.

Environmental parameter	**PRS probe available nutrient**									
	N_{total}		NO_3		NH_4		P		S	
	ρ	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**
Jack pine (n = 9)										
EC	-0.05	0.90	0.18	0.64	-0.43	0.24	-0.28	0.47	0.17	0.67
pH_{CaCl2}	0.47	0.21	0.28	0.46	0.33	0.38	0.18	0.65	0.68	0.04
B % clay	-0.03	0.93	0.02	0.97	-0.01	0.98	-0.31	0.42	0.16	0.68
B % sand	0.47	0.20	0.18	0.64	-0.08	0.85	0.14	0.71	0.28	0.47
Upper % clay	-0.16	0.68	-0.32	0.41	0.42	0.26	-0.43	0.25	-0.11	0.79
Upper % sand	0.41	0.27	0.06	0.88	0.51	0.16	0.61	0.08	0.09	0.81
Lower % clay	-0.40	0.29	-0.32	0.40	0.42	0.27	-0.35	0.36	-0.36	0.35
Lower % sand	0.40	0.29	0.14	0.73	-0.07	0.86	0.15	0.69	0.02	0.97
Shrub biomass	0.32	0.41	0.53	0.14	-0.47	0.21	0.12	0.76	0.50	0.17
Overstory biomass	-0.08	0.83	-0.07	0.86	-0.18	0.64	0.39	0.30	-0.15	0.70
Site index	-0.35	0.36	-0.07	0.86	-0.28	0.46	-0.47	0.20	-0.13	0.73
Aspen (n = 7)										
EC	0.07	0.88	-0.61	0.15	0.14	0.76	-0.27	0.56	0.18	0.70
pH_{CaCl2}	0.07	0.88	-0.14	0.76	0.21	0.64	-0.45	0.31	0.14	0.76
B % clay	0.00	1.00	0.09	0.84	0.19	0.68	-0.29	0.53	-0.19	0.68
B % sand	0.14	0.76	-0.25	0.59	0.29	0.53	-0.63	0.13	-0.11	0.82
Upper % clay	-0.06	0.90	-0.54	0.21	-0.06	0.90	-0.32	0.48	-0.06	0.90
Upper % sand	0.14	0.76	0.40	0.38	0.25	0.59	-0.17	0.71	-0.23	0.61
Lower % clay	-0.85	0.02	0.09	0.85	-0.99	<0.0001	0.15	0.76	0.76	0.05
Lower % sand	0.61	0.15	0.14	0.76	0.82	0.02	-0.18	0.70	-0.71	0.07
Shrub biomass	0.54	0.22	-0.21	0.64	0.75	0.05	-0.23	0.61	-0.68	0.09
Overstory biomass	-0.18	0.70	-0.82	0.02	0.04	0.94	-0.43	0.33	0.04	0.94
Site index (n = 6)*	0.09	0.87	-0.54	0.27	-0.03	0.96	-0.20	0.70	-0.14	0.79

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* Only six values used in the calculation

Table 2.13. Spearman's correlation coefficient (ρ) between PRS probe available nutrients and environmental parameters. Correlations with a p value of ≤ 0.1 are highlighted in light grey.

Environmental parameter	**PRS probe available nutrient**											
	Ca		**Mg**		**K**		**Mn**		**Fe**		**Al**	
	ρ	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**	**ρ**	**p-value**
Jack pine (n = 9)												
EC	-0.40	0.29	-0.27	0.49	-0.65	0.06	-0.32	0.41	0.56	0.12	0.52	0.15
pH$_{CaCl2}$	0.48	0.19	0.55	0.13	0.32	0.41	0.45	0.22	-0.15	0.70	0.27	0.49
B % clay	0.21	0.58	0.15	0.70	-0.02	0.97	0.06	0.88	-0.17	0.65	0.03	0.95
B % sand	0.40	0.28	0.34	0.37	0.13	0.75	0.08	0.85	0.35	0.36	0.25	0.51
Upper % clay	0.05	0.89	0.00	1.00	-0.11	0.79	-0.05	0.89	-0.11	0.79	0.16	0.68
Upper % sand	0.30	0.43	0.30	0.44	0.63	0.07	0.41	0.27	-0.24	0.54	-0.23	0.56
Lower % clay	0.03	0.93	-0.03	0.93	0.11	0.77	-0.24	0.53	-0.51	0.16	-0.29	0.46
Lower % sand	-0.12	0.76	-0.14	0.73	-0.11	0.78	-0.06	0.88	0.47	0.21	0.08	0.83
Shrub biomass	0.03	0.93	0.15	0.70	-0.18	0.64	-0.03	0.93	0.36	0.34	0.37	0.33
Overstory biomass	0.22	0.58	0.12	0.77	0.42	0.26	0.47	0.21	-0.26	0.50	-0.32	0.41
Site index	-0.43	0.24	-0.40	0.29	-0.55	0.13	-0.25	0.52	0.16	0.68	0.17	0.67
Aspen (n = 7)												
EC	-0.04	0.94	0.00	1.00	-0.61	0.15	0.25	0.59	0.20	0.67	-0.07	0.88
pH$_{CaCl2}$	-0.14	0.76	-0.07	0.88	-0.64	0.12	0.14	0.76	0.33	0.47	0.18	0.70
B % clay	-0.76	0.05	-0.66	0.11	-0.38	0.40	0.38	0.40	0.38	0.39	0.66	0.11
B % sand	0.14	0.76	0.21	0.64	-0.25	0.59	-0.04	0.94	0.00	1.00	-0.36	0.43
Upper % clay	-0.70	0.08	-0.70	0.08	-0.32	0.49	0.50	0.26	0.58	0.17	0.48	0.28
Upper % sand	-0.18	0.70	-0.13	0.79	-0.02	0.97	0.05	0.91	0.07	0.88	0.23	0.61
Lower % clay	0.20	0.67	0.13	0.79	0.25	0.59	-0.76	0.05	-0.09	0.84	-0.13	0.79
Lower % sand	-0.46	0.29	-0.36	0.43	-0.21	0.64	0.64	0.12	0.11	0.82	0.36	0.43
Shrub biomass	-0.68	0.09	-0.57	0.18	-0.36	0.43	0.82	0.02	0.24	0.61	0.43	0.34
Overstory biomass	-0.07	0.88	0.04	0.94	-0.36	0.43	0.04	0.94	-0.25	0.58	-0.50	0.25
Site index (n = 6)*	0.31	0.54	0.26	0.62	0.43	0.40	-0.09	0.87	-0.32	0.54	-0.71	0.11

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* Only six values used in the calculation

Table 2.14. Average concentrations (mg kg^{-1}) of different forms of C, N and P in the B horizon for each site grouped by dominant canopy.

Site	B horizon nutrients				
	C_{total}	N_{total}	PO_4-$P_{extractable}$	NH_4-$N_{extractable}$	NO_3-$N_{extractable}$
Jack pine*					
M57-1	690.0	30.0	29.1	3.6	0.0
M57-2	920.0	50.0	30.9	2.2	0.0
M118-1	4135.0	130.0	99.5	2.5	0.0
M118-2	640.0	50.0	129.8	2.5	0.0
M152-1	1880.0	30.0	5.7	1.5	0.0
M152-2	9940.0	180.0	2.7	1.6	0.0
M178	2850.0	190.0	176.0	2.1	0.0
M180	775.0	95.0	109.6	1.8	0.0
M181	2380.0	150.0	214.2	0.8	0.5
$\bar{X}$	2690.0	100.6	88.6	2.1	0.1
s_e	989.0	21.3	25.5	0.3	0.1
Aspen*					
M172	1320.0	130.0	3.5	1.5	0.0
M175	2245.0	160.0	2.0	1.6	0.0
M176	1760.0	160.0	146.6	2.2	0.3
M177	1420.0	140.0	63.9	1.8	0.0
M179	2655.0	190.0	8.0	2.2	1.0
M182	2400.0	150.0	63.9	0.4	0.0
M183	1850.0	170.0	3.5	0.7	23.5
$\bar{X}$	1950.0	157.1	41.6	1.5	3.5
s_e	189.6	7.5	20.5	0.3	3.3
p	0.92	0.10	0.20	0.18	-

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* Dominant canopy species
$\bar{X}$ = Mean of the sample, s_e = standard error of the mean of the sample
p = p value from Wilcoxon test comparing soil property values of that column between the two canopy types

Table 2.15. Spearman's correlation coefficient (ρ) between B horizon nutrients and environmental parameters. Correlations with a p value of ≤ 0.1 are highlighted in light grey.

Environmental parameter	B horizon nutrient							
	C_{total}		N_{total}		PO_4-$P_{extractable}$		NH_4-$N_{extractable}$	
	ρ	p-value	ρ	p-value	ρ	p-value	ρ	p-value
Jack pine (n = 9)								
EC	-0.77	0.02	-0.31	0.42	0.42	0.26	0.55	0.12
pH_{CaCl2}	0.02	0.97	-0.11	0.78	-0.28	0.46	-0.22	0.57
B % clay	0.28	0.47	0.01	0.98	-0.14	0.73	0.05	0.90
B % sand	-0.31	0.42	-0.46	0.21	-0.34	0.37	-0.28	0.47
Upper % clay	0.05	0.89	-0.19	0.63	-0.26	0.49	0.11	0.79
Upper % sand	0.25	0.51	0.14	0.71	-0.30	0.44	-0.62	0.07
Lower % clay	0.50	0.17	0.25	0.51	-0.39	0.30	0.07	0.86
Lower % sand	-0.41	0.27	-0.30	0.44	0.03	0.95	-0.18	0.64
Shrub biomass	-0.45	0.22	-0.13	0.75	0.20	0.61	0.14	0.72
Overstory biomass	0.60	0.09	0.35	0.35	0.23	0.55	-0.40	0.28
Site index	-0.15	0.70	0.03	0.95	0.43	0.24	0.49	0.19
Aspen (n = 7)								
EC	0.14	0.76	-0.25	0.59	-0.27	0.55	-0.81	0.03
pH_{CaCl2}	0.14	0.76	-0.34	0.45	-0.11	0.82	-0.45	0.31
B % clay	-0.19	0.68	-0.62	0.14	0.43	0.33	-0.19	0.68
B % sand	0.07	0.88	-0.09	0.85	-0.44	0.33	0.27	0.56
Upper % clay	-0.30	0.52	-0.66	0.10	0.37	0.42	-0.49	0.26
Upper % sand	0.07	0.88	-0.07	0.88	0.14	0.77	0.37	0.41
Lower % clay	-0.70	0.08	-0.11	0.82	0.14	0.77	0.14	0.77
Lower % sand	0.39	0.38	-0.13	0.79	0.11	0.82	0.05	0.91
Shrub biomass	0.25	0.59	-0.36	0.43	0.16	0.73	-0.29	0.53
Overstory biomass	-0.32	0.48	-0.34	0.45	-0.49	0.26	-0.31	0.50
Site index (n = 6)*	-0.03	0.96	0.35	0.50	-0.44	0.38	0.49	0.33

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* Only six values used in the calculation

Table 2.16. Spearman's correlation coefficient (**ρ**) between B horizon extractable P and select PRS probe available nutrients.

PRS probe nutrient	**B horizon-P$_{extractable}$**			
	Jack pine (n = 9)		**Aspen (n = 7)**	
	ρ	**p-value**	**ρ**	**p-value**
Ca	-0.77	0.02	-0.60	0.15
Mg	-0.70	0.04	-0.76	0.05
Fe	0.47	0.20	0.72	0.07
Al	0.17	0.67	0.93	0.003

Chapter 2 plates

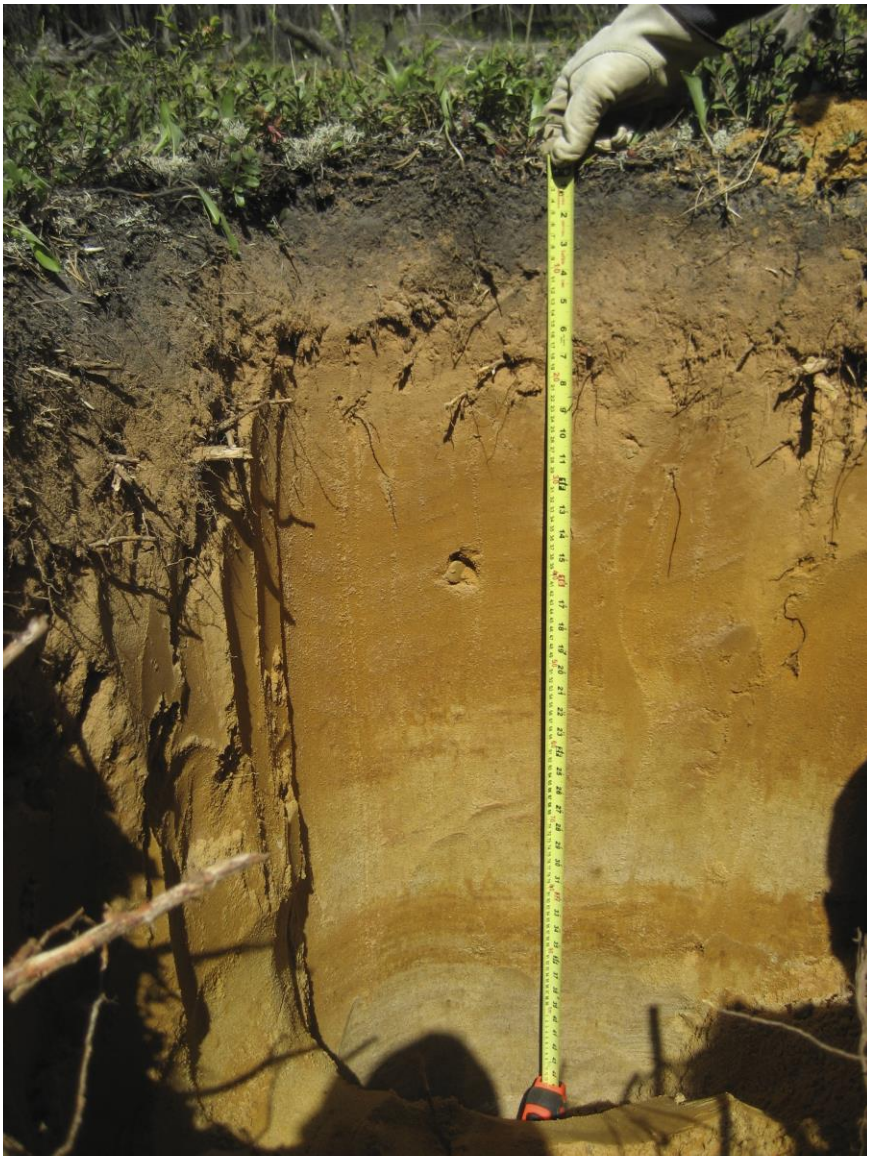

Plate 2.1. Site M57-1 soil profile – Eluviated Dystric Brunisol derived from glaciofluvial outwash sands under a jack pine dominated canopy.

Plate 2.2. Site M57-2 soil profile – Eluviated Dystric Brunisol derived from glaciofluvial outwash sands under a jack pine dominated canopy.

Plate 2.3. Site M118-1 soil profile – Eluviated Dystric Brunisol derived from eolian sands under a jack pine dominated canopy.

Plate 2.4. Site M118-2 soil profile – Eluviated Dystric Brunisol derived from eolian sands under a jack pine dominated canopy.

Plate 2.5. Site M152-1 soil profile – Eluviated Dystric Brunisol derived from glaciofluvial ice contact deposits under a jack pine dominated canopy. Black colored lenses are naturally occurring oil sand deposits.

Plate 2.6. Site M152-2 soil profile – Eluviated Dystric Brunisol derived from glaciofluvial ice contact deposits under a jack pine dominated canopy. Black colored lenses are naturally occurring oil sand deposits.

Plate 2.7. Site M177 soil profile – Eluviated Dystric Brunisol derived from glaciofluvial outwash sands overlying glaciolacustrine deposits under an aspen dominated canopy.

Plate 2.8. Eluviated Dystric Brunisol derived from eolian sands under a jack pine dominated canopy. Note that the location of this profile is in close proximity to sites M180 and M181, although it is not the actual profile used in the characterization of those sites.

Chapter 3. Synthesis

3.1. Summary

The goals of this study were to determine (i) how the physical properties of these sandy soils influence the accumulation of different forms of nutrients in the soil profile, (ii) the processes at work that govern the amounts and availability of soil nutrients, (iii) how nutrient cycling processes differ between aspen and jack pine dominated stands, and (iv) how differences in their associated productivity levels relate to soil physical properties and nutrient levels. When all sites were considered together, differences in forest floor nutrient amounts, quality, and availability were found to largely be influenced by average upper soil profile texture (% silt + clay), most likely through its influence on canopy type and vegetation productivity levels and therefore the quantity and quality of litter nutrient inputs to the forest floor.

Upper profile soil texture is proposed to be the primary factor influencing forest floor nutrient stocks and forest floor quality in jack pine sites of the AOSR, despite differences in texture being only slight ($\leq 8\%$ silt + clay). Greater silt and clay content of the upper soil profile was found to be associated with increased forest floor nutrient stocks for all nutrients measured, as well as higher forest floor quality (lower C:N and C:Ca ratio), greater field moisture content in the forest floor, and greater extractable ammonium concentrations in the B horizon, possibly resulting from greater litter nutrient inputs associated with higher tree productivity while the understory likely contributes less to forest floor nutrients under jack pine due to the very low understory biomass levels associated with the jack pine sites of this study. Therefore increased moisture and potentially nutrient availability associated with finer textured jack pine sites may also lead to improved forest floor quality and moisture conditions, which may further increase site productivity. However, many PRS probe available nutrient concentrations showed little relationship with soil texture and some (NH_4, S, K), interestingly, decreased with greater silt and clay content, possibly resulting from higher nutrient uptake from more productive trees leading to lower available nutrients on finer textured soils, or due to the thin forest floors associated with coarser textured sites which may be leached of nutrients more rapidly.

In aspen sites, correlations were generally weaker than in pine sites, likely due to complex interactions between soil texture, tree and understory productivity litter inputs. Soil textures in aspen sites were highly variable compared to pine, which likely relates to the high variation in tree and understory productivity levels of these aspen stands. Forest floor nutrient stocks (C, N, P, S, Ca, Mg, K) under aspen related most strongly to B horizon texture (silt + clay), with finer B horizon textures having greater nutrient stocks. However, availability of Ca and Mg was lower in sites with finer B horizons (clay; silt + clay), possibly due to higher shrub biomass and therefore higher plant uptake of nutrients with finer B horizon textures. Only soils with fine lower soil profile textures (clay; silt + clay) were associated with higher forest floor quality (lower C:N and C:Ca ratios), potentially due to low shrub biomass levels associated with fine lower soil profile textures. Therefore, while B horizon texture may influence nutrient quantity and availability, lower soil texture may more strongly influence the quality of litter nutrient inputs to the forest floor under aspen, potentially due interactions between B horizon and lower soil profile texture on shrub biomass levels. Therefore sites with fine B horizons but coarse lower soil profile textures may provide more optimal conditions for understory productivity due to decreased tree productivity, resulting in greater forest floor nutrient stocks but lower forest floor quality and nutrient availability, whereas sites with fine lower soil profiles and coarse B horizons may provide more optimal conditions for improved tree productivity due to greater forest floor quality and nutrient availability, although total amounts of nutrients may be lower.

3.2. Study limitations

3.2.1. Quantifying the effect of textural layering on nutrient dynamics

The specific contribution of textural layering to site nutrient dynamics is difficult to quantify with the data available. There is little doubt that textural layering does influence site productivity and vegetation species composition in the AOSR (Zettl et al., 2011) and other areas (Host & Pregitzer, 1992; McFadden et al., 1994), which are factors that play an important role in nutrient cycling processes in sandy soils of the AOSR, as discussed in Chapter 2. However, the high variability in textural properties associated with layered soil profiles in this region in combination with the difficulty in finding replicate profiles of similar textural characteristics make clear statistical relationships difficult to obtain.

The often co-varying nature of these texture layers with other soil textural properties also make quantification of their effects on nutrient cycles difficult. For example, the presence of fine texture layers within the soil profile in all cases will, to some extent, alter the average texture of the soil profile, although the degree to which soil profile texture is affected will depend on the cumulative thickness and specific textures of these layers, as well as the precision with which samples from the soil profile are measured. McFadden et al. (1994) found that average silt + clay in sandy soils derived from glacial sediments related strongly to a qualitative "banding code", which was based on the intensity of fine texture banding observed in the field. The effect of the banding and the effect of the average soil texture are, therefore, difficult to separate.

In my study sites, textural factors co-varied with textural layering types in indirect ways as well. For example, when considered in their broad groupings, fine bands were associated with coarser upper profile textures on average (94 % sand) whereas parent material changes were associated with finer upper soil profile textures on average (87 % sand), even when these fine layers were not included in the average texture calculation. However, these textural differences could likely be minimized with careful site selection. For example, in this study we did have aspen sites (M176 and M177) with a fine texture layer at depth that had very similar upper soil profile textures to many jack pine sites with no fine texture layers (Table 2.3). Zettl et al. (2011) also found that textural heterogeneity in sandy soils of the AOSR can vary between sites despite average soil profile textures being equal, although replication was low in their study. It may be possible, therefore, to select sites with similar average textures but different morphology of physical layers, although in reality this may be difficult to accomplish.

One likely role that fine texture layers play in site nutrient dynamics in the AOSR is by influencing dominant canopy type which, as discussed in Chapter 1, can influence site nutrient dynamics in a variety of ways. For example, sites with a fine textured parent material change at depth always had an aspen canopy whereas soils with consistent sandy textures or fine banding were always associated with jack pine canopies. Sites with oil sand deposits, which supported both jack pine and aspen stands, may occupy a transition zone between jack pine and aspen dominated sites (Appendix 1), likely through the respective influence on water movement of each of these physical layering types. Therefore, sites with finer textured lower soil profiles likely, by acting as a barrier to water movement, allow for an aspen canopy to outcompete jack pine, even in very sandy soils in some cases (M176 and M177; Table 2.3), despite aspen development being highly sensitive to site moisture conditions (Fralish, 1972). This prevalence of aspen over jack pine potentially leads to litter profiles that are associated with greater forest floor quality and nutrient availability (Section 2.3.3 and 2.3.4), compared to similarly textured jack pine sites, further contributing to a positive feedback leading to higher site productivity. Sandy soils underlain by finer textured materials have been shown to increase site index of quaking aspen (*Populus tremuloides Michx.*) in other studies (Stoeckeler, 1960). The relationship between lower soil profile texture and site index in aspen sites of my study was weak (Table 2.5), likely resulting from the very heterogeneous nature of these fine texture layers, which varied from 42 to 82 % sand content (Appendix 3), and the variation in depth of sandy materials which overly these deposits (20 to 132 cm; Appendix 3), which no doubt has an influence on the magnitude of the effect these layers have on productivity and nutrient cycling. Additionally, with lateral water flow likely occurring in sites with subsurface fine textured layers, complex site hydrologic factors may also add a source of error in quantifying the effects of these layers in site nutrient cycling. Therefore, to determine the effects of textural layering on nutrient pools in this region, sites that controlled differences in the specific textures and depths of soil layers and hydrologic environment would need to be selected to minimize the number of confounding factors being interpreted.

3.3. Future research

3.3.1. Textural layering and nutrient cycling

An improved system to quantify textural layering features in sandy soils of the AOSR is necessary if their effect on forest nutrient and productivity dynamics is to be truly quantified. Although textural heterogeneity was shown to be a good predictor of vegetation productivity on sandy soils of the AOSR (Zettl et al., 2011), the sampling required for this measurement is very time consuming and inconvenient. Perhaps a less time consuming scheme, such as that of Host and Pregitzer (1992), who created a soil moisture index based on the presence or absence of fine texture layers within a certain depth of soil combined with the mean weighted particle diameter, would be more effective. Host and Pregitzer found this moisture index to correlate well with species distributions in NW Michigan, although an index would need to be developed specifically for the AOSR study area. The unclear but no doubt important role that these depositional features play in the mosaic of ecosystems found on sandy soils throughout the AOSR, through their effect on moisture and nutrient dynamics, requires further investigation. Particularly the effect of these layers on mineral soil nutrient availability and potentially soil chemical weathering rates, would be interesting, and to the best of my knowledge the latter has not been previously studied even in other study areas.

3.3.2. Extractable soil P

The relatively high levels of extractable P in some sandy soils of the AOSR is an interesting feature that has not been focused on to a great extent beyond the current study. Lanoue (2003) hypothesized that extractable P in sandy soils of the AOSR likely relates the accumulation of secondary Fe and Al minerals, which she based on the morphology of these soils, in particular the redder hues associated with the B horizons compared to adjacent horizons. At least one study has shown enrichment of Fe and Al in B horizons of sandy soils in the AOSR (Pawluk, 1960), although whether or not this enrichment is associated with the accumulation of P has not been explicitly studied. My study found relatively good relationships between PRS probe Fe, Al and Ca with extractable B horizon P levels, all of which are elements that are known to affect P solubility in soils and may relate to the degree of podzolization that has occurred. Greater podzolization in some of these sandy soils may therefore be associated with an increase in Fe and Al bound P, which has been shown to relate to greater available P levels in soils of Alberta (Alexander & Robertson, 1968). A study that characterizes the amounts of different forms of P, including Ca, Fe, Al and organically bound P in relation to plant available P is necessary to determine if high extractable P levels in sandy soils of the AOSR is in fact related to the accumulation of Fe and Al. Additionally, the relatively consistent mineralogical makeup of sandy parent materials (Spiers et al., 1989), climate and time of deposition of soil forming materials in the AOSR (Turchenek & Lindsay, 1982), provides a unique opportunity improve our understanding of the processes controlling chemical weathering and development rates of sandy soils in this region, which may subsequently relate to the accumulation and availability of P in these soils.

3.4. Recommendations for the reclamation of sandy soils in the AOSR

Upper soil profile texture (% sand) related most strongly to differences in quantities of total and available nutrients at the soil surface and quality of the forest floor, most likely through interactions between texture and vegetation productivity. Because soil texture is a relatively permanent site property and has likely changed little in these sandy soils since they were deposited, soil texture should be a primary focus in the reclamation of sandy soils in the AOSR due to its influence on forest productivity levels and nutrient accumulation and availability at the soil surface. If one textural property was to be used to determine the productive capacity of a reclaimed site, it should be upper soil profile texture.

However, if jack pine and aspen stands and their associated range in productivity levels are to be restored, then specific textural characteristics should be considered to ensure the greatest probability of reclamation success. The range in jack pine productivity levels, and therefore forest floor nutrient quantities and quality, should be targeted with soils that vary little in their textures down to a depth of at least 2m, as was the case for all but one jack pine site in this study, which were typically associated with textures that ranged from 94 to 99 % sand in the upper and lower soil profile, but may range down to 88 and 89 % sand in the upper and lower soil profile respectively, which was the case for one site (M178).

The range in aspen productivity and its associated understory may be best targeted with generally finer textured soil materials and a range of upper and lower soil profile textures. Aspen sites associated with high understory biomass and low tree productivity, and therefore high forest floor nutrient stocks but low forest floor quality, may best be captured with relatively fine B horizon textures and coarse lower soil profile textures. Coarse upper soil profile textures and fine lower soil profile textures may best capture sites with relatively high tree productivity but low understory productivity, and therefore high forest floor quality and nutrient availability but low nutrient quantity. Finally, sites with fine upper soil profile textures and fine lower soil profile textures will likely best capture high tree and understory productivity, potentially leading to high nutrient quantity and quality in the forest floor. However, the generally poor correlations between texture parameters and nutrients in aspen sites make these relationships difficult to conclude for certain, and a separate study focused specifically on aspen stands developed on sandy soils in this region may be necessary. Additionally, the use of multiple regression to assess the effect of the interaction between B horizon texture and lower soil profile texture on soil nutrient pools under aspen may be of interest in future research, although at the time of writing I have not tested this. If the range in vegetation productivity levels of aspen and jack pine stands developed on coarse textured soils in the AOSR is to be restored, then textural characteristics that relate to the range in forest floor nutrient capital, quality and availability should be reestablished accordingly, giving reclaimed sandy soils of the AOSR a greater probability of self-sustainability and resilience to future disturbance.

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Appendix 1. Supplementary tables

Site ID	Canopy type	Textural layering type	Parent material type
M57-1	Jack pine	None	Glaciofluvial sand
M57-2	Jack pine	Fine bands	Glaciofluvial sand
M118-1	Jack pine	None	Eolian
M118-2	Jack pine	Fine bands	Eolian
M152-1	Jack pine	Oil sand deposits	Glaciofluvial ice contact
M152-2	Jack pine	Oil sand deposits	Glaciofluvial ice contact
M172	Aspen	Parent material change	Glaciofluvial sand
M175	Aspen	Oil sand deposits	Glaciofluvial ice contact
M176	Aspen	Parent material change	Glaciofluvial sand
M177	Aspen	Parent material change	Glaciofluvial sand
M178	Jack pine	Fine bands	Glaciofluvial sand
M179	Aspen	Parent material change	Glaciofluvial sand
M180	Jack pine	Fine bands	Eolian
M181	Jack pine	Fine bands	Eolian
M182	Aspen	Oil sand deposits	Glaciofluvial ice contact
M183	Aspen	Parent material change	Glaciofluvial sand

Select variable	**Forest floor depth**			
	Jack pine (n = 9)		**Aspen (n = 7)**	
	ρ	**p-value**	**ρ**	**p-value**
C	0.81	0.008	0.86	0.01
N	0.85	0.004	0.68	0.09
P	0.90	0.001	0.89	0.01
S	0.81	0.01	0.64	0.12
Ca	0.85	0.004	0.68	0.09
Mg	0.90	0.001	0.75	0.05
K	0.93	<0.001	1.00	<0.001
Na	0.98	<0.001	0.82	0.02
Mn	0.92	0.001	0.50	0.25
Fe	0.90	0.001	0.64	0.12
Al	0.93	<0.001	0.96	0.001
Site index	0.58	0.10	-0.20	0.70
Overstory biomass	0.31	0.42	-0.18	0.70
Shrub biomass	0.32	0.40	0.64	0.11

Appendix 2. Site and soil description sheets

Site description codes:

Parent geologic material (PGM)	
Glaciofluvial outwash sands	GLFL
Glaciofluvial ice contact deposits	GLFL-IC
Eolian	EOLI
Glaciolacustrine	GLLC
Morainal	TILL
Soil classification (CSSC)	
Orthic Dystric Brunisol	ODB
Eluviated Dystric Brunisol	EDB
Orthic Eutric Brunisol	OEB
Eluviated Eutric Brunisol	EEB

Soil description codes (Watson, 2014):

Moisture	
Class	Code
Dry	D
Moist	M
Wet	W
Texture	
Class	Code
Sand	S
Loamy sand	LS
Sandy loam	SL
Loam	LS
Sandy clay loam	SCL

Horizon Boundary			
Distinctness		Form	
Class	Code	Class	Code
Abrupt	A	Smooth	S
Clear	C	Wavy	W
Gradual	G	Irregular	I
Diffuse	D	Broken	B

Structure

Grade		Size		Type		Consistence	
Class	Code	Class	Code	Class	Code	Class	Code
Weak	W	Very fine	VF	Massive	MA	Loose	1
Moderate	M	Fine	F	Single grain	SGR	Very friable	2
Strong	S	Medium	M	Subangular blocky	SBK	Friable	3
		Coarse	C	Angular blocky	ABK		

Coarse fragments

Size		Shape	
Class	Code	Class	Code
Gravels	G	Rounded	R
Cobbles	C	Subrounded	SR
Stones	S	Subangular	SA
Boulders	B	Angular	A

Rooting

Abundance		Orientation	
Class	Code	Class	Code
Very few	VF	Vertical	VF
Few	F	Horizontal	H
Plentiful	P	Oblique	O
Abundant	A	Random	R

Mottles

Abundance		Size	
Class	Code	Class	Code
Few	F	Fine	F
Common	C	Medium	M
Many	M	Coarse	C

Concretions					
Kind		Abundance		Location	
Class	Code	Class	Code	Class	Code
Oxides	6	Few	F	Around root channels	1
		Common	C	Local concentrations	2
		Many	M	Throughout matrix	3

Concretions continued			
Size		Shape	
Class	Code	Class	Code
Fine	F	Spherical	S
Medium	M	Oblong	O
Coarse	C	Irregular	I
		Plate-like	P

Oil sand deposits*					
Size		Shape		Consistence	
Class	Code	Class	Code	Class	Code
Very fine	VF	Rounded	R	Loose	1
Fine	F	Subrounded	SR	Soft	2
Medium	M	Subangular	SA	Slightly hard	3
Coarse	C	Angular	A	Hard	4
Very coarse	VCO				

Effervescence	
Class	Code
Very weak	VW
Weak	W
Moderate	M
Strong	S

*Size classes are taken from structure size classes, shape classes are taken from coarse fragment classes and consistence classes are taken from dry consistence classes

Site Description				
Site	M57-1		Slope Position	Middle
Location	57.0733889	-111.5936667	Slope Percent	1
Soil Type	EDB		Slope Aspect	NW
PGM (1, 2)	GLFL		High water table	-
Landform	Level		Max Rooting Depth (cm)	46
Land Use	Undisturbed		Depth to Carbonates (cm)	-

Soil Profile Description											
Horizon			LF	Ae	AB	Bm1	Bm2	BC1	BC2	C1	C2
Depth (cm)			2-0	0-7	7-20	20-49	49-75	75-83	83-95	95-135	135-200
Dry color			-	10YR4/2	10YR5/6	10YR5/8	10YR5/8	10YR6/6	10YR5/8	10YR7/4	10YR7/4
Moist color			-	10YR2/1	10YR4/6	10YR4/6	10YR4/6	10YR5/6	10YR4/6	10YR6/6	10YR5/6
Moisture			D	M	M	M	M	M	M	M	-
Texture			-	LS	S	S	S	S	S	S	S
Horizon Boundary	Distinctness		A	C	D	C	A	A	A	-	-
	Form		W	W	-	S	S	B	B	-	-
Structure	Primary	Grade	-	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-	-
		Type	-	SGR	SGR	SGR	SGR	SGR	SGR	SGR	-
		Consistence	-	l	l	l	l	l	l	l	-
	Secondary	Grade	-	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	1	1	1	1	1	1	1	-
		Size	-	G,C	G,C	G,C	G,C	G,C	G,C	G,C	-
		Shape	-	SR,R	SR,R	SR,R	SR,R	SR,R	SR,R	SR,R	-
Rooting	Abundance / Orientation	Very fine	-	P/R	P/V-H	VF/R	-	-	-	-	-
		Fine	-	VF/R	P/V-H	VF/R	-	-	-	-	-
		Medium	-	F/R	P/H	-	-	-	-	-	-
		Coarse	-	F/H	F/H	-	-	-	-	-	-
Mottles	Abundance		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Contrast		-	-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	7.5YR6/8	-
Concretions	Kind		-	-	-	-	-	-	6	-	-
	Abundance		-	-	-	-	-	-	C	-	-
	Size		-	-	-	-	-	-	F	-	-
	Location		-	-	-	-	-	-	2	-	-
	Shape		-	-	-	-	-	-	S	-	-
	Color in field		-	-	-	-	-	-	5YR4/6	-	-
Oil Sands Deposits	Percent		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-	-
	Consistence		-	-	-	-	-	-	-	-	-
Effervescence (10%)			-	-	-	-	-	-	-	-	-

Site Description

Site	M57-2		Slope Position	Middle
Location	57.0730833	-111.5935833	Slope Percent	0
Soil Type	EDB		Slope Aspect	-
PGM (1, 2)	GLFL		High water table	-
Landform	Level		Max Rooting Depth (cm)	61
Land Use	Undisturbed		Depth to Carbonates (cm)	-

Soil Profile Description

			LFH	Ae	Bm1	BC	C1	C2	C3
Horizon			LFH	Ae	Bm1	BC	C1	C2	C3
Depth (cm)			3-0	0-10.5	10.5-49	49-75	75-95	95-114	114-200
Dry color			-	10YR4/2	10YR5/8	10YR6/6	10YR6/6	10YR6/6	10YR6/4
Moist Color			-	10YR2/1	10YR4/6	10YR5/6	10YR5/6	10YR5/4	10YR5/4
Moisture			D	D	M	M	M	M	-
Texture			-	LS	S	S	S	S	S
Horizon Boundary	Distinctness		A	C	G	D	-	-	-
	Form		W	W	W	W	-	-	-
Structure	Primary	Grade	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-
		Type	-	SGR	SGR	SGR	SGR	SGR	-
		Consistence	-	l	l	l	l	l	-
	Secondary	Grade	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	5	-	-	-	-
		Size	-	-	G,C	-	-	-	-
		Shape	-	-	R,SR	-	-	-	-
Rooting	Abundance / Orientation	Very fine	-	A/R	VF/V	-	-	-	-
		Fine	-	A/R	VF/V	VF/V	-	-	-
		Medium	-	P/H	P/H	-	-	-	-
		Coarse	-	F/H	F/H	-	-	-	-
Mottles	Abundance		-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-
	Contrast		-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	7.5YR5/8
Concretions	Kind		-	-	-	6	-	-	-
	Abundance		-	-	-	F	-	-	-
	Size		-	-	-	C	-	-	-
	Location		-	-	-	2	-	-	-
	Shape		-	-	-	P	-	-	-
	Color in field		-	-	-	5YR4/6	-	-	-
Oil Sands Deposits	Percent		-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-
	Consistence		-	-	-	-	-	-	-
Effervescence (10%)			-	-	-	-	-	-	-

Site Description

Site	M118-1	Slope Position	Middle
Location	57.5110278 -111.4299722	Slope Percent	<5
Soil Type	EDB	Slope Aspect	SW
PGM (1, 2)	EOLI	High water table	-
Landform	Level	Max Rooting Depth (cm)	25
Land Use	Undisturbed	Depth to Carbonates (cm)	-

Soil Profile Description

			LFH	Ae	Bm1	Bm2	BCfj1	BCfj2	BCfj3	BCfJ4	BCfj5
Horizon			LFH	Ae	Bm1	Bm2	BCfj1	BCfj2	BCfj3	BCfJ4	BCfj5
Depth (cm)			2-0	0-3	3-25	25-70	70-108	108-143	143-171	171-185	185-200
Dry color			-	10YR5/2	10YR6/4	10YR6/6	10YR7/3	10YR7/4	10YR6/4	10YR6/4	10YR6/4
Moist color			-	10YR3/2	10YR5/4	10YR4/6	10YR5/3	10YR5/3	10YR4/3	10YR4/3	10YR4/3
Moisture			M	M	M	M	M	M	M	MW	MW
Texture			-	S	S	S	S	S	S	S	S
Horizon Boundary	Distinctness		A	C	G	-	-	-	-	-	-
	Form		W	W	W	-	-	-	-	-	-
Structure	Primary	Grade	-	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-	-
		Type	-	SGR	SGR	SGR	SGR	-	-	-	-
		Consistence	-	l	l	l	l	-	-	-	-
	Secondary	Grade	-	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-	-
		Shape	-	-	-	-	-	-	-	-	-
Rooting	Abundance / Orientation	Very fine	-	-	-	VF	-	-	-	-	-
		Fine	-	P	P	-	-	-	-	-	-
		Medium	-	P	P	-	-	-	-	-	-
		Coarse	-	-	F	-	-	-	-	-	-
Mottles	Abundance		-	-	-	F	F	F	F	F	F
	Size		-	-	-	M	M	M	F	C	F
	Contrast		-	-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	5YR6/8	5YR5/8	-	5YR5/8	-
Concretions	Kind		-	-	-	-	-	-	-	-	-
	Abundance		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Location		-	-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-	-
Oil Sands Deposits	Percent		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-	-
	Consistence		-	-	-	-	-	-	-	-	-
Effervescence (10%)				-	-	-	-	-	-	-	-

Site Description				
Site	M118-2		Slope Position	Upper
Location	57.5105278	-111.4301111	Slope Percent	3
Soil Type	EDB		Slope Aspect	S
PGM (1, 2)	EOLI		High water table	-
Landform	Level		Max Rooting Depth (cm)	30
Land Use	Undisturbed		Depth to Carbonates (cm)	-

Soil Profile Description									
Horizon			LF	AE	Bm1	Bm2	BC	C1	C2
Depth (cm)			3.5-0	0-6	6-40	40-60	60-80	80-128	128-215
Dry color			-	10YR5/2	10YR6/6	10YR7/6	10YR7/4	10YR6/4	10YR6/4
Moist color			-	10YR3/2	10YR4/6	10YR5/6	10YR4/3	10YR4/4	10YR4/4
Moisture			D	D	D-M	M	M	M	M
Texture			-	S	S	S	S	S	S
Horizon Boundary	Distinctness		C	C	G	G	C	C	-
	Form		W	W	W	W	S	S	-
Structure	Primary	Grade	-	W	W	M	W	M	M
		Size	-	-	M	M	M	C	M
		Type	-	-	ABK	ABK	ABK	ABK	ABK
		Consistence	-	1	2	2	2	3	3
	Secondary	Grade	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-
		Shape	-	-	-	-	-	-	-
Rooting	Abundance / Orientation	Very fine	-	VF/R	-	-	-	-	-
		Fine	-	F/V	F/R	-	-	-	-
		Medium	-	-	-	-	-	-	-
		Coarse	-	-	-	-	-	-	-
Mottles	Abundance		-	-	-	-	-	M	-
	Size		-	-	-	-	-	M	-
	Contrast		-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	10YR6/6	-
Concretions	Kind		-	-	-	-	-	6	-
	Abundance		-	-	-	-	-	F	-
	Size		-	-	-	-	-	F	-
	Location		-	-	-	-	-	2	-
	Shape		-	-	-	-	-	P	-
	Color in field		-	-	-	-	-	5YR5/8	-
Oil Sands Deposits	Percent		-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-
	Consistence		-	-	-	-	-	-	-
Effervescence (10%)			-	-	-	-	-	-	-

Site Description

Site	M152-1	Slope Position	Mid
Location	57.4289167 -111.5961111	Slope Percent	4
Soil Type	EDB	Slope Aspect	W
PGM (1, 2)	GLFL-IC	High water table	-
Landform	Gently undulating	Max Rooting Depth (cm)	145
Land Use	Undisturbed	Depth to Carbonates (cm)	-

Soil Profile Description

Horizon			LFH	Ae	Bm1	Bm2	BC	C1	C2	C3
Depth (cm)			9-0	0-6.5	6.5-27.5	27.5-42	42-121	121-150	150-170	170-210
Dry color			-	10YR5/4	10YR6/4	10YR5/6	10YR5/6	10YR5/4	10YR5/6	10YR5/4
Moist color			-	10YR3/4	7.5YR4/4	7.5YR4/4	10YR4/4	10YR4/4	10YR4/4	10YR4/4
Moisture			-	M	M	W	W	W	-	-
Texture			-	S	S	S	S	S	S	S
Horizon Boundary	Distinctness		A	A	C	G	C	-	-	-
	Form		W	W	W	W	W	-	-	-
Structure	Primary	Grade	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-
		Type	-	SGR	SGR	SGR	SGR	SGR	-	-
		Consistence	-	l	l	l	l	l	-	-
	Secondary	Grade	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	-	< 1%	< 10%	< 1%	-	-
		Size	-	-	-	G	G	G-C	-	-
		Shape	-	-	-	SR	SR-A	SR	-	-
Rooting	Abundance / Orientation	Very fine	-	VF/V	VF/R	-	VF/V	VF	-	-
		Fine	-	VF/R	VF/H	VF/R	VF/V	-	-	-
		Medium	-	P/H	P/H	-	-	-	-	-
		Coarse	-	P/-	-/R	-	-	-	-	-
Mottles	Abundance		-	-	-	-	-	M	-	-
	Size		-	-	-	-	-	M	-	-
	Contrast		-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	10YR 5/8	-	-
Concretions	Kind		-	-	-	-	-	-	-	-
	Abundance		-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-
	Location		-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-
Oil Sands Deposits	Percent		-	-	-	-	5	15	-	-
	Size		-	-	-	-	F-M	C	-	-
	Shape		-	-	-	-	SR	SR	-	-
	Consistence		-	-	-	-	3	4	-	-
Effervescence (10%)			-	-	-	-	-	-	-	-

Site Description				
Site	M152-2		Slope Position	Depression
Location	57.4285278	-111.5969444	Slope Percent	5
Soil Type	EEB		Slope Aspect	E
PGM (1, 2)	GLFL-IC		High water table	-
Landform	Gently undulating		Max Rooting Depth (cm)	105
Land Use	Undisturbed		Depth to Carbonates (cm)	-

Soil Profile Description											
Horizon			LFH	Ae	AB	Bm1	Bm2	BC	Ck1	Ck2	Ck3
Depth (cm)			15-0	0-10	10-24	24-51	51-70	70-100	100-145	145-175	175-210
Dry color			-	7.5YR5/4	10YR5/6	10YR5/6	10YR6/4	10YR5/4	10YR6/4	10YR5/2	10YR5/2
Moist color			-	5YR4/4	7.5YR4/4	7.5YR4/6	10YR4/4	10YR4/3	10YR4/4	10YR3/2	10YR3/2
Moisture			M	M	M-W	M-W	M-W	M-W	-	-	-
Texture			-	S	S	S	S	S	S	S	S
Horizon Boundary	Distinctness		C	C	G	A	C	-	-	-	-
	Form		W	W	W	S	W	-	-	-	-
Structure	Primary	Grade	-	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-	-
		Type	-	SGR	SGR	SGR	SGR	SGR	-	-	-
		Consistence	-	1	1	1	1	1	-	-	-
	Secondary	Grade	-	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	-	5	-	-	-	-	-
		Size	-	-	-	G	-	-	-	-	-
		Shape	-	-	-	SR	-	-	-	-	-
Rooting	Abundance / Orientation	Very fine	-	P/R	P/R	VF/H	VF/V	VF/R	-	-	-
		Fine	-	VF/H	VF/R	-	VF/H	VF/V	-	-	-
		Medium	-	P/H	F/H	-	-	-	-	-	-
		Coarse	-	P/H	F/H	-	-	-	-	-	-
Mottles	Abundance		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Contrast		-	-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-	-
Concretions	Kind		-	-	-	-	-	-	-	-	-
	Abundance		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Location		-	-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-	-
Oil Sands Deposits	Percent		-	-	-	-	20	10	-	-	-
	Size		-	-	-	-	C-VC	F-M	-	-	-
	Shape		-	-	-	-	SR	SR	-	-	-
	Consistence		-	-	-	-	4	3	-	-	-
Effervescence (10%)			-	-	-	-	-	-	W	M	W

Site Description

Site	M172		Slope Position	Crown
Location	57.1476944	-111.5438333	Slope Percent	3
Soil Type	OEB		Slope Aspect	W
PGM (1,2)	GLFL, TILL		High water table	Seasonal
Landform	Undulating		Max Rooting Depth (cm)	96
Land Use	Undisturbed		Depth to Carbonates (cm)	-

Soil Profile Description

			LFH	Ahj1	Ahj2	Bm1	Bm2	BC	C	IIC
Horizon			LFH	Ahj1	Ahj2	Bm1	Bm2	BC	C	IIC
Depth (cm)			7-0	0-8	8-18	18-33	33-49	49-96	96-132	132+
Dry color			-	10YR5/2	10YR5/2	10YR6/3	10YR6/4	10YR6/4	10YR7/2	10YR4/4
Moist color			-	10YR3/2	10YR3/2	10YR5/3	10YR5/4	10YR5/4	10YR5/2	10YR3/2
Moisture			M	M	M	M	M	M	W	W
Texture			-	SL	SL	S	S	S	S	SL
Horizon Boundary	Distinctness		C	C	A	G	G	D	C	-
	Form		W	I	I	W	W	W	W	-
Structure	Primary	Grade	-	W	M	-	-	-	-	-
		Size	-	F	M	-	-	-	-	-
		Type	-	SBK	SBK	SGR	SGR	SGR	SGR	-
		Consistence	-	2	2	-	-	-	-	-
	Secondary	Grade	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	-	<5%	<5%	30%	-	-
		Size	-	-	-	G	G	S-B	-	-
		Shape	-	-	-	SR	SR	SR/	-	-
Rooting	Abundance / Orientation	Very fine	P/R	F/O	F/O	F/O	VF/H	F/R	-	-
		Fine	P/H	F/O	F/O	VF/O	VF/O	VF/O	-	-
		Medium	F/O	VF/O	F/O	-	-	VF/O	-	-
		Coarse	-	VF/H	VF/H	-	-	-	-	-
Mottles	Abundance		-	-	-	F	M	C	C	-
	Size		-	-	-	F	M	M	M	-
	Contrast		-	-	-	-	-	-	-	-
	Color in field		-	-	-	10YR 4/3	7.5YR 4/6	10YR 4/6	10YR 4/6	-
Concretions	Kind		-	-	-	-	-	-	-	-
	Abundance		-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-
	Location		-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-
Oil Sands Deposits	Percent		-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-
	Consistence		-	-	-	-	-	-	-	-
Effervescence (10%)			-	-	-	-	-	-	-	-

Site Description

Site	M175		Slope Position	Mid
Location	57.42919	-111.59782	Slope Percent	4
Soil Type	EDB		Slope Aspect	SW
PGM (1, 2)	GLFL-IC		High water table	-
Landform	Gently undulating		Max Rooting Depth (cm)	>110
Land Use	Undisturbed		Depth to Carbonates (cm)	48

Soil Profile Description

Horizon			LFH	Ae	Bm1	BM2/Btj	BCk	Ck1	Ck2
Depth (cm)			13-0	0-10	10-25	25-48	48-90	90-110	110-200
Dry color			7.5YR5/4	10YR5/4	10YR5/4	10YR5/3	10YR5/3	10YR5/2	7.5YR5/4
Moist color			7.5YR3/4	7.5YR4/4	7.5YR4/6	10YR4/3	10YR4/3	10YR4/2	7.5YR3/4
Moisture			M	M	M	M	M	D	-
Texture			LS	LS	LS	S	S	S	LS
Horizon Boundary	Distinctness		C	G	G	C	G	-	-
	Form		W	W	W	I	W	-	-
Structure	Primary	Grade	-	W	W	W	-	-	-
		Size	-	M	M	M	-	-	-
		Type	-	SBK	SBK	SBK	SGR	SGR	-
		Consistence	-	1	1	1	-	-	-
	Secondary	Grade	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	30	10	50	60	-
		Size	-	-	G-S	G	G-C	G-C	-
		Shape	-	-	SA-SR	SA-SR	SA-SR	SA-SR	-
Rooting	Abundance / Orientation	Very fine	E/H	F/O	F/O	VF/H	F/R	F/R	-
		Fine	P/O	F/O	VF/O	VF/H	-	-	-
		Medium	F/H-O	VF/O	VF/O	VF/H	VF/H	-	-
		Coarse	VF/H	VF/H	-	-	-	-	-
Mottles	Abundance		-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-
	Contrast		-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-
Concretions	Kind		-	-	-	-	-	-	-
	Abundance		-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-
	Location		-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-
Oil Sands Deposits	Percent		-	-	10	5	-	-	-
	Size		-	-	M	VCO	-	-	-
	Shape		-	-	SR	SR	-	-	-
	Consistence		-	-	3	4	-	-	-
Effervescence (10%)			-	-	-	-	W	W	M

Site Description

Site	M176		Slope Position	Slight depression
Location	57.40796	-111.62553	Slope Percent	5
Soil Type	EEB		Slope Aspect	SE
PGM (1, 2)	GLFL, GLLC		High water table	-
Landform	Undulating		Max Rooting Depth (cm)	80
Land Use	Undisturbed		Depth to Carbonates (cm)	60

Soil Profile Description

			LFH	Ae	Bm1	Bm2	BC	IIC1	IICk2	IICk3
Horizon			LFH	Ae	Bm1	Bm2	BC	IIC1	IICk2	IICk3
Depth (cm)			6-0	0-15	15-32	32-50	50-60	60-80	80-95	95-145
Dry color			10YR6/2	10YR6/4	10YR6/4	10YR6/4	10YR5/4	10YR5/3	10YR5/4	10YR6/2
Moist color			10YR4/2	10YR4/4	10YR4/4	10YR4/3	7.5YR4/4	7.5YR4/4	7.5YR4/4	10YR4/2
Moisture			M	M	M	M	M	M	M	-
Texture			S	S	S	S	SL	LS	LS	S
Horizon Boundary	Distinctness		A	C	G	G	A	C	-	-
	Form		W	W	W	W	I	I	-	-
Structure	Primary	Grade	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-
		Type	-	SGR	SGR	SGR	SGR	MA	MA	-
		Consistence	-	-	-	-	-	-	-	-
	Secondary	Grade	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	-	-	-	50	70	-
		Size	-	-	-	-	-	G-B	G-C	-
		Shape	-	-	-	-	-	SR	SA	-
Rooting	Abundance / Orientation	Very fine	P/R	F/O	VF/O	VF/O	VF/O	VF/O	-	-
		Fine	P/O	F/O	F/O	BF/H	-	F/H	-	-
		Medium	F/O	P/O	VF/H	-	VF/H	VF/H	-	-
		Coarse	-	VF/O	-	-	-	-	-	-
Mottles	Abundance		-	-	-	-	F	-	-	-
	Size		-	-	-	-	F	-	-	-
	Contrast		-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	10YR 5/6	-	-	-
Concretions	Kind		-	-	-	-	-	-	-	-
	Abundance		-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-
	Location		-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-
Oil Sands Deposits	Percent		-	-	-	-	-	5	10	-
	Size		-	-	-	-	-	S	M	-
	Shape		-	-	-	-	-	SR	SA	-
	Consistence		-	-	-	-	-	4	2	-
Effervescence (10%)			-	-	-	-	-	VW	W	M

Site Description

Site	M177		Slope Position	Mid
Location	57.40708	-111.62531	Slope Percent	2
Soil Type	EDB		Slope Aspect	W
PGM (1, 2)	GLFL, GLLC		High water table	-
Landform	Gently undulating		Max Rooting Depth (cm)	>79
Land Use	Undisturbed		Depth to Carbonates (cm)	79

Soil Profile Description

			LFH	Ae	Bm1	Bm2	BC	IIC	IIICk
Horizon			LFH	Ae	Bm1	Bm2	BC	IIC	IIICk
Depth (cm)			5-0	0-15	15-30	30-52	52-68	68-79	79-150
Dry color			10YR7/2	10YR6/4	10YR6/4	10YR6/3	10YR5/4	10YR6/2	10YR7/2
Moist color			10YR5/2	10YR4/6	10YR4/4	10YR4/3	7.5YR4/6	7.5YR4/3	10YR5/2
Moisture			M	M	M	M	M	M	M
Texture			S	S	S	S	SCL	C	S
Horizon Boundary	Distinctness		A	G	G	G	A	A	-
	Form		W	W	W	W	W	W	-
Structure	Primary	Grade	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-
		Type	-	SGR	SGR	SGR	SGR	MA	MA
		Consistence	-	-	-	-	-	-	-
	Secondary	Grade	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	-	-	-	50	-
		Size	-	-	-	-	-	G-C	-
		Shape	-	-	-	-	-	SR	-
Rooting	Abundance / Orientation	Very fine	P/R	P/O	F/O	VF/O	-	F/O	F/H
		Fine	P/O	F/O	F/O	F/O	VF/O	VF/O	F/H
		Medium	VF/O	F/O	-	-	-	VF/H	VF/H
		Coarse	-	VF/O	VF/H	-	-	-	-
Mottles	Abundance		-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-
	Contrast		-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-
Concretions	Kind		-	-	-	-	-	-	-
	Abundance		-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-
	Location		-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-
Oil Sands Deposits	Percent		-	-	-	<5%	-	-	-
	Size		-	-	-	F	-	-	-
	Shape		-	-	-	SR	-	-	-
	Consistence		-	-	-	1	-	-	-
Effervescence (10%)			-	-	-	-	-	-	M

Site Description

Site	M178		Slope Position	Mid (broad ridge top)
Location	57.4064	-111.62176	Slope Percent	3
Soil Type	EDB		Slope Aspect	NW
PGM (1, 2)	GLFL		High water table	-
Landform	Undulating		Max Rooting Depth (cm)	>152
Land Use	Undisturbed		Depth to Carbonates (cm)	-

Soil Profile Description

Horizon			LF	Ae	Bm	BC	C1-1	C1-2*	C2-1	C2-2*	C3
Depth (cm)			2-0	0-7	7-36	36-71	71-110	-	110-152	-	152-204
Dry color			10YR7/2	10YR6/4	10YR6/3	10YR6/2	10YR5/4	10YR6/2	10YR5/4	10YR6/3	10YR7/2
Moist color			10YR5/2	10YR4/4	10YR5/3	10YR4/2	10YR4/4	10YR4/4	10YR4/4	10YR4/3	10YR5/2
Moisture			D	M	M	M	M	-	M-W	-	-
Texture			LS	LS	S	S	S	S	SL	S	LS
Horizon Boundary	Distinctness		A	C	G	C	G	-	-	-	-
	Form		W	W	W	W	W	-	-	-	-
Structure	Primary	Grade	-	W	M	W	W	-	W	-	-
		Size	-	F	M	M	M	-	M	-	-
		Type	-	SBK	SBK	SBK	SBK	-	SBK	-	-
		Consistence	-	-	-	-	-	-	-	-	-
	Secondary	Grade	-	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-	-
		Shape	-	-	-	-	-	-	-	-	-
Rooting	Abundance / Orientation	Very fine	P/R	F/R	VF/H	VF/O	-	-	-	-	-
		Fine	P/O	F/O	F/O	VF/O	-	-	-	-	-
		Medium	F/H	VF/H	VF/H	VF/O	-	-	-	-	-
		Coarse	-	VF/H	VF/H	-	-	-	VF/V	-	-
Mottles	Abundance		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Contrast		-	-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-	-
Concretions	Kind		-	-	-	-	-	-	-	-	-
	Abundance		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Location		-	-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-	-
Oil Sands Deposits	Percent		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-	-
	Consistence		-	-	-	-	-	-	-	-	-
Effervescence (10%)			-	-	-	-	-	-	-	-	-

* = fine texture bands

Site Description

Site	M179		Slope Position	Toe
Location	57.4064	-111.62176	Slope Percent	O
Soil Type	EDB		Slope Aspect	NW
PGM (1, 2)	GLFL, GLLC		High water table	Seasonal
Landform	Undulating		Max Rooting Depth (cm)	95
Land Use	Undisturbed		Depth to Carbonates (cm)	95

Soil Profile Description

Horizon			LFH	Ae	Bm	BC	Cgj1	Cgj2	IIC	IIICk
Depth (cm)			10-0	0-13	13-32	32-52	52-71	71-89	89-95	95-140
Dry color			10YR7/2	10YR6/4	10YR6/3	10YR6/3	10YR6/3	10YR5/4	10YR4/4	10YR7/2
Moist color			10YR4/2	10YR4/4	10YR4/3	10YR4/3	10YR4/3	10YR3/4	10YR3/4	10YR4/2
Moisture			M	M	M	M	M	M	M	M
Texture			LS	LS	LS	LS	LS	SL	S	LS
Horizon Boundary	Distinctness		A	C	G	C	G	A	A	-
	Form		W	W	W	W	W	W	W	-
Structure	Primary	Grade	-	M	M	M	M	-	-	-
		Size	-	M	CO	M	M	-	-	-
		Type	-	ABK	SBK	ABK	ABK	MA	MA	MA
		Consistence	-	2	2	2	2	-	-	-
	Secondary	Grade	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-
		Shape	-	-	-	-	-	-	-	-
Rooting	Abundance / Orientation	Very fine	P/R	F/R	F/O	VF/H	-	VF/H	-	-
		Fine	P/O	F/O	F/O	VF/O	-	VF/H	VF/H	-
		Medium	F/O	VF/O	VF/O	VF/H	VF/H	VF/H	-	-
		Coarse	F/H	VF/O	-	VF/V	-	-	-	-
Mottles	Abundance		-	-	-	-	-	C	M	-
	Size		-	-	-	-	-	M	C	-
	Contrast		-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-
Concretions	Kind		-	-	-	-	-	-	-	-
	Abundance		-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-
	Location		-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-
Oil Sands Deposits	Percent		-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-
	Consistence		-	-	-	-	-	-	-	-
Effervescence (10%)			-	-	-	-	-	-	-	W

Site Description

Site	M180		Slope Position	Shoulder
Location	57.53645	-111.38319	Slope Percent	3
Soil Type	EDB		Slope Aspect	S
PGM (1, 2)	EOLI		High water table	-
Landform	Gently undulating		Max Rooting Depth (cm)	55
Land Use	Undisturbed		Depth to Carbonates (cm)	-

Soil Profile Description

			LF	Ae	Bm1	Bm2	BCfj1	BCfj2	BCfj3	BCfj4	C
Horizon			LF	Ae	Bm1	Bm2	BCfj1	BCfj2	BCfj3	BCfj4	C
Depth (cm)			4-0	0-6	6-55	55-73	73-91	91-122	122-139	139-174	174-200
Dry color			10YR6/2	10YR7/6	10YR7/4	10YR7/3	10YR7/3	10YR7/3	10YR5/4	10YR7/4	10YR6/2
Moist color			10YR4/2	10YR5/6	10YR5/4	10YR5/3	10YR5/3	10YR5/3	10YR5/3	10YR5/4	10YR4/2
Moisture			D	M	M	M	M	M	M	-	-
Texture			S	S	S	S	S	S	S	S	S
Horizon Boundary	Distinctness		A	C	G	G	G	G	-	-	-
	Form		W	W	W	W	W	W	-	-	-
Structure	Primary	Grade	-	-	W	W	-	-	-	-	-
		Size	-	-	F	F	-	-	-	-	-
		Type	-	SGR	SBK	SBK	SGR	SGR	SGR	-	-
		Consistence	-	1	2	2	1	1	1	-	-
	Secondary	Grade	-	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-	-
		Shape	-	-	-	-	-	-	-	-	-
Rooting	Abundance / Orientation	Very fine	-	A/V	-	-	-	-	-	-	-
		Fine	-	F/O	-	-	-	-	-	-	-
		Medium	-	-	F/H	-	-	-	-	-	-
		Coarse	-	-	-	-	-	-	-	-	-
Mottles	Abundance		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Contrast		-	-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-	-
Concretions	Kind		-	-	-	-	-	-	-	-	-
	Abundance		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Location		-	-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-	-
Oil Sands Deposits	Percent		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-	-
	Consistence		-	-	-	-	-	-	-	-	-
Effervescence (10%)			-	-	-	-	-	-	-	-	-

Site Description				
Site	M181		Slope Position	Crown
Location	57.53689	-111.38303	Slope Percent	1
Soil Type	EDB		Slope Aspect	SE
PGM (1, 2)	EOLI		High water table	-
Landform	Gently undulating		Max Rooting Depth (cm)	22
Land Use	Undisturbed		Depth to Carbonates (cm)	-

Soil Profile Description

			LF	Ae	Bm1	Bm2	Bm3	BCfj1	BCfj2	BCfj3	BCfj4
Horizon			LF	Ae	Bm1	Bm2	Bm3	BCfj1	BCfj2	BCfj3	BCfj4
Depth (cm)			2-0	0-5	5-22	22-56	56-93	93-115	115-149	149-175	175-201
Dry color			10YR5/2	10YR6/6	10YR7/6	10YR7/6	10YR7/4	10YR7/3	10YR7/4	10YR7/3	10YR5/2
Moist color			10YR3/2	10YR5/6	10YR5/6	10YR5/4	10YR5/4	10YR5/3	10YR4/4	10YR5/3	10YR3/2
Moisture			D	M	M	M	M	M	-	-	-
Texture			S	S	S	S	S	S	S	S	S
Horizon Boundary	Distinctness		A	C	G	G	G	-	-	-	-
	Form		W	W	W	W	W	-	-	-	-
Structure	Primary	Grade	-	-	-	W	W	W	-	-	-
		Size	-	-	-	F	M	F	-	-	-
		Type	-	SGR	SGR	SBK	SBK	SBK	-	-	-
		Consistence	-	1	1	1	1	1	-	-	-
	Secondary	Grade	-	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-	-
		Shape	-	-	-	-	-	-	-	-	-
Rooting	Abundance / Orientation	Very fine	-	F/V	V/O	-	-	-	-	-	-
		Fine	-	V/H	F/O	-	-	-	-	-	-
		Medium	-	-	V/H	-	-	-	-	-	-
		Coarse	-	-	V/H	-	-	-	-	-	-
Mottles	Abundance		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Contrast		-	-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-	-
Concretions	Kind		-	-	-	-	-	-	-	-	-
	Abundance		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Location		-	-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-	-
Oil Sands Deposits	Percent		-	-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-	-
	Consistence		-	-	-	-	-	-	-	-	-
Effervescence (10%)			-	-	-	-	-	-	-	-	-

Site Description				
Site	M182		Slope Position	Mid
Location	57.42589	-111.59673	Slope Percent	5
Soil Type	EDB		Slope Aspect	NW
PGM (1, 2)	GLFL-IC		High water table	-
Landform	Gently undulating		Max Rooting Depth (cm)	>101
Land Use	Undisturbed		Depth to Carbonates (cm)	137

Soil Profile Description										
Horizon			LFH	Ae	Bm1	Bm2	BC	C1	C2	Ck
Depth (cm)			12-0	0-14	14-26	26-44	44-73	73-101	101-137	137-200
Dry color			10YR5/4	7.5YR6/4	10YR5/8	10YR5/6	10YR6/6	10YR4/2	10YR4/2	10YR5/4
Moist color			7.5YR3/4	7.5YR3/4	10YR4/6	10YR4/4	10YR4/6	10YR3/2	10YR3/2	7.5YR3/4
Moisture			M	M	M	M	M	M	-	-
Texture			S	S	S	S	S	S	S	S
Horizon Boundary	Distinctness		A	C	C	G	G	-	-	-
	Form		W	W	I	W	W	-	-	-
Structure	Primary	Grade	-	-	W	-	-	-	-	-
		Size	-	-	M	-	-	-	-	-
		Type	-	SGR	SBK	SGR	SGR	SGR	-	-
		Consistence	-	1	1	1	1	1	-	-
	Secondary	Grade	-	-	-	-	-	-	-	-
		Size	-	-	-	-	-	-	-	-
		Type	-	-	-	-	-	-	-	-
		Consistence	-	-	-	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	5	-	5	5	-	-
		Size	-	-	G-C	-	G-C	G-C	-	-
		Shape	-	-	SA	-	SR	SR	-	-
Rooting	Abundance / Orientation	Very fine	P/R	F/O	F/R	F/O	F/H	VF/H	-	-
		Fine	P/H	F/O	VF/H	VF/H	VF/H	VF/H	-	-
		Medium	F/O	VF/H	-	VF/H	VF/H	-	-	-
		Coarse	F/H	VF/H	-	-	-	VF/H	-	-
Mottles	Abundance		-	-	-	C	F	F	-	-
	Size		-	-	-	M	M	F	-	-
	Contrast		-	-	-	-	-	-	-	-
	Color in field		-	-	-	7.5YR 5/8	7.5YR 5/8	5YR 5/6	-	-
Concretions	Kind		-	-	-	-	-	-	-	-
	Abundance		-	-	-	-	-	-	-	-
	Size		-	-	-	-	-	-	-	-
	Location		-	-	-	-	-	-	-	-
	Shape		-	-	-	-	-	-	-	-
	Color in field		-	-	-	-	-	-	-	-
Oil Sands Deposits	Percent		-	-	-	5	2.5	-	-	-
	Size		-	-	-	M	F	-	-	-
	Shape		-	-	-	SR	SR	-	-	-
	Consistence		-	-	-	3	2	-	-	-
Effervescence (10%)			-	-	-	-	-	-	-	W

Site Description

Site	M183		Slope Position	Ridgetop
Location	57.25635	-111.62487	Slope Percent	1
Soil Type	ODB		Slope Aspect	W
PGM (1, 2)	GLFL, TILL		High water table	-
Landform	Undulating		Max Rooting Depth (cm)	>56
Land Use	Undisturbed		Depth to Carbonates (cm)	-

Soil Profile Description

Horizon			LFH	Aej	Bm	IIC1	IIC2
Depth (cm)			5-0	0-10	10-20	20-56	56+
Dry color			7.5YR6/3	7.5YR6/4	10YR4/6	10YR5/6	7.5YR6/3
Moist color			7.5YR4/3	7.5YR4/4	7.5YR3/4	10YR3/6	7.5YR4/3
Moisture			M	M	M	M	M
Texture			LS	LS	L	L	LS
Horizon Boundary	Distinctness		C	G	C	C	-
	Form		W	W	I	I	-
Structure	Primary	Grade	-	W	W	-	-
		Size	-	F	M	-	-
		Type	-	SBK	SBK	MA	MA
		Consistence	-	1	2	-	-
	Secondary	Grade	-	-	-	-	-
		Size	-	-	-	-	-
		Type	-	-	-	-	-
		Consistence	-	-	-	-	-
Coarse Fragments (>2mm)	Primary	%	-	-	-	75	-
		Size	-	-	-	C-B	-
		Shape	-	-	-	SA/SR	-
Rooting	Abundance / Orientation	Very fine	P/R	P/O	F/R	P/O	F/H
		Fine	P/O	F/O	F/O	F/H	F/H
		Medium	F/O	F/O	VF/H	VF/H	-
		Coarse	-	VF/O	-	-	-
Mottles	Abundance		-	-	-	-	-
	Size		-	-	-	-	-
	Contrast		-	-	-	-	-
	Color in field		-	-	-	-	-
Concretions	Kind		-	-	-	-	-
	Abundance		-	-	-	-	-
	Size		-	-	-	-	-
	Location		-	-	-	-	-
	Shape		-	-	-	-	-
	Color in field		-	-	-	-	-
Oil Sands Deposits	Percent		-	-	-	-	-
	Size		-	-	-	-	-
	Shape		-	-	-	-	-
	Consistence		-	-	-	-	-
Effervescence (10%)			-	-	-	-	-

Appendix 3. Supplementary soil data

		Depth		Particle size description				Soil chemical info		
		Upper bound	Lower bound	Sand	Silt	Clay	Texture class	pH$_{water}$	pH$_{CaCl2}$	EC
Site	Horizon	cm		%			-	-	-	dS m^{-1}
M57-1	LF	2	0	-	-	-	-	-	-	-
M57-1	Ae	0	7	82	17	1	LS	6.1	5.6	2.11
M57-1	AB	7	20	92	7	1	S	5.4	4.8	0.40
M57-1	Bm1	20	49	97	1	1	S	5.9	5.1	0.24
M57-1	Bm2	49	75	98	1	1	S	5.5	4.8	0.23
M57-1	BC1	75	83	98	2	0	S	5.6	5.0	0.19
M57-1	BC2	83	95	97	2	1	S	5.5	4.8	0.21
M57-1	C1	95	135	99	0	1	S	5.9	5.6	0.61
M57-1	C2	135	200	98	1	1	S	6.5	5.6	0.16
M57-2	LFH	5	0	-	-	-	-	-	-	-
M57-2	Ae	0	10.5	83	14	2	LS	5.4	4.8	2.13
M57-2	Bm	10.5	49	96	4	0	S	5.7	4.9	0.27
M57-2	BC	49	75	98	2	0	S	5.4	4.5	0.14
M57-2	C1	75	95	98	0	1	S	5.5	4.6	0.11
M57-2	C2	95	114	98	1	1	S	6.3	5.4	0.15
M57-2	C3	114	200	98	1	1	S	6.6	5.7	0.13
M118-1	LFH	2	0	-	-	-	-	-	-	-
M118-1	Ae	0	3	93	6	1	S	5.3	4.7	0.73
M118-1	Bm1	3	25	94	6	0	S	5.2	4.5	0.42
M118-1	Bm2	25	70	97	2	1	S	5.5	4.7	0.74
M118-1	BCfj1	70	108	97	1	1	S	6.0	4.7	0.18
M118-1	BCfj2	108	143	97	1	2	S	6.5	5.1	0.10
M118-1	BCfj3	143	171	96	2	2	S	6.6	5.3	0.08
M118-1	BCfj4	171	185	96	1	2	S	6.4	4.9	0.12
M118-1	BCfj5	185	200	97	1	2	S	6.3	4.8	0.12
M118-2	LF	3.5	0	-	-	-	-	-	-	-
M118-2	Ae	0	6	91	7	1	S	5.7	5.0	1.19
M118-2	Bm1	6	40	95	3	2	S	5.9	5.0	0.27
M118-2	Bm2	40	60	97	1	2	S	6.3	5.2	0.18
M118-2	BC	60	80	97	0	4	S	6.5	5.5	0.18
M118-2	C1	80	128	96	0	4	S	6.1	4.9	0.48
M118-2	C2	128	215	96	2	2	S	6.7	5.2	0.10
M152-1	LFH	9	0	-	-	-	-	-	-	-
M152-1	Ae	0	6.5	93	6	1	S	5.8	5.1	0.85
M152-1	Bm1	6.5	27.5	92	4	4	S	5.5	4.5	0.30
M152-1	Bm2	27.5	42	95	1	4	S	6.1	5.1	0.25
M152-1	BC	42	121	95	3	1	S	6.6	5.5	0.17
M152-1	C1	121	150	94	5	1	S	8.3	7.5	1.19
M152-1	C2	150	170	96	2	1	S	7.8	6.7	0.48
M152-1	C3	170	210	95	4	1	S	8.1	7.2	0.79

		Depth		Particle size description				Soil chemical info		
		Upper bound	Lower bound	Sand	Silt	Clay	Texture Class	pH_{water}	pH_{CaCl2}	EC
Site	Horizon	cm		%			-	-	-	dS m^{-1}
M152-2	LFH	15	0	-	-	-	-	-	-	-
M152-2	Ae	0	10	90	6	4	S	5.8	5.1	0.53
M152-2	AB	10	24	92	5	4	S	5.6	4.7	0.31
M152-2	Bm1	24	51	95	1	4	S	6.4	5.5	0.26
M152-2	Bm2	51	70	93	4	2	S	6.5	5.5	0.23
M152-2	BC	70	100	94	5	1	S	7.5	6.9	1.24
M152-2	Ck1	100	145	95	4	1	S	8.6	7.8	1.01
M152-2	Ck2	145	175	93	6	1	S	8.7	7.9	1.01
M152-2	Ck3	175	210	92	6	2	S	8.5	7.8	1.22
M172	LFH	7	0	-	-	-	-	-	-	-
M172	Ahj1	0	8	72	22	6	SL	4.7	4.0	1.11
M172	Ahj2	8	18	67	28	5	SL	5.0	4.4	1.07
M172	Bm1	18	33	95	2	2	S	6.3	5.7	1.27
M172	Bm2	33	49	93	5	2	S	6.7	5.8	0.33
M172	BC	49	96	95	2	2	S	6.8	5.9	0.37
M172	C	96	132	91	8	1	S	6.9	6.1	0.50
M172	IIC	132	+	61	30	9	SL	6.8	6.2	1.34
M175	LFH	13	0	-	-	-	-	-	-	-
M175	Ae	0	10	86	10	4	LS	5.8	4.9	0.36
M175	Bm1	10	25	87	7	6	LS	6.3	5.3	0.40
M175	Bm2/Btj	25	48	86	7	7	LS	6.7	5.7	0.46
M175	BCk	48	90	93	6	1	S	8.3	7.5	1.36
M175	Ck1	90	110	90	8	2	S	8.4	7.8	1.80
M175	Ck2	110	200	90	7	2	S	8.6	7.9	1.72
M176	LFH	6	0	-	-	-	-	-	-	-
M176	Ae	0	15	92	7	1	S	5.9	4.8	0.50
M176	Bm1	15	32	93	0	7	S	6.6	5.7	0.49
M176	Bm2	32	50	96	2	1	S	6.9	6.1	0.40
M176	BC	50	60	95	4	1	S	6.9	6.0	0.44
M176	IIC1	60	80	77	8	15	SL	7.8	7.4	2.51
M176	IICk2	80	95	87	5	7	LS	8.5	7.8	1.87
M176	IICk3	95	145	82	12	6	LS	8.5	7.8	1.89
M177	LFH	5	0	-	-	-	-	-	-	-
M177	Ae	0	15	91	6	2	S	5.2	4.4	0.55
M177	Bm1	15	30	91	6	4	S	6.2	5.2	0.39
M177	Bm2	30	52	95	2	2	S	6.6	5.6	0.38
M177	BC	52	68	96	2	2	S	6.9	6.0	0.37
M177	IIC	68	79	66	12	21	SCL	7.6	6.9	1.82
M177	IIICk	79	99	30	30	40	C	8.1	7.6	2.46

		Depth		Particle size description				Soil chemical info		
		Upper bound	Lower bound	Sand	Silt	Clay	Texture class	pH_{water}	pH_{CaCl2}	EC
Site	Horizon	cm		%			-	-	-	dS m^{-1}
M178	LFH	2	0	-	-	-	-	-	-	-
M178	Ae	0	7	86	12	2	LS	5.6	4.7	0.41
M178	Bm	7	36	85	10	5	LS	5.4	4.3	0.37
M178	BC	36	71	88	9	2	S	5.6	4.7	0.34
M178	C1-1	71	110	93	5	2	S	6.4	5.3	0.17
M178	C1-2*	-	-	89	6	5	S	-	-	-
M178	C2-1	110	152	92	6	2	S	6.4	5.5	0.17
M178	C2-2*	-	-	82	7	11	SL	-	-	-
M178	C3	152	204	92	6	2	S	6.4	5.3	0.44
M179	LFH	10	0	-	-	-	-	-	-	-
M179	Ae	0	13	76	20	4	LS	4.9	4.1	1.22
M179	Bm	13	32	85	12	4	LS	5.4	4.5	0.27
M179	BC	32	52	86	11	4	LS	6.0	4.9	0.30
M179	Cgj1	52	71	86	11	4	LS	5.2	4.2	0.43
M179	Cgj2	71	89	85	8	6	LS	4.7	4.1	1.06
M179	IIC	89	95	74	10	16	SL	6.1	5.3	0.50
M179	IIICk	95	140	88	10	3	S	8.2	7.6	1.63
M180	LF	4	0	-	-	-	-	-	-	-
M180	Ae	0	6	95	4	1	S	5.2	4.4	0.39
M180	Bm1	6	55	97	2	1	S	6.0	4.9	0.17
M180	Bm2	55	73	98	1	1	S	6.3	5.1	0.10
M180	BCfj1	73	91	98	0	3	S	6.2	4.9	0.09
M180	BCfj2	91	122	98	1	1	S	5.4	5.0	0.09
M180	BCfj3	122	139	98	1	1	S	6.0	5.1	0.08
M180	BCfj4	139	174	98	0	3	S	6.2	5.2	0.13
M180	C	174	200	97	0	4	S	6.2	5.2	0.15
M181	LF	2	0	-	-	-	-	-	-	-
M181	Ae	0	5	93	5	1	S	5.4	4.4	0.51
M181	Bm1	5	22	95	2	2	S	5.9	5.0	0.23
M181	Bm2	22	56	98	0	3	S	6.3	5.2	0.12
M181	Bm3	56	93	98	0	3	S	6.7	5.6	0.08
M181	BCfj1	93	115	97	0	2	S	6.5	5.6	0.09
M181	BCfj2	115	149	98	0	2	S	6.5	5.7	0.15
M181	BCfj3	149	175	96	1	3	S	6.3	5.4	0.17
M181	BCfj4	175	201	95	3	2	S	6.8	5.7	0.28

* Fine texture bands sample

		Depth		Particle size description				Soil chemical info		
		Upper bound	Lower bound	Sand	Silt	Clay	Texture class	pH_{water}	pH_{CaCl2}	EC
Site	Horizon	cm		%			-	-	-	$dS\ m^{-1}$
M182	LFH	12	0	-	-	-	-	-	-	-
M182	Ae	0	14	90	8	1	S	5.6	4.6	0.33
M182	Bm1	14	26	90	7	3	S	5.8	4.7	0.27
M182	Bm2	26	44	96	1	2	S	6.3	5.2	0.16
M182	BC	44	73	95	2	2	S	5.9	4.9	0.20
M182	C1	73	101	97	1	3	S	6.4	5.6	0.14
M182	C2	101	137	94	4	3	S	8.1	7.5	1.16
M182	Ck	137	200	94	5	1	S	8.4	7.7	1.27
M183	LFH	5	0	-	-	-	-	-	-	-
M183	Aej	0	10	74	23	2	LS	5.6	4.7	0.76
M183	Bm	10	20	78	20	2	LS	5.9	5.2	0.66
M183	IIC1	20	56	48	35	17	L	-	-	-
M183	IIC2	56	+	35	47	17	L	-	-	-

Appendix 4. Carbon and nitrogen isotopic data

Site	Horizon	Depth		C_{total}	N_{total}	$\delta^{13}C$ vPDB	$\delta^{15}N$ vAIR
		Upper bound	Lower bound				
		cm		%	%	‰	‰
M57-1	LFH	2	0	10.73	0.40	-27.98	-0.95
M57-1	Bm1	20	49	0.06	0.00	-24.07	3.99
M57-1	Bm2	49	75	0.07	0.00	-24.51	3.36
M57-2	LFH	5	0	7.70	0.31	-28.16	0.50
M57-2	Bm	10.5	49	0.09	0.01	-24.90	4.16
M57-2	BC	49	75	0.04	0.00	-24.29	0.93
M118-1	LFH	2	0	7.94	0.30	-27.81	-0.34
M118-1	Bm1	3	25	0.41	0.01	-26.36	4.65
M118-1	Bm2	25	70	0.03	0.00	-25.05	2.17
M118-2	LFH	3.5	0	6.73	0.24	-27.66	0.41
M118-2	Bm1	6	40	0.06	0.01	-24.70	3.24
M118-2	Bm2	40	60	0.03	0.00	-22.79	0.41
M152-1	LFH	9	0	12.29	0.52	-27.09	1.50
M152-1	Bm1	6.5	27.5	0.07	0.00	-25.48	1.48
M152-1	Bm2	27.5	42	0.21	0.00	-28.37	1.71
M152-2	LFH	15	0	9.14	0.39	-27.82	3.49
M152-2	Bm1	24	51	0.10	0.01	-25.43	3.38
M152-2	Bm2	51	70	0.99	0.02	-29.62	3.20
M172	LFH	7	0	24.38	1.33	-27.49	1.50
M172	Bm1	18	33	0.11	0.01	-26.11	4.38
M172	Bm2	33	49	0.13	0.01	-26.67	5.92
M175	LFH	13	0	15.83	0.76	-27.36	2.44
M175	Bm1	10	25	0.31	0.02	-27.02	4.59
M175	Bm2/Btj	25	48	0.22	0.02	-25.42	5.18

Site	Horizon	Depth		C_{total}	N_{total}	$\delta^{13}C$ vPDB	$\delta^{15}N$ vAIR
		Upper bound	Lower bound				
		cm		%	%	‰	‰
M176	LFH	6	0	9.94	0.48	-28.26	2.27
M176	Bm1	15	32	0.18	0.02	-26.43	4.59
M176	Bm2	32	50	0.13	0.01	-26.68	5.18
M177	LFH	5	0	12.01	0.61	-27.89	3.35
M177	Bm1	15	30	0.14	0.01	-26.44	4.37
M177	Bm2	30	52	0.13	0.01	-27.24	2.93
M178	LFH	2	0	24.00	0.91	-27.90	1.52
M178	Bm	7	36	0.29	0.02	-26.63	4.33
M178	BC	36	71	0.23	0.01	-27.65	2.06
M179	LFH	10	0	26.38	1.14	-27.52	2.10
M179	Bm	13	32	0.27	0.02	-27.14	4.75
M179	BC	32	52	0.31	0.02	-27.52	4.51
M180	LF	4	0	9.56	0.35	-27.52	-0.57
M180	Bm1	6	55	0.08	0.01	-25.48	2.27
M180	Bm2	55	73	0.06	0.01	-25.76	1.63
M181	LF	2	0	13.99	0.55	-27.54	-0.17
M181	Bm1	5	22	0.24	0.02	-25.62	4.40
M181	Bm2	22	56	0.06	0.01	-25.33	1.17
M182	LFH	12	0	13.04	0.61	-27.10	3.79
M182	Bm1	14	26	0.24	0.02	-26.47	3.72
M182	Bm2	26	44	0.10	0.01	-26.18	1.49
M183	LFH	5	0	18.25	1.05	-27.92	1.15
M183	Aej	0	10	0.76	0.04	-27.45	4.47
M183	Bm	10	20	0.19	0.02	-26.39	4.35

Appendix 5 Shrub biomass by species

Site	Species		Biomass
	Common name	Latin name	kg 100m^{-2}
M57-1	Common Bearberry	*Arcostaphylos uva-ursi*	42.65
M57-1	Blueberry	*Vaccinium myrtilloides*	0.87
M57-1	Bog cranberry	*Vaccinium vitis-idaea*	0.31
M57-1	Canadian Buffaloberry	*Shepherdia canadensis*	3.85
M57-1	Saskatoon	*Amelanchier alnifolia*	0.99
M57-2	Common Bearberry	*Arcostaphylos uva-ursi*	35.31
M57-2	Blueberry	*Vaccinium myrtilloides*	1.76
M57-2	Bog cranberry	*Vaccinium vitis-idaea*	2.01
M57-2	Green alder	*Alnus crispa*	0.71
M57-2	Saskatoon	*Amelanchier alnifolia*	0.47
M118-1	Common Bearberry	*Arcostaphylos uva-ursi*	2.81
M118-2	Common Bearberry	*Arcostaphylos uva-ursi*	1.24
M152-1	Common Bearberry	*Arcostaphylos uva-ursi*	7.26
M152-1	Blueberry	*Vaccinium myrtilloides*	0.88
M152-1	Prickly rose	*Rosa acicularis*	0.47
M152-1	Saskatoon	*Amelanchier alnifolia*	1.47
M152-2	Blueberry	*Vaccinium myrtilloides*	1.47
M152-2	Bog cranberry	*Vaccinium vitis-idaea*	1.13
M152-2	Canadian Buffaloberry	*Shepherdia canadensis*	0.71
M152-2	Pin Cherry	*Prunus pensylvanica*	0.35
M152-2	Prickly rose	*Rosa acicularis*	0.39
M152-2	Saskatoon	*Amelanchier alnifolia*	2.41
M172	Blueberry	*Vaccinium myrtilloides*	0.82
M172	Canadian Buffaloberry	*Shepherdia canadensis*	1.85
M172	Low bush cranberry	*Viburnum edule*	0.97
M172	Prickly rose	*Rosa acicularis*	0.96
M172	Saskatoon	*Amelanchier alnifolia*	14.99
M175	Common Bearberry	*Arcostaphylos uva-ursi*	0.28
M175	Blueberry	*Vaccinium myrtilloides*	3.53
M175	Bog cranberry	*Vaccinium vitis-idaea*	0.20
M175	Canadian Buffaloberry	*Shepherdia canadensis*	14.03
M175	Pin Cherry	*Prunus pensylvanica*	2.08
M175	Prickly rose	*Rosa acicularis*	5.51
M175	Saskatoon	*Amelanchier alnifolia*	17.11

Site	Species		Biomass
	Common name	Latin name	kg 100m^{-2}
M176	Blueberry	*Vaccinium myrtilloides*	4.13
M176	Canadian Buffaloberry	*Shepherdia canadensis*	11.12
M176	Prickly rose	*Rosa acicularis*	1.55
M176	Saskatoon	*Amelanchier alnifolia*	8.15
M177	Blueberry	*Vaccinium myrtilloides*	12.40
M177	Canadian Buffaloberry	*Shepherdia canadensis*	2.57
M177	Prickly rose	*Rosa acicularis*	0.53
M177	Saskatoon	*Amelanchier alnifolia*	2.65
M178	Blueberry	*Vaccinium myrtilloides*	0.30
M178	Pin Cherry	*Prunus pensylvanica*	0.01
M178	Prickly rose	*Rosa acicularis*	0.33
M178	Saskatoon	*Amelanchier alnifolia*	0.09
M179	Blueberry	*Vaccinium myrtilloides*	3.30
M179	Green alder	*Alnus crispa*	28.92
M179	Common Labrador Tea	*Ledum groenlandicum*	0.10
M179	Prickly rose	*Rosa acicularis*	0.23
M179	Saskatoon	*Amelanchier alnifolia*	0.14
M180	Common Bearberry	*Arcostaphylos uva-ursi*	0.85
M181	Common Bearberry	*Arcostaphylos uva-ursi*	4.09
M182	Beaked Willow	*Salix bebbiana*	0.02
M182	Blueberry	*Vaccinium myrtilloides*	6.21
M182	Canadian Buffaloberry	*Shepherdia canadensis*	0.52
M182	Pin Cherry	*Prunus pensylvanica*	6.69
M182	Prickly rose	*Rosa acicularis*	2.65
M182	Saskatoon	*Amelanchier alnifolia*	12.31
M183	Canadian Buffaloberry	*Shepherdia canadensis*	2.88
M183	Low bush cranberry	*Viburnum edule*	0.63
M183	Prickly rose	*Rosa acicularis*	11.01
M183	Saskatoon	*Amelanchier alnifolia*	4.55