HUMUS AS AN INDICATOR OF NUTRIENT AVAILABILITY IN A CAREFULLY LOGGED BOREAL BLACK SPRUCE-FEATHERMOSS FOREST IN NORTHWESTERN QUÉBEC

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HUMUS IN BLACK SPRUCE BOREAL FORESTS

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ABSTRACT

Black spruce (*Picea mariana* (Mill.) B.S.P.)-feathermoss forests are a common subtype of the northern boreal forests. These forests are associated with large accumulations of mor humus, which is regarded as an important source of nutrients, contributor to soil structure, moisture retention and vital to the long-term sustainability of these forests. Harvesting with protection of advance regeneration (CPRS) is currently used in northwestern Québec as the method for sustainable management, which reduces soil compaction and protects advance regeneration, and genetic diversity. We examined the effects of CPRS on organic matter and advance regeneration 6 years after harvesting. During the summer of 2002, a humus classification based on observable field characteristics was developed and applied to six CPRS sites in the northern Abitibi claybelt region of Québec. At each site 75 humus profiles were surveyed and classified by order and thickness of horizons present. Humus horizons were easily observed using morphological features, and master horizon classes were distinguished by their nutritional and biochemical attributes with differences occurring as a result of the natural process of decomposition. Individual humus horizon and total profile thickness was the variable that most affected profile nutrient mass. High forest floor disturbance was associated with shallow profile depth, resulting in low humus profile nutrient mass and low density advance regeneration. Lower forest floor disturbance resulted in deeper profiles associated with higher available nutrients in humus profiles and higher density of advance regeneration. These results suggest that disturbance caused by harvesting may reduce overall stand productivity in the short term due to the effect of low tree density and possibly in the long-term due to loss of nutrients.

RÉSUMÉ

Les pessières noire à mousses hypnacées constituent un sous-type commun au nord des forêts boréales. Ces forêts sont associées avec des accumulations considérables d'humus de type mor, considéré comme étant une source importante de nutriments et contribuant à la structure et la capacité de rétention d'eau du sol, et donc vital à la durabilité à long-terme de ces forêts. La coupe avec protection de la régénération est présentement utilisée dans le nord-ouest du Québec en tant que méthode pour une gestion durable qui réduit la compaction du sol et protège la régénération avancée, et la diversité génétique. Nous avons étudié les effets de la coupe écologique sur la matière organique et la régénération pré-établie 6 ans après la récolte. Pendant l'été 2002, une classification d'humus basée sur des caractéristiques observables sur le terrain a été développée et appliquée à six sites coupés au nord de la ceinture d'argile dans la région de l'Abitibi au Québec. Dans chacun des sites, 75 profils d'humus ont été inventoriés et classifiés selon l'ordre et l'épaisseur des horizons présents. Les horizons d'humus étaient relativement faciles à identifier grâce aux caractéristiques morphologiques, et les principales classes d'horizons se distinguaient par leurs propriétés nutritionnelles et biochimiques, résultant du processus naturel de décomposition. La masse de nutriments était principalement affectée par l'épaisseur des horizons et des profils. L'épaisseur de la couverture morte était associée, menant à une faible masse de nutriments et à une régénération pré-établie de faible densité. Un niveau de pertubation plus faible semble mener à des profils humiques plus profonds associés à une plus grande disponibilité de nutriments et une régénération pré-établie plus dense. Ces résultats suggèrent qu'une pertubation causée par

une récolte pourrait réduire la productivité d'un site dû soit à court terme à la réduction de la densité de la régénération, ou à long-terme dû à la perte de nutriments.

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FOREWORD

This thesis comprises three chapters: an introduction and two papers describing research findings. The two papers will be submitted for publication with the candidate as the first author, research supervisor Dr. J. Fyles as the co-author.

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INTRODUCTION

0.1 The Boreal Forest

Canada accounts for 40% of the world's circumboreal forest, 28% of which is in Québec. The boreal forest is composed of predominately coniferous trees (*Picea, Pinus, Abies* and *Larix* genera), with sparsely scattered large shrubs, herbaceous plants and underlain by mosses and lichens (Larson 1980). The boreal forest biome is characterized by gently rolling terrain, low annual rainfall (<900 mm/yr), a cold continental climate with severe winter temperatures, cold moist forest soils, and low evapotranspiration rates owing to the short growing season (Burton *et al.* 2003; Fisher and Binkley 2000; Pritchett and Fisher 1987). In these northern forest types, tree growth is slow (1-4 m^3 ha^{-1} yr^{-1}) (Aber and Melillo 1991) and conditions are less than ideal for decomposition, therefore, the forest floor is not completely decomposed, but is modified into humus, which may decompose slowly and accumulate (Prescott *et al.* 2000). A major forest cover subtype of the southern and central Canadian boreal forest is the black spruce (*Picea mariana* (Mill.) B.S.P.)-feathermoss forest. Stands of this forest type are characterized by a closed overstorey canopy with the growth of a nearly continuous ground cover of feathermoss (*Hylocomium splendens, Pleurozium schreberi,* and *Ptilium crista-castrensis*) and sphagnum mosses (*Sphagnum* spp.).

0.2 Humus

Large surface accumulation of organic matter, typically found in northern boreal forest are often referred to as humus. Humus consists mainly of plant remains as well as the recalcitrant products of decomposition (Pritchett and Fisher 1987; Tate 1987; Prescott *et al.* 2000) predominately dark brown to black. Humus is itself an intermediate product of decomposition as it is the biological, microbial or chemical conversion of organic residues, and decomposes at an annual rate of less that 3% in temperate regions (Barbour *et al.* 1999). The process of humus formation is not well understood but is thought to involve microbial modification of lignin and condensation of proteins into humus precursors, followed by their complexing into humus molecules of complex structures (Prescott *et al.* 2000). This humified material although individually highly variable, is microbiologically stable, since only certain fungal populations are known to decompose humic material (Tate 1987; Piccolo 1996). In comparison to original plant material, humus is low in carbohydrates (cellulose, hemicellulose), high in large polyphenolic molecules (lignin component) and high in nitrogen (N) (Prescott *et al.* 2000).

0.3 Humus Formation

Organic matter enters forest soils predominantly via two cycles: as root exudates and decaying roots, and as forest litter (Tate 1987). The prime source of humus is litter, such as dead leaves and branches, either in fresh or partly decomposed forms (Duchaufour 1982). Litter inputs into the forest ecosystem may follow three pathways (1) it may be totally mineralized, returning to carbon dioxide and mineral nutrient pool; (2) it may be assimilated into microbial biomass; or (3) the litter may be incorporated either unchanged or partially modified into the more stable soil humic fraction, that is, it may be humified. (Tate 1987). Aber and Melillo (1991) and Berg (1986) divide the process of litter decomposition to humus (humification) in two phases. In the early stage of decomposition, carbon (C) is readily available and there is rapid loss of soluble substances and cellulose stimulated by raised concentrations of N, among other elements.

The mass-loss rate during this phase is controlled by the concentrations of nutrients limiting the microbial activity. The later stage coincides with a net loss of lignin and net N mineralization. Decomposition slows as the concentration of lignin, a recalcitrant component of litter, increases and degradation by soil microorganisms slows. It is during this later stage that litter is now considered humus. The amount of original litter mass (recalcitrant lignin) remaining once decomposition slows will determine the rate and amount of accumulation.

Incomplete decomposition of the litter and humus are regulated by (1) climate (temperature and moisture); (2) physical and chemical characteristics of litter (lignin) and (3) soil microbial and faunal communities (Berg 1986; Tate 1987; Prescott *et al.* 2000). Particularly in the early stages of decomposition suitable temperature and moisture conditions are required for effective microbial decomposition (Bunnell *et al.* 1976). In general, increases in soil moisture and decreases in soil temperature are known to cause decrease in microbial activity and mineralization of organic matter (Van Cleve *et al.* 1981; Flanagan and Van Cleve 1983; Oechel and Van Cleve 1986). However, litter quality is considered to play a larger role in the later stages of decay. Flanagan and Van Cleve (1983), and Van Cleve *et al.* (1993) demonstrated that substrate chemistry appears to be the most important factor regulating litter decomposition and N availability in boreal forests. Scott and Binkley (1997) and Berg (2000) found that high lignin concentrations generally retard litter decay rates and are related to decreased N availability. Coniferous litter has been found to reduce the availability of soil N because of its high lignin and low N content (Pastor *et al.* 1987). Furthermore, microbial activity is stimulated by the presence of nutrients and carbon especially during the later states of decay, when the readily metabolizable C in litter has been exhausted and C had been transformed into recalcitrant forms (Prescott *et al.* 2000). Root exudates and applications of fresh residues provide readily available C which may stimulate microbial activity and promote humus decomposition (Bingeman *et al.* 1953; Bradley and Fyles 1996). Soil fauna provide preliminary fragmentation enhancing decomposition and if this fragmentation is retarded decomposition is slowed (Fisher and Pritchett 2000). Similarly, soils without soil fauna have incomplete decomposition.

Humus forms are influential in modifying the microclimate of the forest floor, by insulating the soil from extreme temperature and moisture conditions (Olsson 1986; Pritchett and Fisher 1987), contribute to moisture retention and soil structure and may represent a substantial reservoir of nutrient capital, particularly nitrogen. Humus forms are genetically and ecologically linked to the nutrient dynamics, local climate, biological activity, and ecological function of the forests with which they are associated (Pritchett and Fisher 1987; Sims and Baldwin 1996) and exhibit heterogeneity over short distances as a result of spatial variation in local site conditions, vegetation and microclimate (Sims and Baldwin 1996). The type of humus form will greatly influence site fertility; therefore classification is useful in estimating the nutritional status and potential productivity.

0.4 Humus Classification

Humus forms can be viewed as organized natural units and typically consist of one or more layers or "horizons". Generally, three organic horizons L, F, and H are used to describe terrestrial humus forms in dry to wet, very rapidly to poorly drained mineral soils. These horizons are usually not saturated with water for prolonged periods and are typically found at the surface of mineral soils and may have a component of mosses

(SCWG 1987). The L or litter horizon is the uppermost layer and consists of fresh litter; the F or fermentation layer consists of partly decomposed but recognizable plant residues; and the H or humic horizon is characterized by an accumulation of decomposed organic matter in which the original structures are largely indiscernible, resulting in a greater degree of humification (SCWG 1987).

The term humus form was first used by Müller (1879), who discerned and defined the terms mull and mor humus. Mor humus is often referred to, as "raw" humus and is a consequence of fungal decomposition and results in incomplete decomposition (organic matter is not completely mineralized to CO_2 and nutrients), nutrient immobilization (Fisher and Pritchett 2000; Prescott *et al.* 2000) and accumulates as L, F, and H horizons. Mor forest floors are generally found under the spruce-fir forests of the boreal regions of northern and eastern Canada and under much of the coniferous forests of Scandinavia and Siberia (Fisher and Pritchett 2000). Mull humus forms as a result of organic material passing through animals, typically burrowing microfauna (mostly earthworms), and consequent bacterial decomposition (SCWG 1987; Fisher and Pritchett 2000), resulting in greater decomposition and nutrient availability. Mulls do not accumulate as distinct layers due to the microfauna and tend to become mixed with the mineral soil and are often found in the north-central United States and in central Europe. Mulls support greater nitrification, high nutrient availability, and higher productivity than mors. The third humus form is a series of gradual transition between mulls and mors termed moder, encompassing characteristics of both (Green *et al.* 1993). The type of decomposition whether animal, fungal, microbial, determines the amount and type of humus formed (Weetman 1980).

Different systems of humus form classification have been proposed since Müller's (1879), in Europe and Great Britain (Hartmann 1952; Kubiena 1953; Barratt 1964; Duchaufour 1982; Berthelin *et al.* 1994), the United States (Romell and Heiberg 1931; Heiberg and Chandler 1941; Hoover and Lunt 1952; Wilde 1966; 1971), and Canada (Bernier 1968). However, these systems tend to be too complex for field use. Ideally, humus form classification would be based on physical, chemical and biological properties of humus forms that correlated with recognizable structural properties (Klinka *et al.* 1981). However, few studies exist relating structural properties of humus forms with chemical characteristics and biological responses. Hence, most existing humus form classifications make exclusive use of field-observable structural properties to distinguish between various humus form classes (Klinka *et al.* 1981). For field purposes, grouping forest floors into the three broad types-mor, moder and mull is generally adequate. Green *et al.* (1993) attempted to develop an international classification, with a consistent hierarchical structure, a connotative nomenclature and sufficiently detailed taxonomic differentiae based on earlier classifications, however it has yet to be widely tested and accepted.

0.5 Sustainable Forest Management (SFM)

> *"The idea of sustainability is surprisingly simple: resource consumption cannot exceed resource production over time."*
>
> *Donald W. Floyd (2002)*

At the 1992 Rio Earth Summit, forests were recognized as an integral component to sustainable development and lead to international effort to develop guidelines for assessing SFM. Since then, there has been a proliferation of definitions used to describe

SFM, however most definitions embrace multiple values being maintained over generations. Generally, forest values are broken down into three categories; social, economic and ecological referred to as the "three pillars" of sustainability (Goodland 1995). Each pillar refers to a complex set of values that humans have and therefore, sustainability varies across individuals, countries and generations. SFM will then depend on the interpretation and tradeoffs of these values with forest management plans (Adamowicz and Burton 2003). Overall SFM aims to maintain and enhance the long-term health of forest ecosystems for the benefit of all living things while providing environmental, economic, social and cultural opportunities for present and future generations.

Canada adopted the principle of sustainability in 1992, developing a framework of measuring SFM through criteria and indicators (CCFM 2000). Criterion is a category of conditions or processes, which SFM may assess, and the indicator is the measure of the criterion (MPWG 1999). Several indicators are specified for each criterion and are quantitative or qualitative variables that can be measured or described, and when monitored periodically demonstrates trends (MPWG 1999). In Canada, six criteria have been developed, one of which is the conservation of soil and water resources. The primary reason for soil conservation is to guarantee long-term forest productivity, provide potable water for human and wildlife use, and to provide suitable habitats for many other organisms (Adamowicz and Burton 2003). An evolving method for measuring soil conservation and productivity is the use of soil quality indicators.

0.6 Soil Quality Indicators

The concept of soil quality includes assessment of soil properties and processes as they relate to the ability of soil to function effectively as a component of a healthy ecosystem (Schoenholtz *et al.* 2000). Soil function is defined in terms of physical, chemical and biological properties and processes and measured against some definable standard to determine whether a soil is being improved or degraded (Karlen *et al.* 1997). There is seldom a one-to-one relationship between an indicator and soil function. Typically, a given function (e.g. sustain biological productivity) is supported by a number of soil attributes, while any given soil property or process may be relevant to several soil attributes and/or soil functions simultaneously (Harris *et al.* 1996; Burger and Kelting 1999). Due to the dynamic nature of soil, indicators often represent many soil functions. For example organic matter plays a role in most soil functions and is commonly recognized as one of the key chemical parameters of soil quality. Soil organic matter is important to maintaining site productivity by contributing to gas exchange, moisture retention, soil structure and nutrient release and availability (Powers 1990; Henderson 1995; Prescott *et al.* 2000). Previous studies on non-organic forest soils have used organic matter as an indicator of soil organic carbon status (Karlen and Stott 1994), chemical indicator (Burger and Kelting 1999), and index of site fertility (Zutter *et al.* 1997). However, its use in organic soils of boreal black spruce forests has not been explored.

0.7 Black Spruce Harvesting in Québec

With increasing pressure on the forestry industry to assure current management practices are sustainable in the long-term, the Québec Forest Protection Strategy (Government of Québec 1994) introduced harvesting with protection of advance regeneration "coupe avec protection de la régénération et du sol" (CPRS), or careful logging to black spruce feathermoss forests. Careful logging is designed to protect advance tree regeneration and the soil organic horizons by restricting harvesting equipment to 33% of the cut over area (Government of Québec 1994). Harvesting machinery is limited to parallel trails separated by harvested "protection strips" (10-15 m). Seedlings and saplings are left to provide a future seed and layering source for natural regeneration, thus maintaining genetic diversity and reducing artificial regeneration costs after harvesting (Government of Québec1994).

Careful logging creates a mosaic of disturbed and relatively undisturbed zones in the cutover resulting in two different environments for vegetation development after harvesting. Studies have found that, in some cases, the machinery trails were exposed to severe soil compaction and rutting (Brais and Camiré 1998). Following harvesting the machine trails favour pioneer species, "invaders" and "evaders" such as grasses, sedges and raspberry and consisted of fewer and shorter softwood stems (Harvey and Brais 2002). Furthermore, where advance regeneration was lacking, the living feathermoss layer was left intact but discoloured, very dry and susceptible to temperature extremes (Smith *et al.* 2000).

0.8 Research Perspectives

Forest management is evolving from focusing on long-term biomass productivity to managing stands to assure sustainability in a broad sense, securing productivity and vitality, safeguarding biodiversity and protecting adjacent ecosystems for today and future generations. The introduction of careful logging as a sustainable forest management practice in Québec raises concerns for stand structure, growth, and yield (Morin and Gagnon 1991; Lussier *et al.* 1992; Groot and Horton 1994) for future rotations. Considering a substantial proportion of nutrient capital of the site may be located in humus it may be used as an indicator of nutrient availability and long-term productivity. Previous studies (Fyles *et al.* 1991; Wilson *et al.* 2001) demonstrated organic matter types differing in morphological and (or) ecological characteristics differ in their N mineralization and nutrient regime. This suggests that visual assessment of humus forms, particularly after careful logging, may provide insight into site nutrient status.

The objectives of this study were *(i)* to develop a field observable humus classification based on field characteristics and determine nutrient concentrations of the humus horizons *(ii)* determine a method for operational field nutrient mass estimation and *(iii)* correlate nutritional characters with seedling growth. Hence, the first chapter will focus on the determination and effectiveness of an observable classification system, while the second chapter will examine nutritional differences among the humus types and seeding growth following careful logging.

CHAPTER 1

Development of a Field-observable Humus Horizon Classification for Boreal Black Spruce-Feathermoss Forests in Northwestern Québec

1.1 Introduction

Black spruce (*Picea mariana*) feathermoss communities are a major subtype of Canada's northern boreal forest. Low annual temperatures, inputs of recalcitrant litter and short growing seasons result in slow decomposition rates and large accumulations of organic matter, often referred to as humus. Management of surface organic matter is important for forest sustainability and long-term site productivity as it represents a key source of nutrient capital, contributes to moisture retention, soil structure and is essential for soil microflora and microfauna (Harvey *et al.* 1987; Prescott *et al.* 2000).

In the early 1990's the Québec Forest Protection Strategy (Government of Québec1994) introduced harvesting with protection of advance regeneration ("coupe avec protection de la régénération et du sol"), or "careful logging" to black spruce feathermoss sites in an effort to reduce soil disturbance. Essentially, harvesting equipment is limited to parallel trails separated by harvested "protection strips" (10-15 m) and decreases soil disturbance to less than 33% of the cut over area (Government of Québec1994). However, this creates a mosaic of disturbed and relatively undisturbed zones in the cutover.

The concept of sustainable forestry is continually evolving, and it is necessary to measure and monitor the effects of silviculture for the process of adaptive management. Careful logging has been evaluated in terms of vegetation dynamics (Nguyen-Xuan *et al.* 2000; Harvey and Brais 2002), site conditions (Brais and Camiré 1998) and nutrient dynamics relative to natural disturbance (Smith *et al.* 1998; Smith *et al.* 2000). However, little research has been directed at determining the effect of careful logging on humus nutrient status.

The classification of humus horizons using observable field features would provide a useful indicator for estimating the nutritional status and potential productivity of forest sites. The use of organic matter as an indicator of soil productivity has been evaluated (Karlen and Stott 1994; Zutter *et al.* 1997; Burger and Kelting 1999) in terms of soil organic carbon on non-organic soils. However, on organic soils, visual features distinguishing differences in organic materials could be employed to evaluate soil productivity. Fyles *et al.* (1991) demonstrated that organic matter types differing in morphological and (or) ecological characteristics differ in their N mineralization. It should be possible, therefore, to determine the nutrient status of organic horizons based on their visual differences. The objectives of this study were: *(i)* to develop an organic matter classification scheme based on observable field characteristics and *(ii)* determine whether field-observable differences in the organic horizons can account for differences in nutrient concentrations.

1.2 Materials and Methods

1.2.1 Site Description

The study sites were located in northwestern Abitibi-Témiscamingue, Québec, Canada (49°37' N; and 79°00' W) within the northern clay belt region of the boreal forest. The region is characterized by fine textured glacio-lacustrine deposits and flat topography (Robitaille and Saucier 1998) with predominately Dystric Brunisols (Simard *et al.* 2001). During the summer of 2002 a survey of accessible CPRS sites located within the black spruce zone of the boreal forest (Rowe 1972) were examined. Six study sites were selected based on year of harvest, mineral soil type, tree species age and density prior to harvesting, and proximity each site to one another. The selected six sites were dominated by black spruce (*Picea mariana*) with a pre-harvest age of 120 yr and density of 1 000 to 1 200 trees per hectare. All 6 sites were winter CPRS harvested in April of 1997, with harvesters and cable skidders. The logs were transported in December-January of 1997-98. Reforestation took place on three (CPRS-P) of the 6 sites in 1998 with spruce seedlings aged 1.5 yr planted to a density of 2 100 per hectare to ensure sufficient stocking for the next rotation, with an anticipated rotation time of 75-100 yr. The other 3 sites (CPRS-N) were not reforested, and have the same anticipated rotation time as the CPRS-P sites. The dominate distinction between the two site types were CPRS-P were typically drying, low water table and dominated with seedling advance regeneration; CPRS-N were moister, higher water table with seedling to mature advance black spruce regeneration.

The forest floor was dominated by feathermoss (*Polytrichum* spp., *Hylocomium splendens*, and *Pleurozium schreberi*) with sparse patches of sphagnum mosses (*Sphagnum* spp.) and few lichen (*Cladina* spp.). The dominant shrubs were *Kalmia angustifolia, Ledum groenlandicum*, and *Vaccinium angustifolium.*

1.2.2 Development of Classification

The framework of the classification was based on existing classifications for North America. The horizon designations S, F, H follow the Canadian System of Soil Classification (SCWG 1987), with capital letter representing master organic horizons at various stages of decomposition and lowercase letters (eg. l, d, c) representing differentiation within the master organic horizon (SCWG 1987). Humus form description and methodology was based on Green *et al.* (1993) development of a taxonomic classification of humus forms.

1.2.3 Field Sampling

In all CPRS-P and CPRS-N sites, a 0.8 ha plot was established with two 250 m transects intersecting at the centre of the plot. The two transects crossed at 45° angles to the machine and protection strips to ensure no bias of sampling. Seventy-five 1m^2 subplots were randomly located on the two transects, for a total survey of 450 soil pits (6 x 75). The survey of the soil pits determined the 7 horizon classes and 24 replicates (total n = 168) of each horizon class were sampled volumetrically and air dried prior to laboratory analysis. The 24 replicates were modal types from each of the 6 sites. Methods for individual organic matter horizon assessment consisted of describing thickness, boundary shape, moisture status, colour, fabric, consistence, character, roots (abundance, size, and orientation), non-conforming material, and soil biota (Luttmerding *et al.* 1990; Green *et al.* 1993).

1.2.4 Horizon Nutrient Analysis

Ground organic horizon samples were analyzed for: pH (20:1, H_2O:OM horizon) (Hendershot *et al.* 1993b), extractable Ca, Mg, K, Na, Mn, Fe, Al and Zn using the $BaCl_2$ extraction method (Hendershot *et al.* 1993a), and total N, P, K, Ca and Mg by wet digestion (Parkinson and Allen 1975). Concentrations of extractable Ca, Mg, K, Na, Mn, Fe, Al, Zn and total K, Ca and Mg were determined using a Perkin-Elmer 2380 Atomic Absorption Spectrophotometer. Total N and P were determined colorimetrically using a

Lachat QuickChem FIA+ 8000 auto analyzer. Organic carbon was determined using the wet oxidation-redox titration method (Tiessen and Moir 1993).

Potentially-mineralizable N (NH_4^+, NO_3^-) was measured using an aerobic incubation technique adapted from Hart et al. (1994). Two grams of ground OM horizon samples were moistened to 70% field capacity in plastic jars and incubated for 28d at 22°C in the dark. The ammonium and nitrate concentrations of non-incubated subsamples and incubated samples were extracted with 1N KCl and determined with a Lachat QuickChem FIA+ 8000 auto analyzer. Potentially-mineralizable N was determined as the concentration of NH_4^+ and NO_3^- in incubated samples minus the concentration of NH_4^+ and NO_3^- in non-incubated samples. Net nitrification was calculated as the concentration of NO_3^- in incubated samples minus the concentration of NO_3^- in non-incubated samples.

Microbial basal respiration was measured on 3 g of ground organic matter placed in 75 ml plastic jars, moistened to 70% field capacity and sealed with a polyethylene plastic film. Samples were incubated for 10 days, in the dark at a constant temperature of 22°C. After the incubation, the headspace in the container was flushed with ambient air for 1 minute using an aquarium pump and sealed for 1 hour with a lid equipped with a rubber septum. A 3cc air sample of the gas accumulated during the 1 hour was removed from the headspace using a syringe inserted through the septum stopper. CO_2 was measured using a Hewlett Packard 5890-II gas chromatograph equipped with a Poropak Q column and thermal conductivity detector to determine the CO_2 concentration of the air sample.

1.2.5 Data Analyses

Transformations were performed on all humus horizon variables to create frequency distributions close to normal curve of errors. Data for each variable (z) were submitted to the following transformations: ln(z), and (z^{λ}-1) where λ varied between –5 and 5 by steps of 0.25 using the Box and Cox method (1964) performed in MATLAB (2002). Soil variables were standardized following data transformation to account for differences in soil variable units. Analysis of variance was performed on all variables using the *SAS System* (SAS 1992) and means were compared using the Tukey multiple range test.

Canonical discriminant analysis (CDA) was used to distinguish organic matter horizon classes and was performed with the CANDISC procedure of the *SAS System*. Canonical discriminant analysis is a dimension-reduction technique used to classify observations into known groups, in this case horizon categories, on the basis of soil variables, by identifying the contribution of each soil variable to the separation of the horizons (Rencher 1995). The CDA creates linear combinations of the soil variables that have the highest possible multiple correlation with the horizon groups (SAS 1992), the maximal multiple correlation is called the first canonical discriminant function (CDF). The second CDF is obtained by finding linear combination uncorrelated with the first CDF, and this process continues until the number of CDF equals the number of horizons minus one.

1.3 Results

1.3.1 Classification of Humus Horizon Types

Three master upland organic matter horizons, S, F, and H were observed in the field. Classification descriptors are listed in Appendix A. The S horizon comprised living bryophytes (*Sphagnum* spp. and feathermoss), included suspended litter, predominantly conifer needles and fine residues from harvesting. The F horizon consists of partly decomposed plant residues, with an abundance of roots. Plant structures are recognizable as to their origin, with minimal humified organic residues (non-recognizable structures). The H horizon was in advance stages of humification. Humified organic residues contained few recognizable plant structures, and very few roots.

The S horizon was subdivided in three subordinate horizon classes. The Sl (living) consists solely of a layer of living bryophytes, with suspended conifer needles and may be overlain with twigs; Sd (dead) layer of desiccated bryophytes, generally overlain with fine woody material. This surface horizon is visually striking in that it is dark grey to black. Sc (composite) exhibited living as well and dead bryophytes in varying compositions. The F horizon consisted of three subordinate horizons Fs, Fn, and Fc. The Fs (*Sphagnum*) horizon, if present, was directly underlying the Sl horizon of *Sphagnum* mosses. It was columnar in structure and is the yellowish/brown part of the moss where chlorophyll is absent consisting of fascicles on the hanging branches of the bryophyte. The Fn (non-compact) was an F horizon with plant residues aggregated in a non-compact horizontally matted fabric resulting from the profusion of roots and a felty character due to abundance of fungal mycelia. The Fc (compact) horizon consisted of plant residues, including mosses plus litter and fine woody debris, aggregated in a compact matted fabric. Roots were less abundant in the Fc than in Fn, and fungal mycelia was rare. The H horizon was dark black and dominated with humified organic residues and few recognizable plant residues.

1.3.2 Horizon Type Nutrient Concentrations

Humus horizon variables measured in the different horizon types are reported in Table 1.1. The highest concentrations of N_{tot} and P_{tot} were observed in S horizons, and these values decreased in F and H horizons (Table 1.1). K_{ext} and Mn_{ext} decreased from S horizons through to H horizon. The opposite trend was observed with Al_{ext} and Fe_{ext} (S<F<H; Table 1.1). There was no significant difference in Ca_{tot} and Mg_{tot} between the humus horizon classes (Table 1.1). Bulk density levels were highest while organic C and base saturation were lowest in the H horizon (Table 1.1). Basal respiration, an indication of microbial activity, was significantly lower in the H horizon, and increased in the F and S horizons, respectively (Table 1.2). There was no difference in nitrogen mineralization and nitrification between classes (Table 1.2). The N:CO_2-C is the ratio of mineralized N to basal respiration, and was calculated to determine the amount of available N relative to microbial activity. The N:CO_2-C was lower in the S horizons, and increased in the F and H horizons (Table 1.2). Within horizon groups, there was no clear distinction between the S and F subordinate horizons for any of the aforementioned variables (Table 1.1 and 1.2).

1.3.3 Canonical discriminant analysis (CDA)

The CDA extracted five canonical discriminant functions (CDF) but only the first two components were significant (eigenvalues ≤ 1; Table 1.3), these accounted for 82% of the total variation between organic horizons. Since CDA emphasizes sample differences, the total canonical structures (TCS) of variables describe those that account for most of the separation of the individual samples.

The first CDF accounted from 62% of the total variation (Table 1.3) and distinguished S horizons from F and H horizons due, largely to higher concentrations of total and extractable nutrients versus lower FWC and D_b in the S horizons. There was a strong negative correlation with FWC and positive correlation with Mn_{ext} (Table 1.4), demonstrating a moisture gradient in the soil profile. Lower CDF1 values were associated with higher FWC (F and H horizons) and increasing CDF1 values with lower FWC (S horizons; Figure 1.1). However, the first CDF did not distinguish subordinate horizon types within each master horizon (Figure 1.1).

The second CDF accounted for 20% of the total variation within the horizons (Table 1.3). The TCS scores on the second axis determined D_b, K_{ext} and P_{tot} (Table 1.3) as the dominant variables. The second axis separated the F horizon from the H and suggests a decomposition gradient (Figure 1.1). The second CDF did not clearly distinguish within subordinate horizons within any master horizon (Figure 1.1) although Sl horizons tended to have higher values on the second CDF than the other two S subclasses.

H horizon samples fell consistently in the lower left quadrant of the CDF1 and CDF2 space. The biplot suggests a distinction between H samples and the other horizons along a diagonal gradient involving D_b and K_{ext}.

1.4 Discussion

1.4.1 Classification of Organic Horizons

A substantial proportion of nutrient capital is located in the humus, and is of primary importance to the sustainability of long-term site productivity (Romell and Heiberg 1931; Romell 1935; Weetman 1980; Prescott *et al.* 2000). It is, therefore, important to have a method of quantifying humus. A visual classification linked to humus forms in the field, especially following harvest events, to determine the effects on humus nutrient capital. Our survey of black spruce feathermoss forests in northwestern Québec distinguished 7 different humus horizons. Our data shows that the visually different S, F and H horizons had different chemical and biological properties.

1.4.2 Nutrient concentrations of humus horizons

Generally, total and exchangeable nutrients were highest in the S horizons and decreased in the F and H horizons, while the exchangeable metals increased in the H horizons. Our horizon classes demonstrated normal decompositional and profile trends for organic soils. The F and H horizons, which were closer to the mineral soil, had an increasing influence of mineral content (Brady and Weil 1999), while the S horizon dominated by feathermoss accumulated N and P, by acting as a "filtering agent" slowing the downward movement of N and P in the forest floor profile (Weber and Van Cleve 1984; Smith *et al.* 2000). Higher concentrations of exchangeable Mn were found in the H horizon, and is thought to be important in the later phases of decomposition when N is released (Berg 1986). However, the decrease in total and exchangeable nutrients in the lower F and H horizons, excluding exchangeable metals, suggests that nutrient mobilization is faster than decomposition.

Both analysis of variance and CDA suggest that subclasses delineated within horizon classes, while visually different, are nutritionally similar. This suggests that field description is not only practical but adequate at the master horizon level (S, F, H) for nutritional estimation. Canonical discriminant analysis demonstrated that a moisture gradient down the profile distinguished between the S horizons, which had relatively low field water contents and F and H horizons, which had higher field water contents. This is likely an indication of the influence of poor drainage in mineral soil underlying the humus horizons. A gradient reflecting the degree of decomposition distinguished the F and H horizons. Our results show that there are clear distinctions between nutrient concentrations down the profile. However, within each horizon group there is no difference between the subgroups of each master horizon.

1.4.3 Biological properties of humus horizons

Microbial respiration decreased from the S to the H horizons, while the amount of N mineralized per unit of microbial activity (N:CO_2-N) increased. Temperature and moisture levels were at standard levels throughout the aerobic incubations, with moisture content maintained within the typical field range during the growing season. The F and H horizons have been exposed to decomposition processes for the most extended time period and therefore would reflect microbially mediated changes in organic matter quality (Flanagan and Van Cleve 1983), which may account for the lower respiration rates. Nitrogen availability did not differ between horizons in the soil profile, contrasting with

Fyles *et al.* (1990) and Klenk (2001), however the ratio of N mineralized to microbial respiration indicates that in the lower horizons, especially the H horizons, there is more N mineralized per unit of microbial activity. These results indicate inherent differences in the quality of organic matter as a control on microbial activity.

1.5 Conclusion

In the boreal forest, organic matter is important to long-term site productivity and sustainability, by providing a substantial portion of the total nutrient capital. This study has shown that the organic horizons of black spruce-feathermoss forests in northwestern Québec can be classified according to relatively easily observed morphological features. The master horizon classes were distinguished by their nutritional and biochemical attributes. The genesis of the different horizon types appear to be a relatively straight forward process of decomposition, with a gradient from undecomposed moss residues on the surface to humified material at the base of the profile. Horizon class features were perhaps modified by a gradient in moisture regime from driest at the surface to wetter at depth and as well, by contact of the deep horizons with mineral soil. This study suggests that inferences about the nutrient supplying capacity of a site may be made on the basis of field observations and that the classification may present opportunities for operational evaluation of the effects of forest management on forest nutritional conditions.

Table 1.1 Humus horizon chemical characteristics (*z*) and selected transformations; ln (*z*) or the value of λ in $(z^{\lambda} - 1)/\lambda$

Horizon Properties	Abbrev.	Units	Horizon Sl	Sc	Sd	Fs	Fn	Fc	H	Transformation
total N	N_{tot}	mg g^{-1}	8.3 a[1]	8.5 ba	9.0 bac	6.5 bdc	6.7 d	7.0 dc	7.9 a	$\lambda = 0.75$
total P	P_{tot}	mg g^{-1}	0.74 bac	0.67 ba	0.64 a	0.54 d	0.49 dc	0.52 bdc	0.45 bdac	$\lambda = 0.50$
total K	K_{tot}	mg g^{-1}	2.5 a	1.5 ba	1.2 bdc	1.6 bac	0.95 d	0.93 dc	2.4 bda	ln (K)
total Ca	Ca_{tot}	mg g^{-1}	3.9 a	4.3 a	3.8 a	3.3 a	3.9 a	4.4 a	4.8 a	ln (Ca)
total Mg	Mg_{tot}	mg g^{-1}	0.85 a	0.76 a	0.63 a	0.75 a	0.65 a	0.63 a	0.99 a	$\lambda = 0.25$
Extractable K	K_{ext}	mg g^{-1}	2.02 a	0.69 cb	0.58 cb	0.74 b	0.48 c	0.39 c	0.20 d	$\lambda = -0.25$
Extractable Ca	Ca_{ext}	mg g^{-1}	3.23 a	3.34 a	3.17 a	2.93 a	2.84 a	2.82 a	3.40 a	ln (Ca)
Extractable Mg	Mg_{ext}	mg g^{-1}	0.51 ba	0.31 b	0.28 b	0.51 a	0.62 a	0.43 ba	0.56 ba	$\lambda = -0.50$
Extractable Na	Na_{tot}	mg g^{-1}	0.07 ba	0.04 bc	0.04 c	0.07 a	0.06 ba	0.05 bc	0.05 bc	$\lambda = -0.50$
Extractable Al	Al_{tot}	mg g^{-1}	0.10 d	0.11 dc	0.09 dc	0.25 bdc	0.32 ba	0.32 bac	0.67 a	$\lambda = -2$
Extractable Fe	Fe_{ext}	mg g^{-1}	0.04 b	0.05 b	0.04 b	0.12 a	0.14 a	0.13 a	0.18 a	$\lambda = -5$
Extractable Mn	Mn_{ext}	mg g^{-1}	0.39 a	0.40 a	0.39 a	0.15 b	0.11 cb	0.11 cb	0.05 c	$\lambda = -2$
Extractable Zn	Zn_{ext}	mg g^{-1}	0.03 dc	0.04 ba	0.04 a	0.03 bac	0.03 bdac	0.03 bdc	0.02 d	$\lambda = -5$
CEC	CEC	cmol kg^{-1}	29 a	25 a	23 a	25 a	33 a	29 a	33 a	$\lambda = -0.50$
base saturation	BS	%	90 a	88 ba	88 ba	86 ba	78 bc	80 bc	63 c	$\lambda = 5$
organic C		%	36 ba[2]	44 a	37 ba	44 a	45 a	36 ba	27 b	ln (C)
pH			4.3 a	4.4 a	4.3 a	3.9 b	4.0 b	3.9 b	4.5 a	$\lambda = -2$
soil bulk density	D_b	kg m^{-3}	39 c	82 b	71 b	34 c	69 b	62 b	240 a	ln (ρ_b)
field water content	FWC	%	600 c	250 d	210 d	850 ba	840 a	560 bc	680 bac	ln (FWC)

Abbreviations: CEC – cation exchange capacity. Means within a row followed by the same letter are not significantly different ([1]$p < 0.05$, n=24; [2]$p < 0.05$, n=6)

Table 1.2 Humus horizon biological properties (z) and selected transformations; ln (z) or the value of λ in $(z^{\lambda} - 1)/\lambda$

Horizon Properties	Units	Horizon							Transformation
		Sl	Sc	Sd	Fs	Fn	Fc	H	
NO_3-N	$\mu g\ g^{-1}$	0.12 a	0.29 a	0.0 a	0.0 a	0.14 a	0.0 a	0.0 a	$\lambda = 2$
NH_4-N	$\mu g\ g^{-1}$	240 a	249 a	201 a	340 a	270 a	230 a	230 a	$\lambda = 0.50$
basal respiration	$\mu g\ CO_2$-C $g^{-1}\ h^{-1}$	39 cb[2]	77 a	55 b	39 cb	18 ed	28 cd	11 e	$\lambda = 0.25$
N: CO_2-C		6.2 bc[2]	3.2 c	3.7 c	8.7 ba	15 a	8.2 ba	21 a	$\lambda = -5$

[1] Means within a row followed by the same letter are not significantly different ($p < 0.05$, $n = 24$)
[2] ($p < 0.05$, $n = 6$)

Table 1.3 Canonical discriminant functions (CDFs) and their canonical correlations and eigenvalues for humus horizon classes.

CDF	Canonical Correlation	Eigenvalue (proportional, cumulative)
1	0.87	3.1 (0.62, 0.62)
2	0.71	1.0 (0.20, 0.82)
3	0.60	0.57 (0.11, 0.93)
4	0.42	0.21 (0.04, 0.97)
5	0.32	0.11 (0.02, 1.00)

Table 1.4 Total canonical structures (TCS) of the variables used of the first two CDF axis used to differentiate humus horizons.

Variable	**TCS1**	**TCS2**
N_{tot}	0.40	-0.33
P_{tot}	0.23	-0.50
K_{tot}	0.25	-0.30
Ca_{tot}	0.21	-0.18
K_{ext}	0.50	0.56
Mg_{ext}	-0.27	0.31
Na_{ext}	-0.27	0.29
Mn_{ext}	0.78	0.12
Zn_{ext}	0.37	0.17
pH	0.35	-0.50
FWC	-0.70	0.34
D_b	-0.22	-0.64

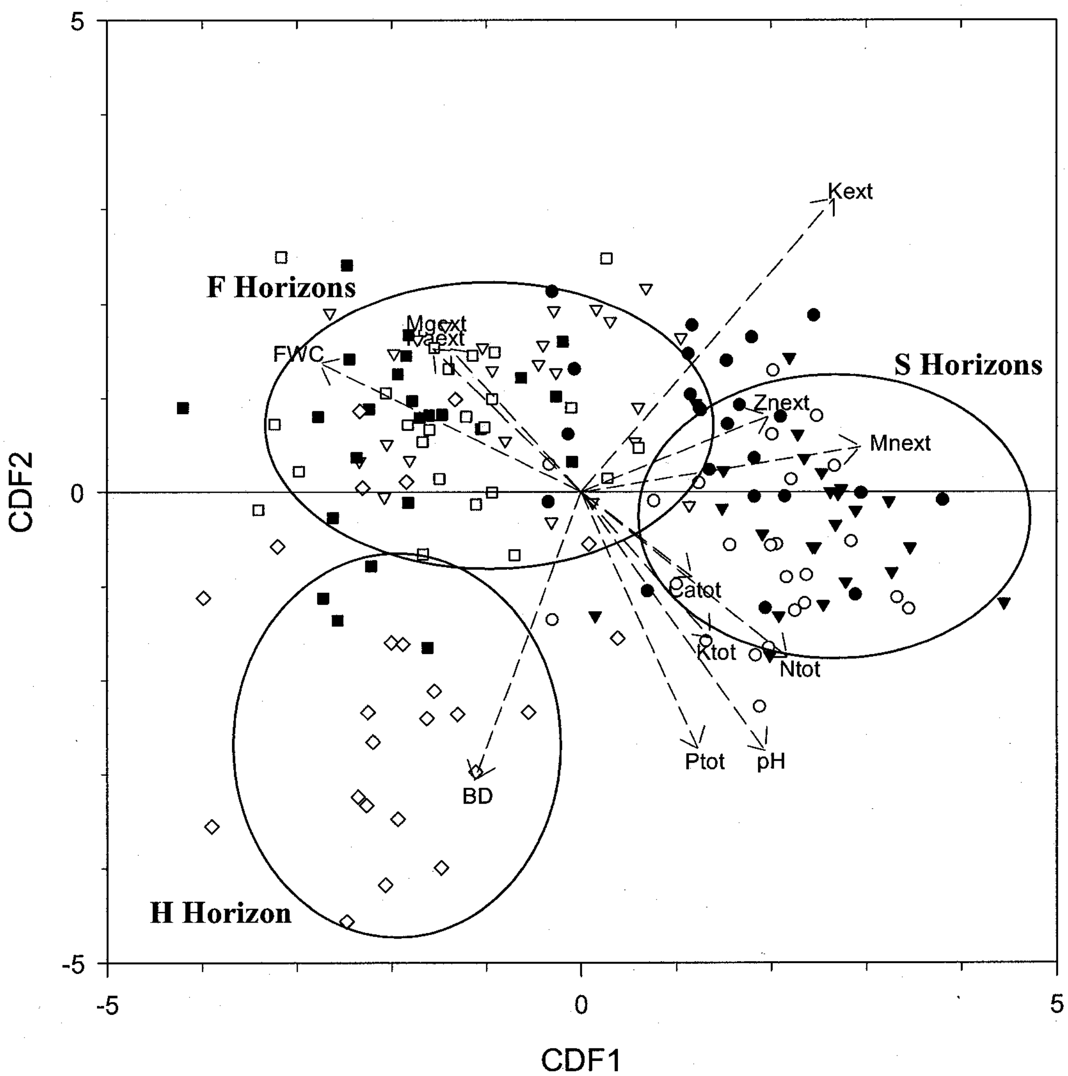

Figure 1.1 CDA biplots of humus horizons with axis descriptors. Where: Sl (○); Sc (●); Sd (▼); Fs (▽); Fc (■); Fn (□); H (◇). $p < 0.0001$.

CONNECTING PARAGRAPH

The first chapter focuses on the development of an observable classification scheme for humus in a black spruce-feathermoss boreal forest of northwestern Québec. The second chapter will look at the effects of careful logging on humus profiles in relation to nutrient availability and spruce advance regeneration.

CHAPTER 2

Humus Forms Following Careful Logging in a Boreal Black Spruce-Feathermoss Forest in Northwestern Québec

2.1 Introduction

The forest floor is an important nutrient source, containing up to 72% of the available soil nutrients (Foster and Morrison 1987) and thus is an important link in the biogeochemical cycling of nutrients in the forest ecosystem (Vesterdal *et al.* 1995). In northern Québec, boreal black spruce (*Picea mariana*) feathermoss communities dominate the landscape. These forests are associated with the growth of a nearly continuous ground cover of *Sphagnum* and feathermoss overlying large accumulations of organic matter or humus.

Humus forms in the boreal forest are typically mor humus. Mor or "raw" humus consists of surface accumulation in three distinct layers; fresh litter (L), partly decomposed but recognizable formultningsskiktet (F) and relatively homogeneous humus (H) (Prescott *et al.* 2000). Identification and classification of humus forms is important for estimating nutrient status and potential long-term productivity, and has been ongoing since the work of P. E. Müller (1879). Recently, Green *et al.* (1993) proposed a classification and methodology for field description of humus forms, which is still being tested in North America. Most field evaluation consists of defining the humus form as a mull, moder or mull as other systems are still too complex. In terms of operational evaluation in the boreal forest it would be beneficial to distinguish different mor humus forms within a site.

In Québec harvesting with protection of advance regeneration "coupe avec protection de la régénération et du sol" (CPRS), or careful logging has been applied to most black spruce feathermoss sites in an effort to prevent soil erosion and reduce costs of artificial regeneration following harvesting. Careful logging is designed to protect advance regeneration and organic soil horizons by restricting harvesting equipment to 33% of the cut over area (Government of Québec1994). Harvesting machinery is limited to parallel trails separated by harvested "protection strips" (10-15 m). Although many studies have been done on the effects of natural and anthropogenic disturbances on organic matter following harvest, no studies have dealt with careful logging.

Due to the nature of careful logging, a mosaic of disturbed and relatively undisturbed zones are created in the cut over. In terms of future stand management it is important to determine what type of organic matter is on site following careful logging. It may be possible, therefore, to use past humus classification methods as a base for developing an observable organic matter classification system as an indicator of nutrient availability. The objectives of this study were to *(i)* determine and classify organic matter profile types following careful logging, *(ii)* determine nutrient availability of each profile type *(iii)* correlate nutritional characters of each profile type with regeneration growth and site disturbance and *(iv)* evaluate relationships between easily observed features and profile nutrient mass to estimate site nutrient status.

2.2 Material and Methods

The classification of humus profile types was performed by using the procedures and horizon classes determined in Chapter 1 from the survey of the 3 CPRS-N and CPRS-P during the 2002 field season (see study sites, horizon classification, field sampling). The spruce growth study was conducted during the 2003 field season on the CPRS-P sites. These reforested sites allowed access to abundant seedlings allowing for sampling of leader growth.

2.2.1 Development of Humus Profile Classification

The framework of the classification was based on existing classifications for North America. The horizon designations S, F, H followed the Canadian System of Soil Classification, where capital letters represent master organic horizons at various stages of decomposition and lowercase letters represent differentiation within the master organic horizon (SCWG 1987). Humus horizon class descriptions were based on Green *et al.*'s (1993) methodology for taxonomic classification. Three master upland humus horizons; S, F, and H were delineated into subordinate horizons; Sl, Sc, Sd, and Fs, Fn, Fc (See Chapter 1). Humus profile types were distinguished by the presence and/or absence of the above-mentioned subordinate horizons. Similar combinations of horizons with different thickness were defined as different humus profiles. Furthermore, order of horizons within the profile was a determinant. Humus profile data was collected from both the CPRS-N and CPRS-P sites.

2.2.2 Disturbance Evaluation

Location of each humus profile type was recorded in relation to degree of disturbance. Disturbance categories were defined as either 1) low, protection strip with very little canopy removal; 2) medium, edges of the machine strip and/or areas with 50% canopy removal; or 3) high, machine strip with 100% canopy removal.

2.2.3 Field Sampling

In each of the 3 CPRS-P sites, a new 0.5 ha site plot was established with two 200 m transects intersecting at the center of the plot. The two transects crossed at 45° angles to the machine and protection strips to ensure no bias of sampling. Forty circular $3.14 m^2$

subplots were established at 10 m intervals on the two 200 m transects. In each subplot the humus profile type was determined and all trees (seedling to mature) were tagged. Species, total height, basal diameter, and leader length (2002) were recorded for each tree. In the late summer of 2003 the leader length (2003) of the tagged trees were recorded. Current and previous year needles were sampled from all black spruce seedlings with a height of 65-70 cm.

2.2.4 Spruce Foliar Total Nutrient Analysis

All black spruce needles were oven dried at 60°C and sorted, removing all damaged and non-needle material. Prior to analysis, black spruce needles were ground with a Wiley Mill to pass a 1mm sieve. Needles were digested for total N, P, K, Ca and Mg (Parkinson and Allen, 1975). Concentrations of total K, Ca and Mg were determined using a Perkin-Elmer 2380 Atomic Absorption Spectrophotometer. Total N and P were determined using a Lachat QuickChem FIA+ 8000 auto analyzer.

2.2.5 Data Calculations and Analysis

Nutrient masses (kg m^{-2}) for each horizon class were calculated by multiplying the horizon concentration (mg g^{-1}) by horizon thickness and bulk density. Humus profile nutrient mass was the sum of all horizon classes present in each respective profile type. Nutrient mass estimations were calculated similarly, except that average horizon class nutrient mass and bulk density measurements were used. The horizon samples used for nutrient mass estimation were different than the samples used to calculate actual nutrient masses. Total leader length per area (cm m^{-2}) was used as an indicator of productivity instead of the basal area increment as sampling occurred once at the end of the growing season in 2003. It was calculated by using the sum of all leader lengths per total area sampled for each humus profile type.

Transformations were performed on all humus horizon variables to create frequency distributions that are as similar as possible to normal curve of errors. Data for each variable (z) were submitted to the following transformations: ln(z), and (z^{λ}-1) where λ varied between –5 and 5 by steps of 0.25 using the Box and Cox method (1964) and performed in MATLAB (2002). Soil variables were standardized following data transformation to account for differences in soil variable units. Analysis of variance was performed on all variables using the *SAS System* (SAS 1992), means were compared using the Tukey multiple range test. Linear regressions and chi squared analysis were performed using the *SAS System* (SAS 1992).

Soil variables that differed significantly between humus profile types were subjected to a principal component analysis (PCA) performed with the PRINCOMP procedure of the *SAS System* (SAS 1992). PCA is a dimension reducing technique allowing the transformation of correlated soil variables (nutrient masses) into a decreased number of uncorrelated variables (principal components). The principal components are linear combinations of maximum variation between observations, where no grouping of observation is assumed. These principal components provide information to understand the role and relationship of soil variables on individual observations (Legendre and Legendre 1998). The first principal component accounts for the largest variability in the data, and each succeeding component accounts for less variability.

2.3 Results

2.3.1 Humus Profile Descriptions

Seven different humus profile types were identified following the survey of the 6 field sites (Table 2.1). Types 1 and 2 had surface horizons of desiccated and fragmented feathermoss. Typically, the surface was dark grey/black overlain with fine woody debris and the profile had one or more relatively thin F horizons and no discernable H horizon. Humus profiles 1 and 2 had lower accumulations of organic matter (Figure 2.1) and consistently low concentrations of roots. Types 3, 4 and 5 had surface horizons of living feathermoss as well as various amounts of the black fragmented feathermoss and patches of *Sphagnum* mosses. Typically, these types had one or more relatively thick F horizons and a thin H horizon, with more accumulated organic matter than types 1 and 2 (Figure 2.1). Types 6 and 7 were associated with microsites of *Sphagnum* moss with relatively thick F and H horizons. Both types 6 and 7 had the deepest profiles of all seven (Figure 2.1). A detailed description of representative profile types can be found in Appendix B.

2.3.2 Humus Profile Nutrient Mass

Nutrient concentrations were similar between horizon types (Chapter 1), therefore horizon and profile thickness was the variable that most affected profile nutrient mass. Types 1 and 2 had the lowest total and extractable nutrient mass, with class 1 being the lowest (Table 2.2). Types 6 and 7 had the highest levels of nutrients and available N, with class 7 (excluding Mn_{ext}), the highest (Table 2.2). Profile types 3, 4 and 5 all behaved similarly, with moderate nutrients levels in comparison to the other classes (Table 2.2). Types 1 and 2 were approximately 6 times lower in nutrient mass relative to type 7 and 2 times lower relative to types 3, 4 and 5. Furthermore, type 1 was 14 times lower in nutrient mass relative to type 7 and 6 times lower relative to types 3, 4 and 5.

2.3.3 Disturbance and Humus Profile Type

Typically the same humus profiles were observed in a similar disturbance zone, suggesting a relationship with disturbance. A chi squared analysis on the frequency of profile types relative to disturbance resulted in a highly significant $X^2 = 113.84$, $p < 0.001$, suggesting a relationship between humus profile type and disturbance (Table 2.3). Eighty-two percent of profile types 1 and 2 were found in the highest disturbance areas, the machine strips (Table 2.3). Generally, profile types 3, 4 and 5 were found in the areas of moderate disturbance 46, 63, and 55%, respectively. Humus types 6 and 7 were associated with low disturbance, with 68 and 71% of all observations being found in low disturbance areas (Table 2.3).

2.3.4 Principal Component Analysis

The PCA derived 14 principal components, however, only the first two components will be interpreted (eigenvalues ≥ 1). The first two PC axes accounted for 79% of the total variation in the observations. The first PCA axis, which accounted for 66 % of the total humus profile type variation, was influenced primarily by the masses of nutrients and reflected the disturbance gradient (Figure 2.2). Increasing values of PCA1 coincided with a transition of high to low disturbances humus types (Figure 2.2). The descriptor coordinates demonstrate a lack of nutrients in the low disturbance categories and an increase in nutrients with decreasing disturbance (Figure 2.2).

The second ordination axis represented 13 % of the total variation and corresponded with a natural nutrient gradient, with increasing PCA2 values associated decreasing contents of base cations (Ca_{ext}, Mg_{ext}, Mn_{ext}) and increasing contents of Al_{ext} and Fe_{ext} (Figure 2.2). Generally, all disturbance categories are situated in the center of the of PCA2 axis.

2.3.5 Humus Profile Nutrient Mass Estimation

Two methods of nutrient mass estimation in humus profile types were tested. The first method summed the nutrient masses for each respective horizon class in each profile type. The second method estimated total nutrient mass on the basis on total profile depth. Regression analysis of both methods demonstrated the first method using the more complex calculations had higher R^2 values for all nutrients than the easier second method (Table 2.4). N_{tot}, P_{tot} and Na_{ext} were estimated well using the first method with R^2 = 0.89, 0.73, and 0.79 respectively. Generally, all estimates using only depth were approximately 14.5% lower that using the first method of classifying humus profile type. N_{tot}, P_{tot} and Na_{ext} were estimated the best with R^2 = 0.50, 0.61, and 0.62, respectively.

2.3.6 Spruce Seedling Growth and Nutrition

At the beginning of the study, spruce seedlings sampled were not statistically different, reducing height as a confounding factor (Table 2.5). Six years after harvest the average basal diameter and leader length were not significantly different between humus types (Table 2.5). Humus types 1 and 2 accounted for 28.6% of the total sampled area but spruce seedling growth in these areas represented 21% of the total leader growth

(Table 2.5). Types 3, 4 and 5 covered 52.3% of the total sample area and accounted for 54.2% of the total leader growth and humus profile types 6 and 7 covered 19% of the total area sampled and accounted for 24.8% of the total leader growth. Generally, there were no differences in total nutrient concentrations for spruce trees growing on the different profile types, however Ntot and K_{tot} foliar concentrations were lower in type 6 and higher in 4 and 5 (Table 2.5).

2.4 Discussion

2.4.1 Surface Classification

Surface horizon classes provided an easily identifiable indicator of which humus profile type may be present. Humus forms are influential in modifying the microclimate of the forest floor, by insulating the soil from extreme temperature and moisture conditions (Pritchett and Fisher 1987), contribute to moisture retention and soil structure and may represent a substantial reservoir of nutrient capital, particularly nitrogen. Profiles 1 and 2 had dark grey/black surface horizons with fragmented dead feathermoss with few ericaceous species or spruce seedlings growing. The feathermoss had been exposed to intense radiation, due to the canopy removal during harvest. On our sites the radiation damage (Busby *et al.* 1978) in conjunction with the severe moisture stress (Skre *et al.* 1983) has most likely resulted in mortality. Feathermoss is important as it intercepts nutrients from dust and precipitation and are known for nitrogen fixation and decompose relatively rapidly providing a source of readily available nutrients for spruce trees (Foster 1985). The mortality of the feathermoss mats may have an impact on nutrient availability in the long-term.

Humus profiles 3, 4 and 5 were found under surface horizons consisting of both dark grey/black and living feathermoss, with rare patches of *Sphagnum*. These profiles were typically in areas with less than 50% overstorey removal and hence favorable conditions for feathermoss growth. This type of canopy removal may, in the long-term, provide moister greener feathermoss cover, as it provides optimal light and throughfall for moss growth (Jeglum 1984).

Humus profile types 6 and 7 had surface horizons of *Sphagnum* moss and were found in microsites where perhaps the underlying moisture conditions were suitable for the colonization of *Sphagnum*. *Sphagnum* has the advantage over feathermoss in that it can grow under a wide range of light conditions as long as there is sufficient moisture. It may be that *Sphagnum* is able to adapt to the new light and moisture conditions following the harvest where as feathermoss, which is more sensitive to light, can not. Furthermore, *Sphagnum* was found in limited abundance on these sites and it is possible that a profile type with highly disturbed *Sphagnum* mats was not observed. However, if this were in fact true, the expected profile type would be different relative to types 1 and 2, which were found under feather mosses.

2.4.2 Humus Profile Nutrient Mass

Both analysis of variance and PCA demonstrated that nutrient mass in humus profile types decreased with increasing site disturbance. Harvesting is known to impact the decomposition of organic matter by the alteration of soil physical and chemical conditions (Prescott *et al.* 2000) and can be controlled by the amount of canopy removal (Armson 1996). Careful logging is known to create gradients of disturbance microsites

(Brais and Camiré 1998; Harvey and Brais 2002); leaving half the site with undisturbed advance regeneration and intact feathermoss layers, and the other half clearcut with compacted and mixed organic horizons (Smith *et al.* 2000). The clearcut strips provide an environment of increased soil temperature and moisture increasing decomposition and nutrient availability in the short term (Covington 1981; Keenan and Kimmins 1993). However, the nutrients are liable to be removed from the system by leaching and runoff during the first few years after harvest (Hornbeck and Kropelin 1982; Prescott *et al.* 2000), potentially reducing site nutrient capital and long-term productivity. Furthermore, Vesterdal *et al.* (1995) reported decreases in nutrient accumulation with increasing thinning intensity. A confounding factor is the mortality of the feather mosses in the machine strips, which apparently results in decreases in nutrient accumulation, while the profiles with living feather mosses and *Sphagnum* continue to grow and accumulate organic mass and, hence nutrients.

2.4.4 Estimation of Humus Profile Nutrient Mass

Two nutrient estimation approaches, (a) sum of individual horizon class nutrient mass using bulk density and horizon thickness and (b) nutrient mass based on total profile depth, were tested. Both methods provided an adequate estimation of nutrients, but the first, more complex, method provided better estimates. Classification of organic matter forms is essential in estimating the nutritional status and potential productivity of forest sites (Green *et al.* 1993). Our classification method provides nutrient estimation that is probably adequate for operational assessment.

2.4.5 Spruce Seedling Growth

There was no difference in seedling growth on different humus profile types, but tree density was lower on higher disturbance profile types. Although we do not know initial seedling density immediately following harvesting, these results suggest that the machine traffic killed pre-existing seedlings and the trees we observed were probably planted. Harvey and Brais (2002) found protection strips were characterized by dense softwood regeneration with a high proportion of native understory species, while machine strips had fewer and shorter softwood stems and a plant community dominated by ruderal species. Nutrient status plays a large role in spruce regeneration and establishment following harvesting (Brumelis and Carleton 1988; Dussart and Payette 2002) with the forest floor representing an important nutrient pool (Krause *et al.* 1978). Mature black spruce rooting habitat many penetrate to 60 cm depending on water table depth, with the bulk of the root biomass in the upper 20 cm (Lieffers and Rothwell 1987; Viereck and Johnston 1990). Typically, the fine roots are spread laterally at the base of the decomposing moss-humus interface. This suggests that while seedling growth during the one year study did not vary, in the long term the available nutrients in the humus profile particularly in the top 20 cm is critical to growth. It is therefore, possible for trees growing in profiles 1 and 2 to have nutrient availability higher or equal to other classes where there is less decomposition but more total profile nutrients and more trees.

2.4.6 Harvesting Effect on Humus Profiles

The data suggest the relationship between disturbance and humus forms within high disturbance areas is vastly different nutritionally and ecologically. Disturbance could be interpreted as creating losses of nutrients from these microsites resulting in significantly different humus forms. Harvesting occurred in the winter and, it therefore seems likely that humus forms would have an equal chance of being affected by and/or found in a machine track. This suggests that profile type 1 and 2 are a result of disturbance. Furthermore, the frequency of these profile types with high disturbance zones also supports this statement. Nevertheless, it may be possible that the dark grey/black surface colour and lack of vegetation found in the high disturbance areas increase soil temperature and moisture resulting in high decomposition. Decomposition rates reported by Moore et al. (1999) at similar latitudes were approximately 30% after 3 years, after seven years we would expect 50% loss of organic mass. It is not unreasonable then, to expect the differences in humus profile depth and available nutrients are a result of different decomposition rates induced by the different microsite conditions created by careful logging. Further research on decomposition and nutrient release in disturbed and undisturbed microsites will be required to test this speculation.

2.5 Conclusion

Harvesting can have a major impact on soil properties and advance regeneration productivity. Humus profiles defined by combinations of field observable horizon classes reflected differences in masses of total and extractable nutrients. Nutrient mass in these humus profiles can be estimated reasonably well by classifying horizons, measuring their thickness and applying nutrient concentration and bulk density values derived previously for each horizon class. More simply, nutrient mass can be estimated from the total thickness of the organic profile. The dominant organic profile classes differed between categories of disturbance suggesting that harvesting or environmental conditions induced by harvesting can modify the organic profile causing a concomitant reduction in profile nutrients. Differences in organic profile type did not affect seedling growth but did affect seedling density and thus total growth per unit area. This, in combination with the relationship between profile type and disturbance suggests that disturbance caused by harvesting may reduce overall stand productivity in the short term due to effects on density and, possibly, in the long-term due to loss of nutrients.

Table 2.1 Description of horizon classes present in each humus profile type and frequency of each profile type (%).

Horizon		**Depth (cm)**	**Class**						
			1	2	3	4	5	6	7
S	Sl	0-6						◆	◆
	Sc	0-5		◆	◆	◆	◆		
	Sd	0-4	◆						
F	Fs	< 9					◆	◆	◆
	Fn	< 11		◆	◆			◆	
		> 11							◆
	Fc	< 10	◆	◆					
		>10			◆	◆	◆		
H	H	< 8				◆	◆		
		> 8						◆	◆
Frequency (%)			15.7	26.7	11.9	18.9	14.3	8.8	3.7

Table 2.2 Chi Squared of humus profile types found in each disturbance category. Frequency distribution is expressed in percentages.

Disturbance	Profile Type						
	1	*2*	*3*	*4*	*5*	*6*	*7*
Low	0	15	23	15	35	68	71
Medium	18	33	46	63	55	32	29
High	82	52	31	22	10	0	0

$X^2 = 114$ with 12 degrees of freedom. ($p < 0.001$)

Table 2.3 Humus profile type characteristics (z) and selected transformations; ln (z) or the value of λ in $(z^{\lambda} - 1)/\lambda$

Profile Properties	Abbrev.	Units	Humus Type 1	2	3	4	5	6	7	Transformation
total N	N_{tot}	kg m^{-2}	50 c	91 c	240 b	250 b[1]	210 b	220 b	410 a	$\lambda = 0.50$
total P	P_{tot}	kg m^{-2}	3.6 c	7.7 c	16 b	20 b	19 b	21 b	35 a	$\lambda = 0.50$
total K	K_{tot}	kg m^{-2}	6.8 d	19 dc	26 bc	43 bac	71 a	61 ba	87 a	$\lambda = 0.25$
total Ca	Ca_{tot}	kg m^{-2}	22 d	39 dc	100 bc	120 ba	170 ba	160 bc	390 a	ln (Ca)
total Mg	Mg_{tot}	kg m^{-2}	3.5 d	7.9 dc	18 bc	18 bc	29 ba	32 ba	66 a	ln (Mg)
extractable K	K_{ext}	kg m^{-2}	2.6 c	8.6 b	13 ba	12 b	10 b	9.3 b	23 a	$\lambda = 0.50$
extractable Ca	Ca_{ext}	kg m^{-2}	18 c	36 bc	65 ba	62 b	111 b	113 ba	160 a	$\lambda = -0.50$
extractable Mg	Mg_{ext}	kg m^{-2}	2.4 d	5.8 c	10 bc	13 bc	13 bc	14 ba	46 a	ln (Mg)
extractable Na	Na_{tot}	kg m^{-2}	0.23 d	0.72 c	1.3 b	1.3 b	1.6 b	1.4 b	3.2 a	$\lambda = 0.50$
extractable Al	Al_{tot}	kg m^{-2}	0.9 b	5.0 ba	6 ba	16 a	17 a	14 a	24 a	$\lambda = 0.25$
extractable Fe	Fe_{ext}	kg m^{-2}	0.44 b	2.8 a	2.4 a	5.0 a	3.8 a	4.0 a	11 a	$\lambda = 0.25$
extractable Mn	Mn_{ext}	kg m^{-2}	1.66 b	3.4 ba	6.5 a	3.1 ba	2.4 b	2.6 ba	3.4 ba	ln (Mn)
extractable Zn	Zn_{ext}	kg m^{-2}	0.26 c	0.5 bc	1.1 a	1.0 ba	0.9 ba	0.5 d	1.5 a	ln (Zn)
NO_3-N		kg m^{-2}	0.0 a	0.0 a	0.0 a	0.0 a	0.01 a	0.0 a	0.02 a	$\lambda = -5$
NH_4-N		kg m^{-2}	1.9 b	3.4 b	9.5 ba	6.6 b	6.3 b	8.1 ba	18 a	$\lambda = 0.25$

[1]Means within a row followed by the same letter are not significantly different ($p < 0.05$, $n = 6$)

Table 2.4 Linear regressions (r^2) of soil nutrient mass (g m^{-2}) estimations for humus profiles. Comparison of the two estimation methods; classification of the humus profile type using horizon class thickness and bulk density or total humus profile depth. Both regressions had a $n = 42$ with $^{*}p < 0.0001$; $^{\dagger}p < 0.005$; $^{\ddagger}p < 0.05$.

R^2	N_{tot}	P_{tot}	K_{tot}	Ca_{tot}	Mg_{tot}	K_{ext}	Ca_{ext}	Mg_{ext}	Na_{ext}	Fe_{ext}	Mn_{ext}	Al_{ext}	Zn_{ext}
horizon & D_b	0.892*	0.733*	0.413*	0.538*	0.595*	0.641*	0.482*	0.529*	0.793*	0.336*	$0.147^{\ddagger}$	0.287*	0.410*
profile depth	0.502*	0.616*	0.376*	0.532*	0.580*	0.438*	0.445*	0.464*	0.629*	$0.193^{\dagger}$	$0.113^{\ddagger}$	$0.114^{\ddagger}$	$0.235^{\dagger}$

Table 2.5 Spruce seedling characteristics (z) and selected transformations; the value of λ in $(z^{\lambda} - 1)/\lambda$

Tree Properties	Units	Class 1	2	3	4	5	6	7	Transformation
total area sampled	m^2	57	41	53	107	41	35	38	
total trees		12	40	38	69	33	35	46	
tree density	trees m^{-2}	0.21 b[1]	0.98 ba	0.71 ba	0.65[1] ba	0.81 ba	1.0 ba	1.2 a	$\lambda = -1.0$
total height	cm	79 a[1]	73 a	64 a	70 a	66 a	71 a	70 a	$\lambda = -1.50$
leader length	cm	21 a[1]	20 a	17 a	21 a	16 a	15 a	15 a	$\lambda = 0.50$
leader growth	cm m^{-2}	4.3 b[1]	14 ba	13 ba	9.9 ba	9.9 ba	11 ba	15.9 a	ln (TT)
basal diameter	cm	6.3 a[1]	5.7 a	5.3 a	6.0 a	6.0 a	6.3 a	5.7 a	$\lambda = 2$
needle weight	g	0.07 a[1]	0.09 a	0.06 a	0.06 a	0.04 a	0.07 a	0.06 a	ln (NW)
needle N	mg g^{-1}	8.4 ba[2]	8.4 ba	8.0 ba	9.4 a	9.2 a	5.7 b	8.0 ba	$\lambda = 1.75$
needle P	mg g^{-1}	1.0 a[2]	1.3 a	1.0 a	1.2 a	1.2 a	0.89 a	1.1 a	$\lambda = 2.25$
needle K	mg g^{-1}	2.5 b[2]	2.7 ba	2.3 b	3.7 a	3.4 ba	2.5 b	2.9 ba	$\lambda = 0.75$
needle Ca	mg g^{-1}	4.2 a[2]	4.4 a	3.8 a	3.1 a	3.6 a	4.1 a	4.2 a	$\lambda = 0.75$
needle Mg	mg g^{-1}	0.48 a[2]	0.68 a	0.60 a	0.54 a	0.60 a	0.67 a	0.59 a	$\lambda = 1.25$
needle Mn	mg g^{-1}	1.4 a[2]	1.4 a	0.98 a	1.2 a	1.1 a	0.84 a	1.2 a	$\lambda = 0.75$

[1] Means within a row followed by the same letter are not significantly different ($p < 0.05$, $n = 6$)

[2] Means within a row followed by the same letter are not significantly ($p < 0.05$, n = 33, 12, 16, 17, 12, 10, 11 for classes 1-7, respectively)

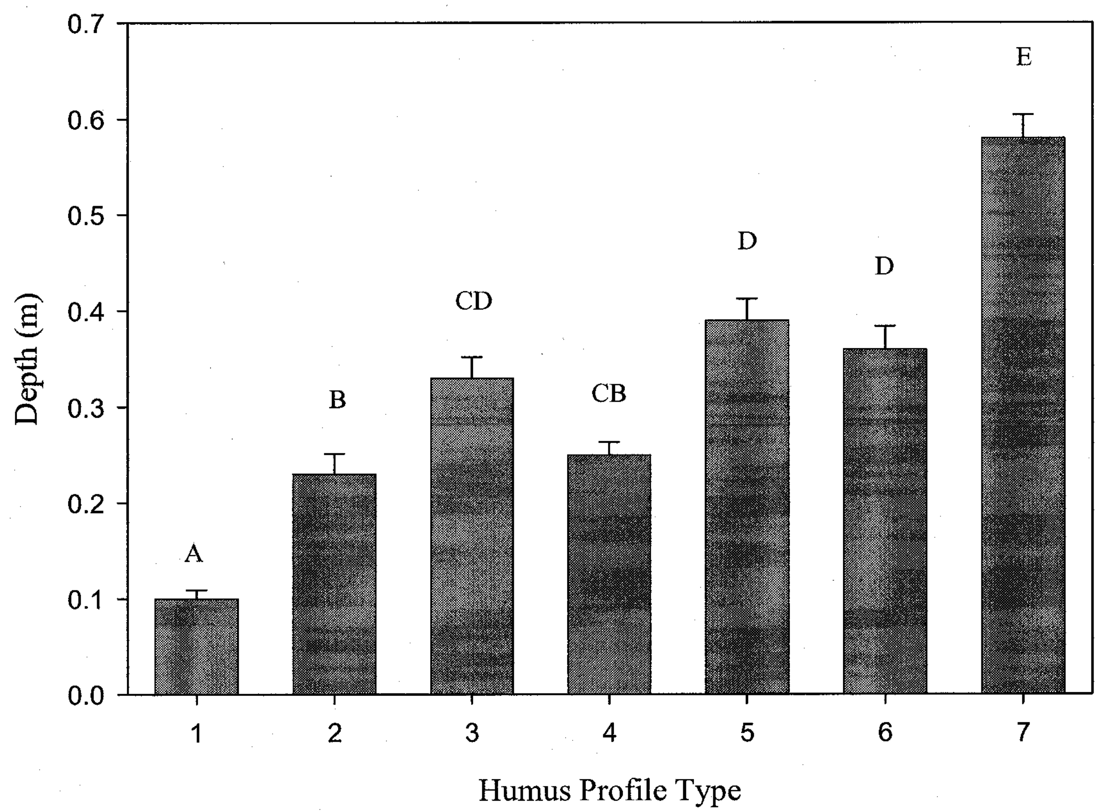

Figure 2.1 Average total depth (m) of humus profile types. (values are means ± SE; significance performed on transformed data ($\lambda = 5$) with different letters indicating significantly different means ($p = 0.05$)

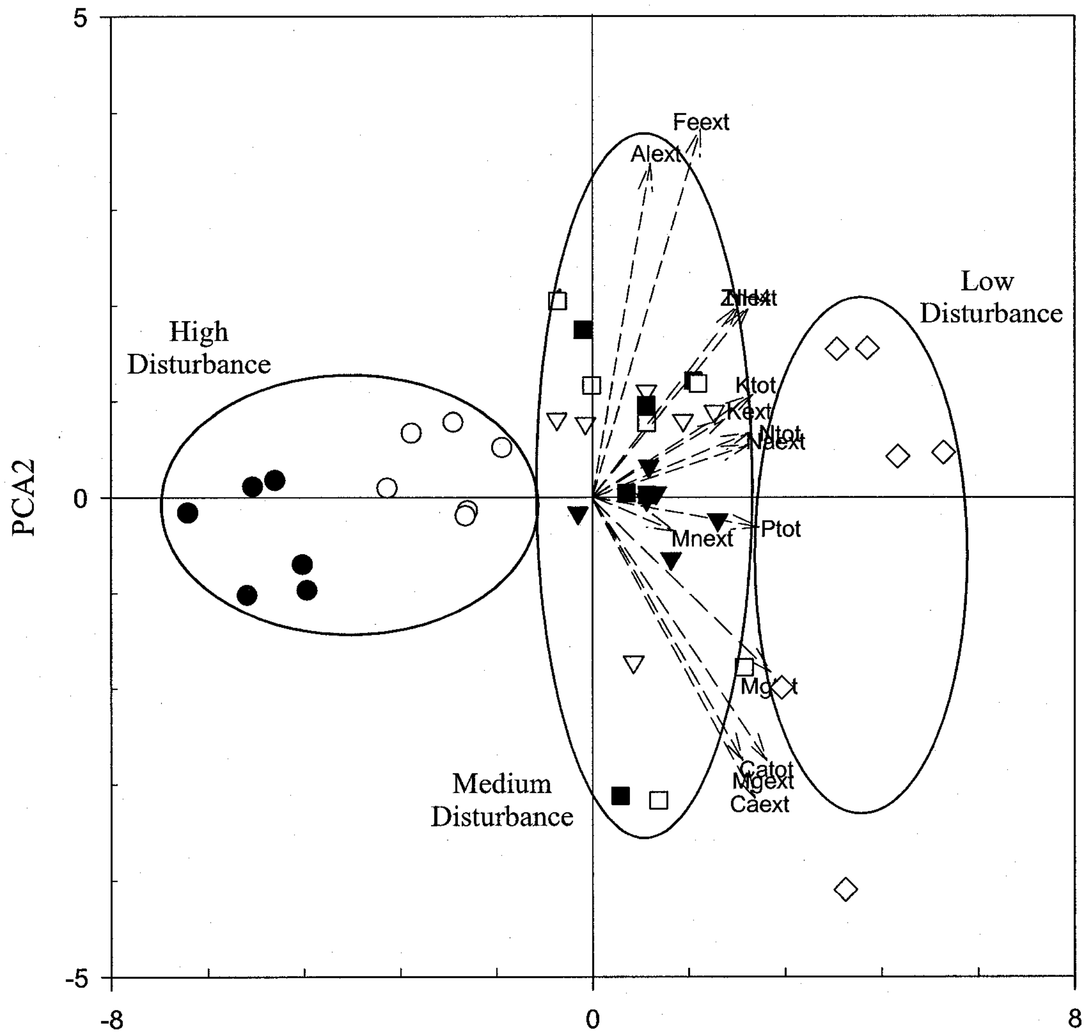

Figure 2.2 PCA biplot of organic classes with axis descriptors PCA1 and PCA2. Where: Class 1 (○); 2 (●); 3 (▼);4 (▽); 5 (■); 6 (□); 7 (◇). $p < 0.0001$.

CONCLUSION

This study has shown that careful logging and/or the environmental conditions induced by harvesting on boreal black spruce-feathermoss forests in northwestern Québec can modify the organic profile causing a concomitant reduction in profile nutrients. There is sufficient data to suggest that there is a significant change in the humus profile types following the harvest. Furthermore, seedling growth density varied with disturbance, creating alternating bands of plant communities reflecting high and low levels of disturbance.

The classification of humus horizons presents an opportunity for evaluation of the effects of forest management on forest nutritional condition. Nutrient mass estimation was reasonable and suggests that operational inferences of the nutrient supplying capacity of a site may be made on the basis of field observations.

Careful logging created heterogeneity in the post-harvest forest floor structure, and was a dominant character in predicting humus profile types. This suggests that in the short term overall stand productivity may be limited due to lower density and possibly in the long-term due to loss of nutrients. However, differences in disturbance strips may attenuate with time.

Further research is necessary to evaluate the long-term effects of the heterogeneity in black spruce stands following harvest. Considering increased decomposition may be a large role in the decreasing organic matter following harvesting, further investigations are necessary. Evaluating the decomposition rates of the dark grey/black fragmented feathermoss surface horizons following harvesting would provide an estimate of the rate and release of nutrients. This would provide a better understanding of the effect of careful logging on nutrient availability following harvesting.

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APPENDICES

Appendix A

Organic matter horizon classification descriptions

Characteristics	Horizons						
	Sl	**Sc**	**Sd**	**Fs**	**Fn**	**Fc**	**Hh**
Thickness (cm)	3-6	3-6	2-5	3-5	20-40	5-20	5-20
Boundary	clear smooth	clear wavy	clear smooth	clear smooth	gradual broken	gradual wavy	clear smooth
Moisture Status	moist	dry	desiccated	moist	wet	wet	moist
Colour	living bryophytes	combination of Sl,Sd	dead bryophytes	yellowish brown	medium brown	dark brown	black
Structure	columnlike errect	varies from Sl, Sd	platelike non-compact matted	columlike errect	platelike compact	platelike compact	structureless massive
Consistence	resilient	friable	friable	loose	firm	firm	pliable
Character	mossy	mix of Sl, Sd	crusty	Mossy	felty	fibrous	greasy
Roots	none	none	none	very few	abundant	abundant	none
Soil flora	none	none	none	none	common	few	none
Soil fauna	none	none	none	none	Few; *Areneida, Acarina*	Few; *Areneida, Acarina*	none

Appendix B
Descriptions of humus form profiles for the seven representative groups

High disturbance classes

Class 1

Horizon	*Depth (cm)*	**Description**
Sd	0-4	Desiccated feathermoss; dry; friable; crusty; conifer needles and overlain with slash.
Fc	5-15	Moist; noncompact matted (in clumps); fibrous; few fine roots.

Class 2

Horizon	*Depth (cm)*	*Description*
Sc	0-5	A layer of living mosses intermixed with desiccated moss; conifer needles and blueberry leaves.
Fs	6-15	Moist; columnlike erect; loose; mossy.
Fc	16-24	Moist; compact matted; firm; felty; abundant, medium roots; common yellow mycelia; few spiders.

Moderate disturbance classes

Class 3

Horizon	*Depth (cm)*	*Description*
Sc	0-5	A layer of living mosses intermixed with common desiccated moss; conifer needles, kalmia and blueberry leaves.
Fc	6-26	Moist; compacted matted, firm; fibrous; plentiful, fine roots; random spiders
Fn	27-38	Moist; slightly compact matted; firm; fibrous; plentiful, medium roots.

Class 4

Horizon	*Depth (cm)*	*Description*
Sc	0-6	A layer of living mosses intermixed with common desiccated mosses; conifer needles
Fc	7-32	Moist; compacted matted; firm; fibrous; common fine roots; common white mycelia.
Hh	33-41	Moist; massive; pliable; greasy; plentiful of roots all sizes.

Class 5

Horizon	*Depth (cm)*	*Description*
Sc	0-4	Desiccated feathermoss intermixed with few living mosses; conifer needles; overlain with common slash;
Fs	5-11	Dry (moister at the bottom); compacted matted (platelike); firm; felty; plentiful, fine roots; common, very coarse roots (surrounding a tree stump).
Fc	12-32	Moist; compact matted; firm; fibrous; few, fine roots.
Hh	33-41	Moist; massive; pliable; greasy.

Low Disturbance Classes

Class 6

Horizon	*Depth (cm)*	*Description*
Sl	0-5	A layer of living mosses.
Fs	6-15	Moist; erect; loose; mossy; few, fine roots.
Fn	16-35	Wet; non-compact; pliable; mushy; very few, fine roots.
Hh	36-44	Wet; massive; pliable; greasy.

Class 7

Horizon	*Depth (cm)*	*Description*
Sl	0-6	A layer of living mosses.
Fs	7-35	Moist; erect; loose; mossy; few, fine roots.
Fn	36-72	Wet; non-compact; pliable; mushy; very few, fine roots.
Hh	73-91	Wet; massive; pliable; greasy.