UNIVERSITY OF ALBERTA

PEATLAND DRAINAGE AND FEN pH EFFECTS ON SOIL NITROGEN MINERALIZATION AND BLACK SPRUCE GROWTH

BY

WILLIAM DAVID HUMPHREY

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ABSTRACT

Effects of ditch drainage in minerotrophic peatlands of central Alberta were investigated. The seven studied fens with paired undrained and drained areas ranged in peat pH from 7.2 to 4.0. The specific organic soil-black spruce responses studied were nitrogen mineralization ($NH4^+$ and $NO3^-$), foliar nutrient status, and stemwood growth.

Net N mineralization (per mass carbon basis) correlated negatively with volumetric water. Post-ditching increases in peat bulk density in some drained areas correlated with increased volumetric water and lower mineral N compared to undrained areas. NO_3^--N correlated positively with volumetric water. No pH or drainage effects on N mineralization occurred but mineral N decreased with depth down to 30 cm. Interactions between pH and drainage and pH and depth were attributed to stage of humification, bulk density, and volumetric water changes following ditching.

Nitrogen and P in current-year needles of black spruce improved with drainage from acutely to moderately deficient and moderately to transitionally deficient respectively. K and Ca remained sufficient. Vector diagrams allowed ranking of micronutrient responses relative to macronutrient responses which were matched to known nutrient class limits. Micronutrient responses were then used to derive their approximate nutrient class limits. Zn and Mn were variable and occasionally deficient. Cu responses indicated acute deficiency at some sites. Correlations between peat content (volume basis) and foliage (content per needle) were found for N, Zn, and Mn.

An initial radial stemwood growth depression in drained areas was followed by increases reaching 360% over undrained areas. Responses climbed for as long as 30 years at one site but levelled off at 10 years on average. Analysis of covariance, using initial basal area as the covariate, and the ratio method were used to analyze radial growth of black sruce. Correlations were found between rate of N mineralization per unit peat volume, mass of N per needle, and stemwood area growth.

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1. INTRODUCTION

This study describes some of the changes induced in the peatlands of Alberta's boreal forest when the local water table is lowered by drainage ditch construction. More specifically, drainage-induced changes in the fertility of organic soil and changes in the growth rate of existing black spruce stands are assessed. Soil and stand responses to drainage are examined from sites varying in soil pH to determine if the relative magnitude of drainage responses relates to site pH.

The economic importance of peatland drainage lies in the potential for enhanced forest productivity in the large areas of boreal wetlands present in Canada's north. Canada contains about 127 million hectares of wetland, of which about 14 percent is considered suitable for drainage. In Alberta about 14 million hectares of wetlands exist with about 4 million suitable for drainage for forestry purposes (Canada Lands Directorate 1986). Nevertheless, peatland drainage for the purpose of increasing forest productivity has only been practiced experimentally in Canada; and in Alberta, only one drainage research site was established prior to 1980. Recent interest in the potential usefulness of peatland drainage has resulted in the establishment of several wetland research sites in northern Alberta during the 1980's (Hillman 1987).

The most prevalent coniferous species growing in Alberta's wetlands are black spruce (*Picea mariana* (Mill.) B. S. P.), and tamarack (*Larix laricina* (DuRoi) K. Koch). Information on the growth responses of these species to drainage is scanty and much work remains to be done before operational drainage can be undertaken. Black spruce was chosen for this study because of its prevalence in Alberta's boreal wetlands and its occurrence over a wider range of site pH levels than tamarack will tolerate.

As wetland drainage and fertilization may be only marginally economical, the ability to predict stemwood growth response and rank sites accordingly would be useful to forest managers. Thus a site parameter correlating with such a ranking would be a useful classification tool. Finnish studies conducted since the 1910's have shown that the two principal factors determining post-drainage tree growth are peatland site type, as determined from the plant communities, and air temperature sum (Heikurainen 1979). Post-drainage tree growth rates varied approximately twofold due to differences in temperature sum when comparing northern to southern areas, and as much as fourfold due to differing site types within areas of similar temperature sum.

In Swedish peatlands a range in plant communities representing bog to rich fen categories was found to correlate with the ionic concentrations and pH of surface water (Sjörs 1952) and peat water (Malmer 1986). Peat decomposition occurred more quickly in rich fens than in bogs (Farrish and Grigal 1988) resulting in greater recirculation of N and P and a higher total N content in rich fens compared to bogs (Malmer 1986). In Canada, Stanek and Jeglum (1977) found a correlation between plant communities and the macronutrient contents of peat, including N, P, K, Ca, and Mg. Thus the pH of surface water or of water expressed from peat provides an indication of the degree of site minerotrophy which may effect nutrient turnover, peat contents of macronutrients, and tree growth response following drainage. Previous work which had varying degrees of success correlating post-drainage tree stand growth with pH and other peat characteristics is discussed by Starr and Westman (1978).

In Alberta, fen pH levels range from less than 3.7 to higher than 7.9 (Vitt et al. 1975, Slack et al. 1980, and Nicholson and Vitt 1990). Given this range of site pH, possible relationships between rate of N mineralization and/or tree growth response to drainage and site pH were questioned.

Nutrient deficiencies occur in boreal wetlands because the peat is inherently nutrient deficient or because mineralization and uptake of nutrients from peat is limited by cold temperatures, acidic conditions, and high water tables (Watt and Heinselman 1965, Lowry 1972, Fox and Van Cleve 1983, Tyrrell and Boerner 1986, Van Cleve and

Yarie 1986 and Yavitt et at. 1987). If these environmental constraints were removed more of the growth potential of black spruce would be realized.

According to Liebig's Law of the Minimum, among soil nutrients, one will be the most limiting, and if that nutrient limitation is alleviated growth rates will improve until the next most limiting nutrient imposes itself. Using similar reasoning, the practice of peatland drainage to increase tree growth is based on the assumption that the high water table imposes the most severe constraint on growth, and that lowering the water table removes that constraint thereby allowing growth to increase until some other limiting factor is imposed. A tree's growth response to drainage is variously attributed to an increase in available rooting volume (Boggie 1977, Sanderson and Armstrong 1980, Strong and LaRoi 1983), an increase in the rate of nutrient mineralization from peat (Williams 1974, Braekke 1987, Williams and Wheatley 1988), and an increase in near-surface rooting temperatures after drainage (Pessi 1958, Lieffers and Rothwell 1987). The interactions of these factors makes it difficult to rank their relative importance in influencing tree growth.

The three major components of this study are assessment of: *i)* nitrogen mineralization rates with depth in organic soils, *ii)* black spruce foliar nutrient levels, and *iii)* black spruce stemwood growth rates. Sampling was designed to detect differences in these three components amongst variable levels of drainage status and site pH. The N mineralization component separetely examines ammonification and nitrification rates. A final, synthesis chapter attempts to elucidate the natural links among the three study components.

Mineralization of N in peat depends upon microbial decomposition of peat which proceeds more rapidly in aerobic conditions than in anaerobic conditions and hence may be expected to occur more rapidly in drained than undrained peat (Williams and Wheatley 1988). Furthermore, since the source of plant-available N in organic soils is almost entirely from mineralization of peat (Dickinson 1983) the rate at which N becomes available for uptake is dependent upon the rate of mineralization. Given this reasoning, the working hypothesis was formed that drained peatlands have greater levels of N availability than natural peatlands.

Foliar analysis is one of the preferred methods of diagnosing nutrient deficiencies. However, our present understanding of the nutritional requirements of black spruce is limited to the results from a small number of studies. Lowry (1972) published figures for foliar nutrients of pole-sized black spruce growing on mineral soils in Ontario but nutritional diagnosis in Alberta is hampered by the lack of previous work in this region. Watt (1966) successfully predicted response of pole-sized black spruce to fertilization using foliar analysis. Watt and Heinselman (1965) and Lowry and Avard (1968) showed that foliar concentrations of N and P can be related to site index on sites with organic soils, and that both N and P limit growth of black spruce.

Little quantitative information is available on the micronutrient requirements of black spruce. Micronutrient deficiencies are not common in mineral forest soils. However, in arable organic soils copper and boron deficiencies are common and occasional deficiencies of other micronutrients are found (Veijalainen 1977). In black spruce, micronutrients in near-deficient concentrations in foliage may be diluted as a result of macronutrient fertilization to a level where deficiency symptoms appear (Smith 1962, Veijalainen 1977).

The expected benefit of peatland drainage is increased forest productivity expressed as increased stemwood growth. This increased productivity may take several years to be realized (Richardson 1981). The stemwood response pattern of black spruce is a depression of radial growth rates for a period of two to three years, followed by a linearly-increasing growth rate for a period of 13-19 years, followed by near-steady growth near the maximum level (Dang and Leiffers 1989).

Given the aforementioned time required for response development, for this study we decided to include only sites which had been drained for at least 10 years. However, only one such long-established research site existed in Alberta (Hillman 1987). Hence most of the sites sampled for this study had undergone incidental drainage, i.e., for a purpose other than research.

The simplest approach to assessing stemwood growth response is to compare growth rates in contiguous drained and undrained areas. However, one of the objectives was to compare growth response amongst sites representing a wide range of pH levels. Sites which met the pH criterion were widely scattered in central Alberta and had been drained in different calendar years. This increased the likelihood that results could be effected by climatic differences. To overcome this problem a relatively new approach to measuring growth response was used (Ballard and Majid 1985).

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2. SITE DESCRIPTION AND SAMPLING DESIGN

2.1 STUDY SITES

In order to investigate peat mineralization rates and long-term stemwood growth response, sites were desired that had already been drained for several years. However, only one such experimental site existed in Alberta (Hillman 1987). As an alternative, sites were chosen that had undergone incidental drainage, i.e., for a purpose other than research at least 10 years prior to the start of the study. During the summer of 1987 eight sites were chosen in central and north-central Alberta (Fig. 2-1) with the assistance of Canadian Forestry Service, Fisons Corporation, University of Alberta, and Alberta Agriculture personnel.

Each site met several stand, soil and drainage criteria. They had sapling to pole size predominantly black spruce stands. Inclusions of tamarack were allowed to a maximum of 20% by stem count. Surface peat layers were at least 50 cm thick. Sites were selected to represent varying degrees of minerotrophy (Sjörs 1952). Two sites from each of the 7.2, 6.6, 5.2, and 4.0 pH levels (Table 2-1), as measured in expressed water from peat in the 10-20 cm depth in the undrained area, were selected.

Each site had part of its area drained for at least 10 years (except Tomahawk which was accepted due to a scarcity of sites at pH 4.0). Ditching dates for Saulteaux, Fort 2, Westlock, Niton, and Tomahawk were estimated from county records of road building activity and the exact year in which construction activity effected water table heights is uncertain. Ditching dates for Fort 1 and Seba were determined from Canadian Forestry Service and Fisons Corporation records respectively. The period since ditching and depth to water table (single measurement in time) are given in Table 2-2. Ditch drainage had occurred either purposely for productivity improvement as at Fort 1 (drained as a demonstration project) and at Seba Beach (drained to facilitate peat harvesting) or for construction of a road with an elevated grade as in the case of all the other sites. Black spruce in the drained portion had an increased radial increment as compared to pre-drainage increment.

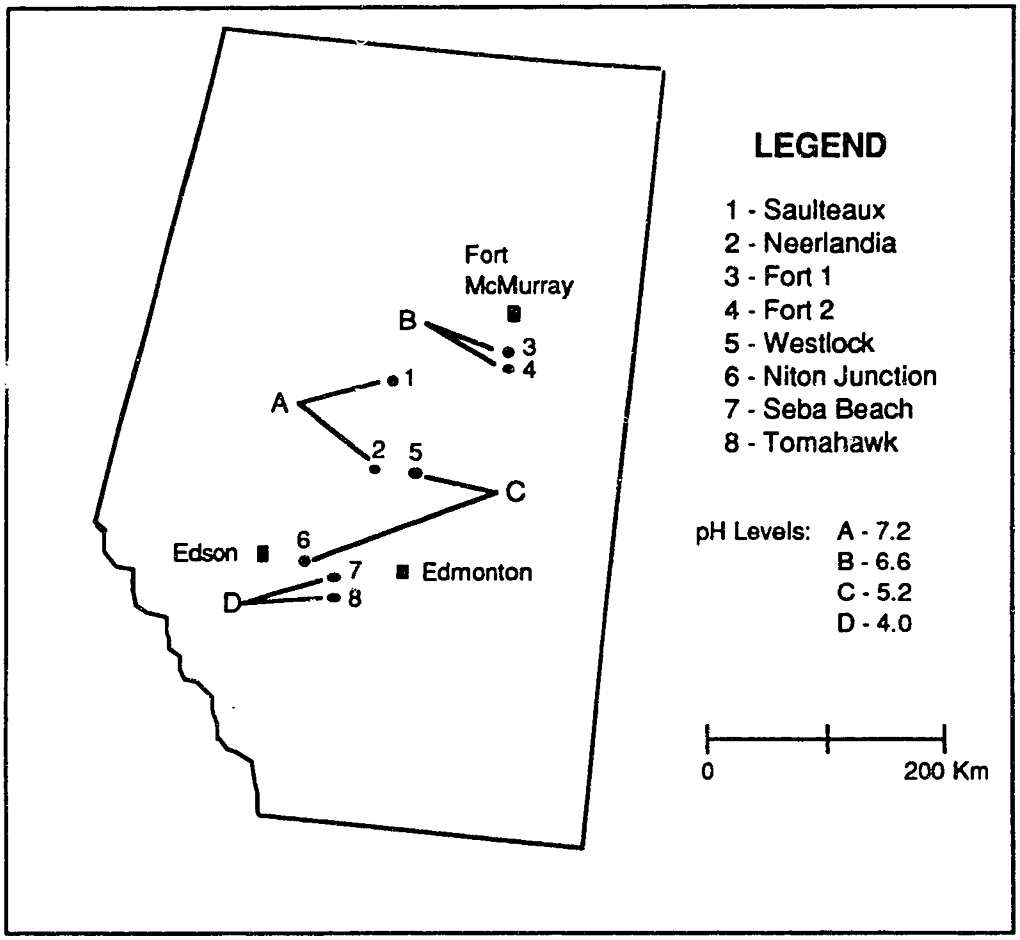

Fig. 2-1. Location of study sites

The Neerlandia site was omitted from the study at the analysis stage because the following evidence indicated the drainage effect extended across the entire site: the water table was below 75 cm depth throughout the entire site, the bulk density (Db) was not significantly different between the assumed undrained and drained areas, and the radial increment at 0.3 m height on boles of black spruce indicated that tree growth accelerated at the same time over the entire site. The Niton Junction site was destroyed by highway construction during the experiments and was omitted from all but the growth analysis

(Chapter 5). Right-of-way clearing took place at Fort 2 during the experiment and the only trees available for foliar sampling were younger (approx. 10 years) than in the undrained area.

Table 2-1. Site description data

Site	Dominant Mosses †	Stand Age (y)§		von Post¶		Peat pH††	Location
		Undrd	Drnd	Undrd	Drnd		
Sault.	*Tomenthypnum nitens* *Sphagnum fuscum* *(Pleurozium schreberi* *Aulacomium palustre)* §§	29	16	2.1	2.4	7.2	55° 5′ Lat. 114° 7′ Long.
Fort 1	*T. nitens, S. fuscum* *(A. palustre* *Campylium stellatum)*	16	11	2.7	4.6	6.6	56° 30′ Lat. 119° 19′ Long.
Fort 2	*P. schreberi, Cladina spp* *(Hylocomium splendens* *Polytrichum strictum)*	21	21	3.9	3.7	6.7	56° 28′ Lat. 111° 19′ Long.
West	*P. schreberi, A. palustre* *(H. splendens)* *(S. fuscum, S. nemoreum)*	10	6	1.8	2.1	5.1	54° 18′ Lat. 113° 46′ Long.
Niton	*P. schreberi* *S. angustifolium* *S. magellanicum*	21	21	2.4	2.6	5.2	53° 37′ Lat. 115° 48′ Long.
Seba	*S. fuscum, P. schreberi* *(P. strictum, T. nitens* *Cladonia)*	60	46	2.7	2.4	3.9	53° 29′ Lat. 114° 50′ Long.
Tom	*S. angustifolium* *S. magellanicum* *S. fuscum*	65	56	3.2	3.3	4.0	53° 23′ Lat. 114° 48′ Long.

† A comprehensive listing of species is in Appendix 2-1.
§ Expressed as age when ditching occurred. Measured at 30 cm bole height (n=10)
¶ Each number represents the mean of 9 samples (3 reps x 3 depths) for the 0-30 cm peat layer according to von Post and Granlund (1925). Individual rep x depth data are in Appendix 2-2.
†† Measured in field in expressed peat water from 10-20 cm depth
§§ Dominant mosses include major species (cover> 20%) and minor species (cover 10 - 20%, in parentheses).

Table 2-2. Depth to water table (cm, n=3) and period since drainage (y) compared among sites and pH levels

Drainage treatment	pH Level and Site						
	7.2	6.6		5.2		4.0	
	Salt	Fort 1	Fort 2	West	Niton	Seba	Tom
Undrained	32 cm	24	38	76	41	40	28
Drained	42 cm	60+	59	71	72	100+	44
Years Drained	21 y	12	21	30	33	12	7

Table 2-3. Peat thickness (cm) and soil classification to subgroup (Anon. 1987) for the drained and undrained areas within the seven study sites

Site	Drained Thickness (cm)	Class.†	Undrained Thickness (cm)	Class.
Saulteaux	120+	Typic Fibrisol	120+	Typic Fibrisol
Fort 1	50	Humic Luvic Gleysol	70	Terric Fibrisol
Fort 2	50	Humic Luvic Gleysol	60	Terric Mesisol
Westlock	80	Terric Fibrisol	80+	Terric Fibrisol
Niton	80	Terric Fibrisol	90	Terric Mesic Fibrisol
Seba Beach	100+	Typic Fibrisol	90+	Typic Fibrisol
Tomahawk	130+	Mesic Fibrisol	100+	Typic Fibrisol

† In some cases peats were not sampled to sufficient depth to allow positive identification. In these cases the assumption was made that the lowest layer sampled continued through the uncertain portion of the control section.

2.2 SAMPLING AND ANALYSIS

In August 1987 sampling transects 100 m in length and parallel to the drainage ditch were established in both the drained and undrained areas. The drained transects were 3-5 m from the drainage ditch, while the undrained transects were 30-35 m from the ditch (Fig. 2-2). The 30 m spacing between drained and undrained sampling transects was considered sufficient distance to avoid any significant influence from the drainage ditch based on ditch spacings used in Finnish drainage operations (Jeglum 1985). Peat, black spruce bole, and spruce foliar samples were collected along these transects for use in their respective studies. The predominant understory vegetation was determined by visually estimating areal coverage of each species found within a 1 m diameter ring placed in a pre-determined location within 2 m of each peat sampling point (Table 2-1 and Appendix 2-1). The von Post method (von Post and Granlund 1925) was used in the field to estimate degree of decomposition of peat from cores obtained with a Macaulay sampler (Table 2-1 and Appendix 2-2). For the purpose of classification, determination of the named layers (fibric, Of; mesic, Om; humic, Oh) was based on equivalencies with values of von Post scale of decomposition (Anon. 1987). The equivalencies were: von Post 1-4 = fibric, 5-6 = mesic, and 7-10 = humic.

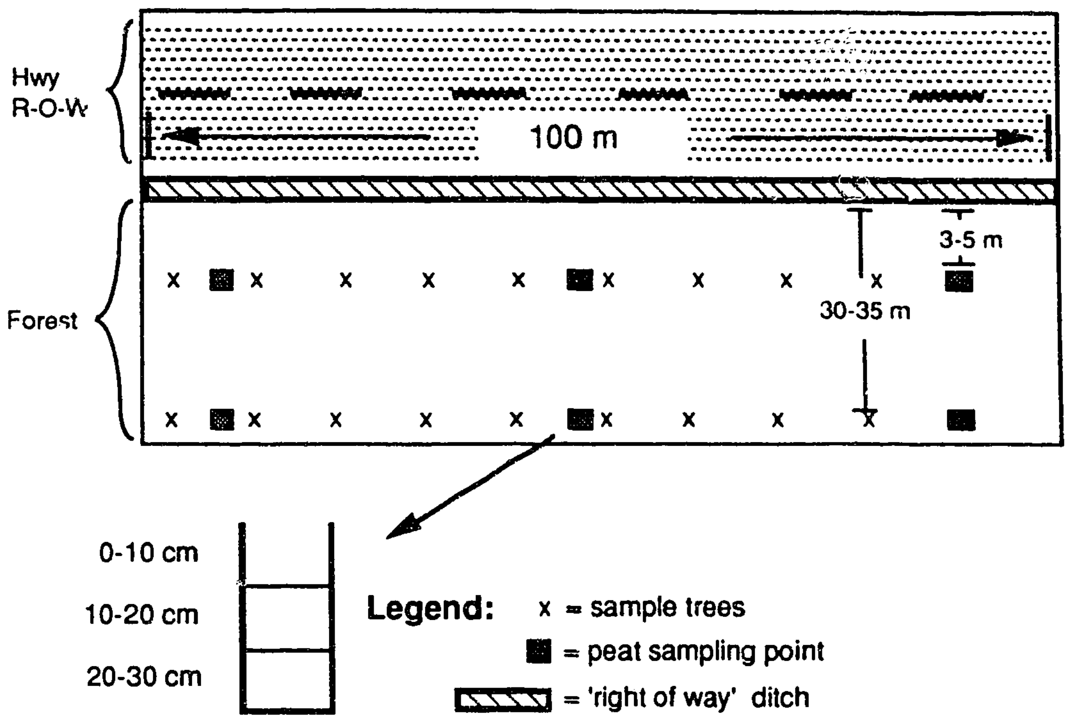

Fig. 2-2. The common sampling layout

Peat samples for bulk density (Db) determination were collected in August 1988 with a box sampler. Depth to water table was measured once in August, 1988 by inserting perforated 5 cm (inside diameter) by 1 m PVC tubes into holes made with a Macualay sampler. A 24 hr period was allowed for equilibration before measurement. At each peat sampling point (Fig. 2-2) Db samples, incubation samples (Chapter 3), and water table measurements were taken within a meter of each other. Samples were collected from nearly level surfaces representative of the average level of the bases of hummocks. Samples were not collected from tops of hummocks or bottoms of hollows. Each sample was a 10 x 10 x 30 cm deep, undisturbed core obtained with a box sampler. The lower limit of live green moss was the datum.

Little information was available regarding the preparation of peat samples for laboratory determination of mineral N content (Chapter 3). The work devoted to developing a reliable homogenization and extraction technique is described in Appendix 2-3.

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3. NITROGEN MINERALIZATION IN UNDRAINED AND DRAINED ORGANIC SOILS OF FENS COMPRISING A pH GRADIENT

3.1 INTRODUCTION

Net N mineralization response to peatland drainage depends largely on the change in peat decomposition rate which depends on environmental and substrate factors. Environmental factors include temperature, aeration, water content, and pH (Williams 1974, Waughman 1980, Fox and Van Cleve 1983, Lieffers 1988). Substrate factors include stage of decomposition of the peat (Williams and Wheatley 1988, Yavitt et al. 1987, Wiklander and Nômmik 1987), nutrient content of the peat (Farrish and Grigal 1988, Damman 1988), and chemistry of the peat solution (Williams and Wheatley 1988). Lowering of the water table should eliminate poor aeration as the foremost limitation to decomposition. However, in oligotrophic peats or in cold environments the improved aeration may have little effect on decomposition rates if nutritional or temperature constraints still inhibit microbial activity. If the next most limiting factor to decomposition after water table height is nutrient availability, differences in decomposition among sites may correspond to differences in pH. In such cases tree growth response following drainage may correlate with site pH.

Nitrification is the biochemical oxidation of NH_4^+ to NO_3^-, and has traditionally been described as being mediated by obligately aerobic chemo-autotrophic bacteria. More recently, the occurrence of nitrification in acidic forest soils was attributed to acid-tolerant heterotrophs (Paul and Clark 1989). Nitrification organisms are affected by environmental conditions such as pH, aeration, and temperature (Paul and Clark 1989). Nitrification can lead to undesirable effects such as leaching and denitrification losses of N, and environmental problems such as eutrophication of waterways and human health problems. For these reasons it was desired to know if nitrification was affected by drainage of peatlands such that nitrate inputs into local streams would increase following drainage.

In relation to the above discussion the following null hypotheses were formed concerning both net N mineralization and nitrification in a boreal peatland (expressed on a m/m and/or a m/v basis): *i)* Lowering the water table with ditching has no effect on the rate of net N mineralization or nitrification, *ii)* Net N mineralization or nitrification do not differ with depth below the surface within the rooting zone of black spruce, *iii)* Peat pH does not effect the response of net N mineralization or nitrification to changes in water table height through drainage.

The objectives were to assess net N mineralization and nitrification rate among: *i)* areas of differing drainage status, *ii)* sites of varying pH, and *iii)* ten centimeter depth increments down to 30 cm (considered the rooting zone of black spruce; Strong and LaRoi 198[illegible]

3.2 MATERIALS AND METHODS

3.2.1 Field Sampling and Incubation

Six study sites were selected and sampled as described in Chapter 2. Three peat sampling points were spaced at 50 m intervals along the transects (Fig. 2.2). Samples were collected from nearly level surfaces representative of the average level of the bases of hummocks. Samples were not collected from tops of hummocks or bottoms of hollows. Each sample was a 10 x 10 x 30 cm deep, undisturbed core obtained with a box sampler. The lower limit of live green moss was the datum. Each core was halved vertically and each half was then divided into a set of three 10 cm depth segments. One set of three depth segments was extracted for pre-incubation mineral-N, while the other set was returned to their respective positions in the peat profile for *in situ* incubation. *In situ* incubation used 1 mil polyethylene bags which permit aerobic incubation while maintaining a constant water content (Bremner and Douglas 1971).

The incubation period was 54 days (July 20 and 21 to September 12 and 13, 1989). In general, in the Boreal Wetland region in Alberta, the annual maximum in organic soil temperature at 10 cm depth occurs in early August (Swanson and Rothwell 1989). At each sampling point two adjacent cores (within one meter) were taken with the box sampler, one for determination of bulk density (Db) and the other for other physical/chemical properties. Peat samples were packed with ice for up to 48 hours during transport and stored frozen (-10° C) for two months prior to analysis.

3.2.2 Laboratory Analysis

Samples were homogenized by hand breaking into pieces of approximately 1-2 cm length prior to sub-sampling. Gravimetric water content was determined by drying sub-samples (approx. 20-50 cm^3) at 105 °C for 24 hours. Volumetric water content (θ) was calculated using gravimetric water content and Db. Total porosity was calculated from Db and a mean particle density of 1.52 Mg m^{-3} (Sherstabetoff 1987). Mineral-N was extracted from 6 g oven-dry equivalent sub-samples of field-moist peat using 180 mL of KCl solution equivalent to 1 M after dilution by the peat water. Shaking for 1 hour was followed by gravity filtration through Whatman No.1 filter paper. The extracts were analyzed for NH_4-N and NO_3-N individually by steam distillation (Bremner and Shaw 1955) using 0.005 N H_2SO_4 as a titrant. Total carbon was determined using a Leco furnace (Model 780-000) employing infra-red absorption. Ash content was determined by loss on ignition in a muffle furnace at 495° C for 16 hr. Total N was determined by semi-micro Kjeldahl digestion (Bremner and Mulvaney 1982) followed by analysis with an auto analyser using a Berthelot (1859) procedure (Technicon Industrial Method # 98-70W). P and K were determined by dry digestion (Zoltai 1988) followed by ICP-AES analysis (Soltanpour et al. 1982).

3.2.3 Data Analysis

Analysis of variance of peat mineral-N results was performed using the GLM procedure in SAS (SAS Institute Inc. 1987). Sites were nested within pH levels, sites were split into drainage treatments and depth levels were crossed with all other factors. The statistical model of the sampling design used (Chapter 2) is:

$$Y_{ijklm} = \mu + \tau_i + \beta_{j(i)} + \gamma_k + \tau\gamma_{ik} + \beta\gamma_{j(i)k} + \varepsilon_{(ijk)l} + \delta_l + \tau\delta_{il} + \beta\delta_{j(i)l} + \gamma\delta_{kl} +$$

$$\tau\gamma\delta_{ikl} + \beta\gamma\delta_{j(i)kl} + \varepsilon_{(ijkl)m} \quad \begin{cases} i=1\ldots4 \\ j=1\ldots2 \\ k=1\ldots2 \\ l=1\ldots3 \\ m=1..3 \end{cases}$$

Where τ_i is the effect of the 'i'th pH level, $\beta_{j(i)}$ is the effect of the 'j'th site within the 'i'th pH level, γ_k is the effect of the 'k'th drainage treatment, and δ_l is the effect of the 'l'th depth level. Analysis of covariance employed the same model except that the term $\phi(x_{ijklm} - \bar{x}_{....})$ was added where ϕ is the regression coefficient of the covariate log10(θ) as an attempt to isolate the effects of volumetric water content (θ) differences during the incubation from differences arising from substrate quality.

The initial analysis of variance identified four cases (two NH_4-N values and two NO_3-N values) which were potential statistical outliers based on the criterion that their standardized residual was greater than three standard deviations (Draper and Smith 1981, Montgomery 1984). The analysis of variance results reported here (Table 3-1 and Appendix 3-3) are for the complete data set including these potential outliers. Where omission of the outliers caused the analysis of variance results to change these changes are noted in the text.

3.3 RESULTS

The original design included a pair of sites nested within each pH level. However, as discussed in Chapter 2, two sites (Neerlandia and Niton Junction) were deleted from the original design resulting in the pH levels 7.2 and 5.2 consisting of one site only (Fig. 2-1), and the error term for testing the pH effects having only two degrees of freedom (Table 3-1). Where the purpose of the discussion is to identify environmental factors effecting N mineralization, total mineral N is reported as a weight percent of the organic carbon present because organic carbon is the substrate which the microorganisms utilize in the mineralization process. Mineral N was reported as a weight percent of total N when substrate effects were being investigated. Mineral N was also expressed on a volumetric basis as this represents the amount of N potentially available to a tree's root system. Total porosity varied little (mean = 95.1% volume, std. dev. = 2.7%; Appendix 3-5) and thus volumetric water content (θ) is essentially the inverse of air-filled porosity. θ is used in place of air-filled porosity for results pertaining to aeration status as θ was measured directly. When mineral N was summarized across treatment levels for purposes of displaying the data, weighted means were calculated by weighting the mineral N $(g\ C)^{-1}$ in each cell with the peat Db in that cell. Appendix 3-5 contains complete data sets for Db, total porosity, ash content, volumetric water content (θ), % C, NH_4-N, NO_3-N, and total mineral N.

3.3.1 pH Effects

Analysis of variance indicated that pH had no significant effect on net NH_4-N or total N (NH_4-N+NO_3-N) mineralization whether expressed on a per unit mass of peat carbon basis or on a volumetric basis (Table 3-1). Analysis of covariance (Appendix 3-3) also indicated that pH had no significant effect on net NH_4-N or total N (NH_4-N+NO_3-N) mineralization.

Table 3-1. Analysis of variance summary for concentration of mineral N on a mass and volume basis from in-situ incubation

SOURCE†	DF	MS	F Ratio	P>F	MS	F Ratio	P>F
		NH_4-N (g C)$^{-1}$			NH_4-N cm^{-3}		
L	3	39040	5.99	0.147	50.22	4.27	0.195
S(L)	2	6521			11.75		
D	1	17423	3.85	0.189	16.92	1.32	0.369
L*D	3	33265	7.34	0.122	8.06	0.63	0.661
S*D(L)	2	4530			12.78		
R(L*S*D)	24	11113			8.71		
P	2	144442	15.88	0.013	76.03	5.16	0.078
L*P	6	48271	5.31	0.064	60.68	4.12	0.096
S*P(L)	4	9095			14.74		
D*P	2	1473	0.09	0.914	2.19	0.11	0.900
L*D*P	6	14279	0.89	0.573	4.84	0.24	0.941
S*D*P(L)	4	16026			20.23		
		NO_3-N (g C)$^{-1}$			NO_3-N cm^{-3}		
L	3	331.4	2.01	0.350	1.977	5.19	0.166
S(L)	2	165.2			0.381		
D	1	687.7	5.39	0.146	5.752	20.32	0.046
L*D	3	826.7	6.48	0.137	3.131	11.06	0.084
S*D(L)	2	127.5			0.283		
R(L*S*D)	24	118.6			0.331		
P	2	206.3	8.61	0.036	0.519	10.87	0.024
L*P	6	109.4	4.57	0.082	0.123	2.58	0.189
S*P(L)	4	24.0			0.047		
D*P	2	76.6	2.48	0.199	0.125	1.57	0.315
L*D*P	6	100.6	3.26	0.136	0.095	1.19	0.454
S*D*P(L)	4	30.9			0.080		
		Total Mineral N (g C)$^{-1}$			Total Mineral N cm^{-3}		
L	3	32178	7.19	0.125	40.36	4.53	0.186
S(L)	2	4473			8.91		
D	1	11405	3.49	0.203	42.95	4.83	0.159
L*D	3	29263	8.96	0.102	4.45	0.50	0.719
S*D(L)	2	3266			8.90		
R(L*S*D)	24	11892			10.51		
P	2	154816	18.51	0.010	82.09	5.91	0.064
L*P	6	45032	5.38	0.063	57.83	4.17	0.094
S*P(L)	4	8365			13.88		
D*P	2	754	0.05	0.956	2.87	0.14	0.877
L*D*P	6	13877	0.84	0.597	4.51	0.21	0.954
S*D*P(L)	4	16523			21.18		

† Where:
L = peat pH level (7.2, 6.6, 5.2, 4.0)
S = sites within pH levels (1 or 2)
D = drainage treatment (undrained or drained)
P = depth level (0-10 cm, 10-20 cm, and 20-30 cm below live moss)

Table 3-2. Weighted means† of mineral N in peat from in situ incubation compared among pH and depth levels and drainage treatments

Levels and Treatments	n	NH_4-N	NO_3-N	Total Min. N	Total Min. N
		ug (g C)$^{-1}$			ug (g N)$^{-1}$
pH 7.2	18	100.6	9.3	109.9	4520
pH 6.6	36	31.8	18.0	49.8	1730
pH 5.2	18	111.6	6.4	118.0	6110
pH 4.0	35	83.1	8.9	92.0	5310
0-10 cm	35	139.6	16.3	155.9	7540
10-20 cm	36	39.9	8.5	48.4	1930
20-30 cm	36	54.3	12.2	66.5	2990
Undrained	53	97.1	7.6	104.7	5460
Drained	54	58.3	14.2	72.4	2940

† Weighted means for mineral N (g C)$^{-1}$ were obtained by multiplying mineral N cell means by corresponding g C cm^{-3} cell means (each cell equals one 'site x drainage x depth' combination; n=3) then dividing by the overall g C cm^{-3} mean of the current treatment level. Mineral N (g N)$^{-1}$ was weighted with the same procedure except corresponding g N cm^{-3} cell means were used as the weighting factor.

Table 3-3. Total mineral N in peat from in situ incubation compared among pH and depth levels and drainage treatments expressed on a per hectare basis

Drainage Treatment	pH Level 7.2	6.6	5.2	4.0
	kg ha^{-1} to 30 cm depth			
Undrained	4.72	5.35	14.79	7.09
Drained	12.91	8.80	17.57	9.01
	Depth Level 0-10 cm	10-20 cm	20-30 cm	0-30 cm
	kg ha^{-1} in each layer			
Undrained	3.64	1.24	2.57	7.45
Drained	5.44	2.15	3.43	11.02

3.3.2 Drainage Effects

Net NH_4-N and total N (NH_4-N+NO_3-N) mineralization per unit mass of peat carbon were lower in the drained than undrained areas (Table 3-2), but total mineral N per unit volume was higher in drained areas (Table 3-3). Analysis of variance (Table 3-1) indicated these differences were not significant. With outliers (p. 17) omitted significant pH by drainage interactions (L*D) for NH_4-N (g C)$^{-1}$ (P=0.084), and total mineral N (g C)$^{-1}$ (P=0.057) occurred.

Volumetric water (θ) was greater in the drained areas of the pH 6.6 and 5.2 levels while the opposite was true at other pH levels (Fig. 3-1). Figure 3-2 illustrates these same pH levels also had significantly ($P < 0.001$) greater ash free Db values in the drained areas. Furthermore, log10(θ), summarized in Appendix 3-1 correlated positively ($r = 0.627$, $P < 0.001$) with the ash-free bulk density (Db) values. This trend can be explained by the relationship between Db and matrix potentials. Peat with a greater Db has a smaller mean pore size such that a higher matric potential (Ψ_m) is produced at equal θ compared to a peat with lower Db (assuming the Ψ_m is more negative than approx. -0.5 kPa as is usually the case above the water table). Conversely, at equal Ψ_m, e.g., field capacity, the peat with the greater Db will contain more water than the peat with the low Db (Boelter 1969). Data for θ and Db (Appendix 3-5) can be used in conjunction with nomograms in Boelter (1969) to show that in approximately 90% of the observations Db and θ were in the range where Db correlated positively with θ given a constant Ψ_m such that higher θ would be present where Db was higher assuming an equal Ψ_m, e.g., field capacity.

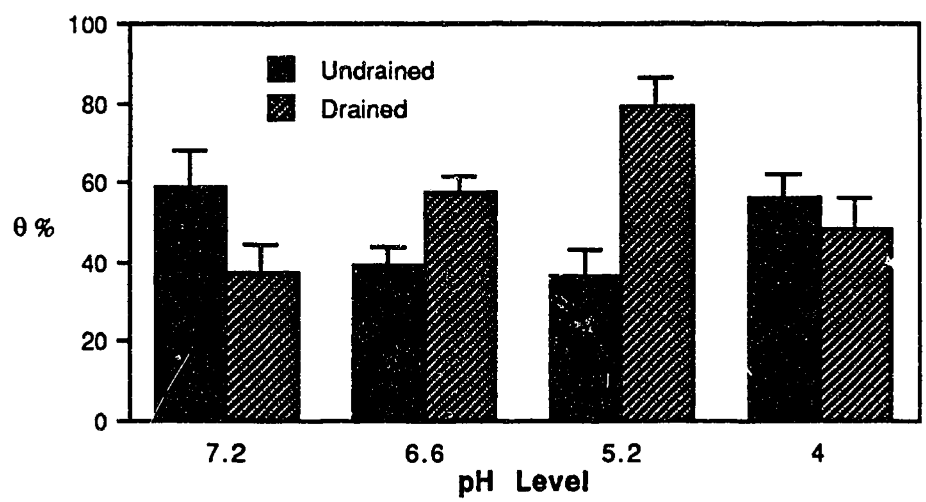

Fig. 3-1. Volumetric water content in the upper 30 cm of peat compared among pH levels and drainage treatments (SE bars)

At 3 of the 4 pH levels, net N mineralization was greater in the treatment with lower θ (Fig. 3-1 and 3-3). Only the pH 4.0 level opposed this trend and the differences in θ and N mineralization were both insignificant at this pH level. Furthermore, a simple regression of total mineral N against log10(θ) revealed a negative correlation with $r = -0.418$ and $P < 0.001$ (Fig. 3-4). It was thus reasoned that the influence of water content was inappropriately modelled with the use of drainage categories, and that the representaton of water by log10(θ) as a continuous variable would be a more realistic approach to assessing the influence of θ on mineralization.

Log 10(θ) was used as a covariate to isolate the effect of water content on N mineralization. Log10(θ) was preferred over θ because inspection of the data revealed that the slope of net N mineralization rate on θ lessened as θ increased, and that correlation between θ and net mineral N improved when θ was transformed logarithmically. The use of log10(θ) as a covariate may isolate effects of water content on net N mineralization, but does not account for substrate differences such as peat Db and stage of decompositon between drainage treatments. To account for these possible differences, the drainage categories were retained in the statistical model along with the covariate. The analysis of variance produced by the covariate model (Appendix 3-3) was similar to the non-covariate model except that the pH by drainage interaction (L*D) was no longer bordering on significant for total mineral N (P=0.171).

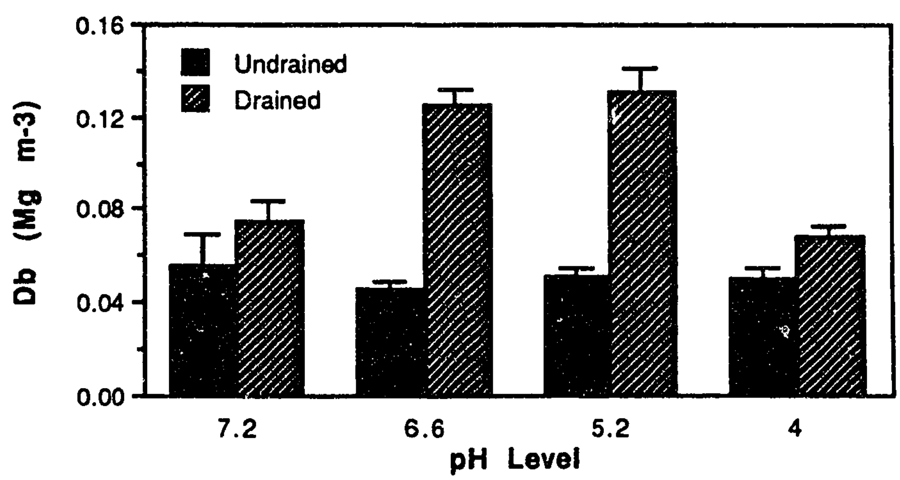

Fig. 3-2. Average peat bulk densities for 0-30 cm compared among pH and drainage treatments (n=108, SE bars)

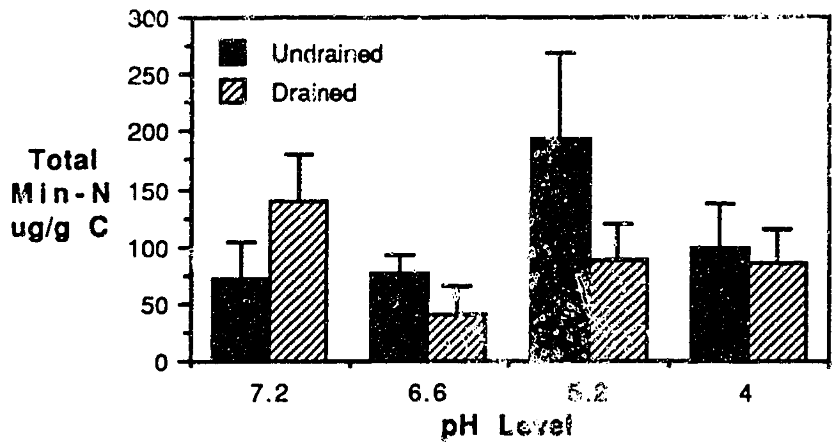

Fig. 3-3. Weighted means of total mineralized nitrogen compared among pH levels and drainage treatments (n=107, SE bars). Weighted means for mineral N $(g\ C)^{-1}$ were obtained by multiplying mineral N cell means by corresponding $g\ C\ cm^{-3}$ cell means (a cell is one 'site x drainage x depth' combination; n=3) then dividing by the overall $g\ C\ cm^{-3}$ mean of the current treatment level.

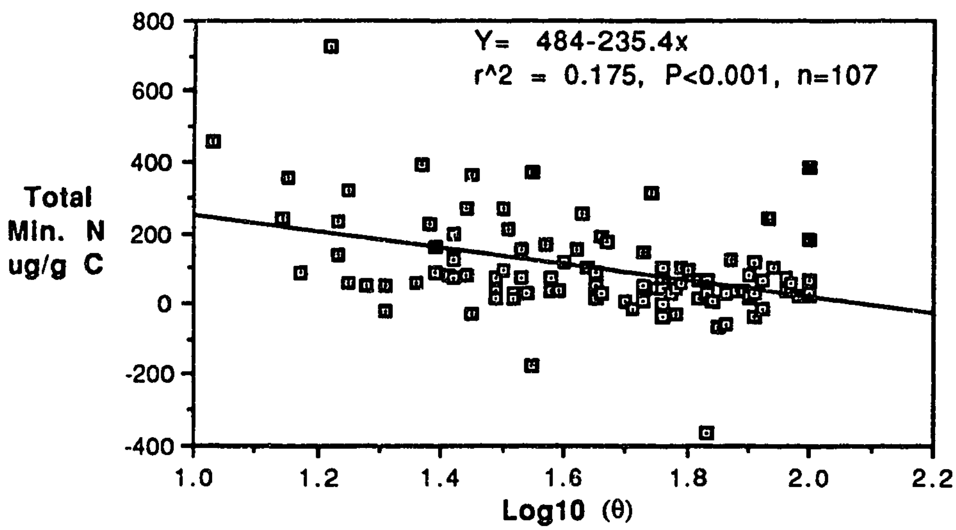

Fig. 3-4. Relationship between nitrogen mineralized during in situ incubation and the log of volumetric water content (θ)

3.3.3 Depth Effects

The analysis of variance (Table 3-1) reveals a significant depth effect on NH_4-N (P= 0.013) and total mineral N (P= 0.010). When log10(θ) was included in the statistical model (Appendix 3-3), depth became borderline significant (P=0.057) for total mineral N. Total mineral N (g C)$^{-1}$ and mineral N per unit volume were greatest in the 0-10 cm layer and lowest in the 10-20 cm layer (Tables 3-2 and 3-3). When potential outliers (the four described in Section 3-2) were omitted, mineral N (g C)$^{-1}$ in the 20-30 cm layer was slightly lower than the 10-20 cm layer.

When total N mineralization is compared across depth levels, the effects of variable θ (or the assumed inverse to θ, air-filled porosity) are confounded with other effects such as variable substrate characteristics or temperatures. Inclusion of log10(θ) as a covariate in the statistical model removes the θ effect such that these other effects can be detected. A pH x depth interaction (P=0.063) was found for total mineral N (Table 3-1, Fig. 3-5). This interaction was unchanged by analysis of covariance with θ (Appendix 3-3) or by omission of potential outlier cases, providing further evidence of other influences besides θ on N mineralization.

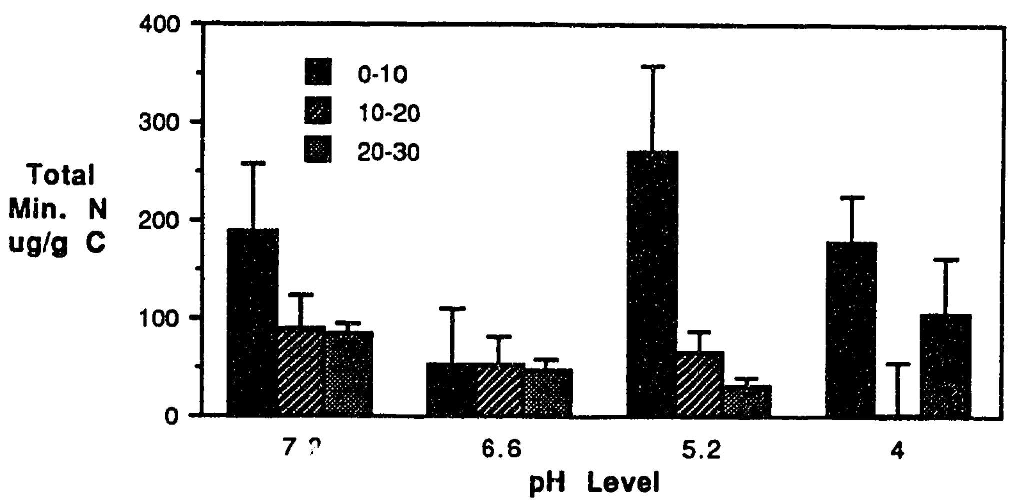

Fig. 3-5. Weighted means of total mineral N from in situ incubation compared among depth and pH levels (n=107, SE bars). Weighted means for mineral N (g C)$^{-1}$ were obtained by multiplying mineral N cell means by corresponding g C cm^{-3} cell means (a cell is one 'site x drainage x depth' combination; n=3) then dividing by the overall g C cm^{-3} mean of the current treatment level.

C:N ratios, summarized in Appendix 3-4, trend towards lower ratios in drained versus undrained areas (45:1 versus 53:1, P=0.121). No noticable trend with depth

(P=0.714) was found. A direct correlation was found between C:N ratio and mineral N per unit mass total N (r=0.182, P=0.060; Table 3-2) but none occurred between C:N ratio and mineral N (g C)$^{-1}$ (P=0.741) or log10(θ) (P=0.430).

3.3.4 Nitrification

Analysis of variance revealed no pH or drainage effect on NO_3-N (g C)$^{-1}$ although NO_3-N per unit volume was significantly higher (P=0.046) in the drained versus undrained areas (Tables 3-1 and 3-4). When the NO_3-N (g C)$^{-1}$ data were divided into 3 classes based on ascending θ, all 3 classes indicated a positive correlation between NO_3-N and θ though the correlation was only significant (P=0.041) in the class with highest θ (60-100%). Furthermore, NO_3-N (g C)$^{-1}$ was greater only in those drained areas where θ was also greater than in the undrained area (Fig. 3-1 and Table 3-2).

Table 3-4. NO_3-N in peat from in situ incubation compared among pH and depth levels and drainage treatments expressed on a per hectare basis

Drainage Treatment	pH Level 7.2	6.6	5.2	4.0
	kg ha^{-1} to 30 cm depth			
Undrained	0.66	0.32	0.38	0.89
Drained	0.94	4.32	1.44	0.76
	Depth Level 0-10 cm	10-20 cm	20-30 cm	0-30 cm
	kg ha^{-1} in each layer			
Undrained	0.17	0.14	0.27	0.58
Drained	0.75	0.49	0.86	2.09
Overall	0.46	0.31	0.56	1.34

Depth affected NO_3-N (P<0.04) which was lowest in the middle depth level as was NH_4-N and total mineral N (Tables 3-1 and 3-2). The pH x depth interaction (Fig. 3-6) bordered on significant (P=0.082) for the mass/mass expression. When log10(θ) was used as a coviarate in the statistical model the significance of both the depth effect and the pH x depth interaction were slightly weakened to P=0.063 and P=0.110 respectively (Appendix 3-3). Omission of potential outlier cases further weakened the depth and pH x depth interaction effects ($P=0.097$ and $P=0.280$ respectively). Depth trends of the two concentration expressions for NO_3-N were similar (Tables 3-2 and 3-4).

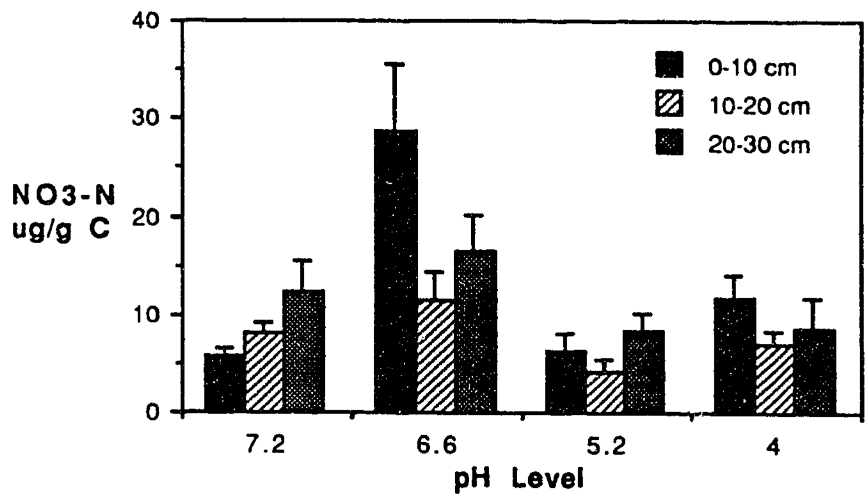

Fig. 3-6. Variation of NO_3-N with pH and depth level (SE bars, n=107)

3.4 DISCUSSION

3.4.1 pH by Drainage Interactions

As regards pH effects, theory suggests that at the most acidic sites a drainage effect may be minimal because, although drainage removes the limiting effect of poor aeration, N mineralization may still be inhibited by acidity. However, at high pH sites acidity does not limit microbial activity and improved aeration should result in increased mineralization (Alexander 1977, Farrish and Grigal 1988) . Results in Section 3.3.2 support this theory at the pH 4.0 level which did not respond to drainage, and at the pH 7.2 level which responded significantly (Fig. 3-3). In contrast, both intermediate pH levels (pH 6.6 and 5.2) had unexpectedly lower N mineralization in the drained versus undrained areas. Drainage was expected to increase N mineralization as a result of decreased θ and increased aeration. However, θ was higher in the drained versus undrained areas of pH levels 6.6 and 5.2 (Fig. 3-1). The higher Db values in these drained versus undrained areas indicates a smaller mean pore size n the drained areas. Given a smaller mean pore size, the drained areas of pH levels 6.6 and 5.2 would have hic θ at equal Ψ_m, e.g., field capacity (Boelter 1969) assuming the Ψ_m is more negative than approx. -0.5 kPa as is usually the case above the water table. This suggests that Db may be used as a predictor of net N mineralization responses to drainage.

The L*D interaction term for total mineral N still bordered on significant after the effects of θ were removed by the covariate log10(θ) (Section 3.3.2) indicating that some drainage effect other than θ had affected N mineralization. The Db data and C:N ratios suggested a substrate effect may be responsible. The Db values (Fig. 3-2) indicate greater consolidation had occurred in the drained areas of pH levels 6.6 and 5.2 compared to drained areas of other pH levels. The greater consolidation would result in samples from the higher Db drained areas including deeper peat than in the paired undrained areas. Sample depth and Db both relate to stage of decomposition (Clymo 1983, Boelter 1969) and indeed the drained peats of pH levels 6.6 had a mean von Post (1925) value of 4.2 compared to 2.4 and 2.9 for pH levels 7.2 and 4.0 (Table 2-1). However, the mean von Post (1925) value for the 5.2 pH level was the lowest overall (2.1). Evidence of heavy equipment activityin that drained area suggests the high Db may have been due to compaction rather than consolidation following decomposition. C:N ratios (Appendix 3-4) also relate to stage of decomposition (Damman 1988). C:N ratios were lower in drained (45:1) compared to undrained areas (53:1) suggesting greater decompositon in drained areas. Since selective decomposition of easily metabolized compounds results in increasing recalcitrance with increasing decomposition (Clymo 1965, Farrish and Grigal 1988) incubated samples from drained areas, and especially drained areas with high von Post (1925) values (pH 6.6), would yield less mineral N $(g\ C)^{-1}$ thus contributing to the L*D interaction.

If C:N ratio and recalcitrance are both a function of stage of decomposition one may expect to find a relationship between C:N ratio and rate of mineralization of N (g C)$^{-1}$ or N (g total N)$^{-1}$. Indeed, a correlation was found between C:N ratio and mineral N (g total N)$^{-1}$ but not between C:N ratio and mineral N (g C)$^{-1}$. This further supports the argument that drained areas had more recalcitrant forms of N and that substrate effects contributed to the decreased mineral N (g C)$^{-1}$ in drained areas.

Long term changes in N mineralization following drainage may have been a factor as the time since ditching varied from 7 to 33 years among sites. However, no trend is obvious between period since drainage and N mineralization response (Table 2-2 and Appendix 3-2).

The possibility that low θ following drainage may have limited N mineralization was considered. However, the lowest gravimetric water values (derived from Appendix 3-1) found in the 0-10 cm layer in the drained areas were well above the 200% range which Heal et al. (1978) reported as being the threshold below which peat decomposition would begin to decline. At Fort 1 and Fort 2, where the mineralization response to drainage was negative, the inferred Ψ_m (derived from Table 3-2 and Boelter 1969) was near an assumed field capacity (-0.01 MPa) for both the drained and undrained areas. Since this inferred Ψ_m is greater than the inferred Ψ_m of -0.05 MPa (derived from Table 3-2 and Boelter 1969) in the Saulteaux drained area where a large net N mineralization response occurred, low Ψ_m can be ruled out as a cause of decreased N mineralization following drainage.

Soil temperature was not measured but could contribute to the variability among drainage treatments. In studies with similar water contents in boreal peatlands (Pessi 1958, Lieffers and Rothwell 1987, Lieffers 1988) soil temperatures increased 2-4° C in drained areas compared to undrained areas at both the 10 cm and 30 cm depths during periods from July to September. Stewart and Wheatley (1990) reported a CO_2-C evolution increase of 20% when soil temperature increased from 7 to 15° C giving a calculated Q_{10} of about 1.24 for peats of pH < 4.0. Reddy (1982) found a Q_{10} of 1.5 for N mineralization from peats of pH 5.5 in the 10-30° C range. If a Q_{10} of 1.5 is assumed for this study, a soil temperature increase of 3° C in drained versus undrained areas would result in a mineralization increase of factor 1.2. However, the temperature increases discussed above were a consequence of the lowering of θ. Since much of that soil temperature variation correlates with variation in θ, the use of log10(θ) as a covariate should largely remove temperature effects.

3.4.2 Depth Effects

A decrease in N mineralization with depth has been related to both soil environmental and substrate composition variables. By placing a uniform substrate at different depths, Farrish and Grigal (1988) and Lieffers (1988) found decomposition decreased with increasing depth indicating that environmental conditions play a role in determining decomposition rates. Aeration and temperature have been identified as the environmental variables in this regard (Fox and van Cleve 1983, Lieffers 1988, Williams 1974). However, Williams and Wheatley (1987) found that N mineralization responded to increased aeration in only the upper 20 cm of peat, and Yavitt et al. (1987) found that peat decomposition was temperature insensitive below 30 cm. Clymo (1965), Wiklander and Nômmik (1987), and Lévesque and Mathur (1979) found differences in decomposition rates among depth levels and related these differences to stages of decomposition. These studies indicate that peat decomposition responds to changes in environmental variables but that the response can be limited by the stage of decomposition of the substrate.

Considerable variability was found in the N mineralization trend with depth (Appendix 3-2) when individual site by drainage areas were considered. This did not appear to correspond to θ or pH level and may be due to high variability in the peat substrate. Alternatively, Williams (1974) found that peat samples from a transitional aerobic-anaerobic zone, when incubated aerobically, accumulated an anomalously high amount of mineral N. His explanation was that the aerobic portion of the sample contained bacteria adapted to the aerobic environment which, following aeration, were able to colonize the entire sample and take advantage of readily available carbon sources from the formerly anaerobic zone and thereby mineralize high amounts of N. Our experiment was designed such that in-situ incubation occurred with a minimum disruption to the normal N mineralization processes by minimal disturbance of peat structure and by vertical repositioning of the bagged sample. However, samples which were straddling the top of an assumed capillary fringe (anaerobic zone) may have been aerated during sample extraction and bagging as the procedure permitted some excess water to drain away. This would likely occur more often in the undrained areas because the water table was more often within the sampling zone (Table 2-2) and could explain some of the increases in mineral N with depth, as well as some of the instances where mineral N was lower in drained versus undrained areas (Fig. 3-3).

Lieffers (1988) reported a temperature decrease of about 2° C from 10 cm to 30 cm depth. Assuming the same Q_{10} of 1.5 used in Section 3.4.1, a temperature decrease of 2° C between 10 cm and 30 cm depth would result in a mineralization rate decrease of factor 1.1. This difference may explain some but not all the total mineral N variations with depth (Table 3-2, Appendix 3-2). Again, the use of log10(θ) as a covariate should largely remove temperature effects.

Although analysis of variance revealed no significant differences in C:N ratio, changes in C:N ratio with depth tended to parallel mineral N changes, especially in the drained areas (Table 3—2 and Appendix 3-4). Thus the relationship between C:N ratio and mineralization of N g^{-1} total N (Section 3.4.1) helps to explain the significant depth effect (P=0.077) found after the covariate log10(θ) removed the effects of water content (Appendix 3-3).

At C:N ratios higher than 10-17 N deficiency can be a limiting factor to microbial growth and net immobilization of N may result (Damman 1988). In this study net mineralization occurred despite C:N ratios averaging 45:1 and ranging between 34:1 and 78:1 (Appendix 3-4). Damman (1988) suggested that deficiencies of available of P or K may limit microbial activity and cause the C:N ratio at which net N mineralization occurs to be unusually high. The P $(g\ C)^{-1}$ and C:N ratios of site x drainage areas (averaged across depth) are strongly negatively correlated ($r=-0.747$, $P<0.001$) and furthermore, the correlation in undrained areas ($r=0.883$) is much stronger than in the drained areas ($r=0.694$) (Appendix 3-4).

3.4.3 Nitrification

The fact that drainage increased nitrification only in those areas where θ was actually higher following drainage (Section 3.3.4) suggests that controlled drainage projects are unlikely to increase NO_3-N production in fens of the Boreal Wetland ecoregion. The positive correlation of NO_3-N with θ suggests that nitrification may be inhibited by insufficient water at low θ values. The organisms responsible for nitrification are obligate aerobes (Paul and Clark 1989) and hence their metabolic activity should be inhibited by high θ values. However, poor aeration may only begin to inhibit their activity after the soil solution has become anaerobic due to microbial and root respiration. This may not have occurred during the incubation period. Alternatively, higher θ may result in improved contact between the nitrifying organisms and the NH_4^+ substrate. It is also, possible that organisms that immobilize NO_3-N were inhibited with increasing θ values. The fact that the pH by depth effect on NO_3-N was weakened with analysis of covariance suggests it was related to θ.

3.5 CONCLUSIONS

Results support the null hypothesis that long term N mineralization response to drainage would not be higher at the higher pH sites. However, the variability of θ response following drainage may have obscured any pH effect as the N mineralization from those pH levels which support the null hypothesis can be partially explained by the unexpectedly high θ which, in turn, can be related to the increase in Db in those drained areas versus their paired undrained areas. This result has two implications. Firstly, acceptance of the null hypothesis should be qualified by the variable experimental conditions. A controlled study with comparable drainage, or more specifically air-filled porosity, at all pH levels is required. Secondly, variation in Db appears able to control N mineralization response by affecting θ.

Significant drainage and depth effects were found which were largely unrelated to θ suggesting that substrate effects were present. Lower C:N ratios in drained versus undrained areas and a positive correlation between mineral N (g total N)$^{-1}$ and C:N ratio was evidence that peat was more decomposed in drained areas and that these more decomposed peats contained more recalcitrant forms of N. However, no correlation was found between C:N ratio and mineral N (g C)$^{-1}$ suggesting that increased N concentration in more decomposed peats tended to counteract the effect of increased N recalcitrance.

The above arguments suggest that although drainage may initially increase the N mineralization rates, this increase may be diminished or even reversed over time because: 1) accelerated depletion of easily metabolized compounds leads to increased recalcitrance of N sources in the drained areas(Clymo 1965, Farrish and Grigal 1988), and 2) increased consolidation of near surface peat may diminish the θ response to drainage or even lead to higher θ in drained versus undrained areas.

Nitrification was not influenced by pH or drainage factors and correlated positively with θ, especially at values above 60%. This suggests that drainage of fens in the Boreal Wetlands ecoregion will not increase NO_3-N production during a seven to 33 year post-ditching period.

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4. FOLIAR RESPONSES OF BLACK SPRUCE GROWING IN UNDRAINED AND DRAINED FENS COMPRISING A pH GRADIENT

4.1 INTRODUCTION

Trees growing in boreal wetlands encounter nutrient deficiencies because mineralization and uptake of nutrients from organic soils is limited by cold temperatures, acidic conditions, and high water tables (Watt and Heinselman 1965, Lowry 1972, Tyrrell and Boerner 1986). Peatland drainage has been recognized as a potential means of ameliorating nutrient deficiency by increasing both the available rooting volume and nutrient mineralization rate. (Lowry 1968; Page 1969a, 1969b, 1970). However, nutrient deficiencies may still persist after drainage, and further growth benefits may be achieved through a combination of drainage and fertilization (Watt and Heinselman 1965, Lowry 1975).

Although foliar analysis is a preferred method of assessing site fertility (van Dreissche 1974), few such studies have been done with black spruce. Lowry (1972, 1968) and Swan (1970) published critical concentrations for foliar nutrients of black spruce growing on mineral soils. Watt and Heinselman (1965) and Lowry and Avard (1968) showed that foliar concentrations of N and P can be related to site index of black spruce on organic soils, and Watt (1966) successfully used foliar analysis to predict black spruce stemwood response to NPK fertilization. These studies suggested that both N and P limit growth of black spruce on organic soils. Until recently no foliar analysis of black spruce growing on organic soils had been done in Alberta (Lieffers and Macdonald 1990).

Fens in Alberta range in pH from about 3.7 to 7.9 (Chapter 1). At low pH sites fewer nutrient cations are available due to replacement by H^+ ions on peat exchange sites. Also, peat acidity may limit nutrient release by inhibiting microbial decomposition. Thus foliar nutrient responses to drainage may be limited by pH at low pH sites.

Little work has been done to quantify the micronutrient requirements of black spruce. Micronutrient deficiencies are not common in mineral forest soils (Braekke 1983). However, in organic soils micronutrients are often present in near-deficient amounts and increased growth brought about by addition to the soil of macronutrients may dilute foliar micronutrients to concentrations where deficiency symptoms such as apical shoot dieback or decreased height growth begin to appear (Veijalainen 1983).

In relation to the above discussion the following null hypotheses were formed concerning foliar nutrients (expressed on a concentration and content per needle basis) in boreal peatlands in Alberta: *i)* Lowering the water table through drainage has no effect on foliar nutrients, *ii)* Peat pH does not affect the response of foliar nutrients to changes in water table height through drainage, *iii)* Foliar nutrient classes described for black spruce growing elsewhere are not applicable in Alberta, and *iv)* Foliar nutrient contents per needle are not correlated with peat elemental contents.

The objectives were to: *i)* determine foliar responses of black spruce growing on paired natural and drained fens with a range of pH, *ii)* determine the applicability of existing limits for foliar nutrient concentrations of classes representing a range of nutrient status for black spruce, and *iii)* relate foliar nutrent-status to elemental contents of peat.

4.2 MATERIALS AND METHODS

4.2.1 Field Sampling

The study sites met several selection criteria as outlined in section 2-1. Foliar sampling occurred during 3 successive days in mid-September, 1989. At each site two transects were established 100 m in length and parallel to the drainage ditch. The drained transects were 3-5 m from the drainage ditch, while the undrained transects were 30-35 m from the ditch (Fig. 2-2). Along each transect 5 sample trees were randomly selected from the co-dominant crown class, and the upper 0.5-0.75 m of crown was collected, then transported and stored with ice prior to processing.

Current-year needles were separated from shoot stems and dried for 16 hr at 70°C during the week following sampling. After needles equilibrated with room temperature and humidity, the weights of four sub-samples of 100 needles each were recorded for each tree. The remaining current-year needles were ground in a Wiley mill and stored at room temperature until elemental analysis.

Foliar N was determined by semi-micro Kjeldahl digestion (Bremner and Mulvaney 1982) followed by analysis with an auto analyser using a Berthelot (1859), procedure (Technicon Industrial Method # 98-70W). Foliar P, K, Ca, Mn, Zn, and Cu were determined by dry ashing (Zoltai 1988) followed by analysis using inductively coupled plasma-atomic emission spectrometry (Soltanpour et al 1982).

The interpretation of the foliar nutrient levels employed foliar concentrations and concentration class limits in the traditional sense, and also employed vector diagrams which use elemental nutrient masses per needle and unit needle mass. The vector diagrams are a graphical method first devised by Krauss (1965), and later refined by Weetman (1971), Timmer and Stone (1978), and Weetman and Fournier (1982). This method depicts foliar response to treatments by displaying nutrient concentration on the *y*-axis, nutrient content on the *x*-axis, and unit needle mass as a series of lines radiating from the origin (Fig. 4-1). All parameters are standardized by setting the control value equal to 100 and the treatment values proportional to control. Whereas foliar concentration is a measure of the nutritional status of the tree relative to a calibrated standard, the foliar content can provide a more meaningful measure of a tree's response to a treatment because it accounts for the dilution effect of increased growth (Krauss 1965). This graphical method provides a more complete picture of nutritional changes in the foliage than the use of either the nutrient concentration or the nutrient content alone. Interpretation of the diagrams is discussed by Timmer and Stone (1978).

Analysis of variance of foliar data was performed using the Systat software package (Systat Inc. 1986). Sites were nested within pH levels and sites were split into drainage treatments. The statistical model of the sampling design used (Chapter 2) is:

$$Y_{ijkl} = \mu + \tau_i + \beta_{j(i)} + \gamma_k + \tau\gamma_{ik} + \beta\gamma_{j(i)k} + \varepsilon_{(ijk)l} \quad \begin{cases} i=1\ldots4 \\ j=1\ldots2 \\ k=1\ldots2 \\ l=1\ldots3 \end{cases}$$

Where τ_i is the effect of the 'i'th pH level, $\beta_{j(i)}$ is the effect of the 'j'th site within the 'i'th pH level, and γ_k is the effect of the 'k'th drainage treatment.

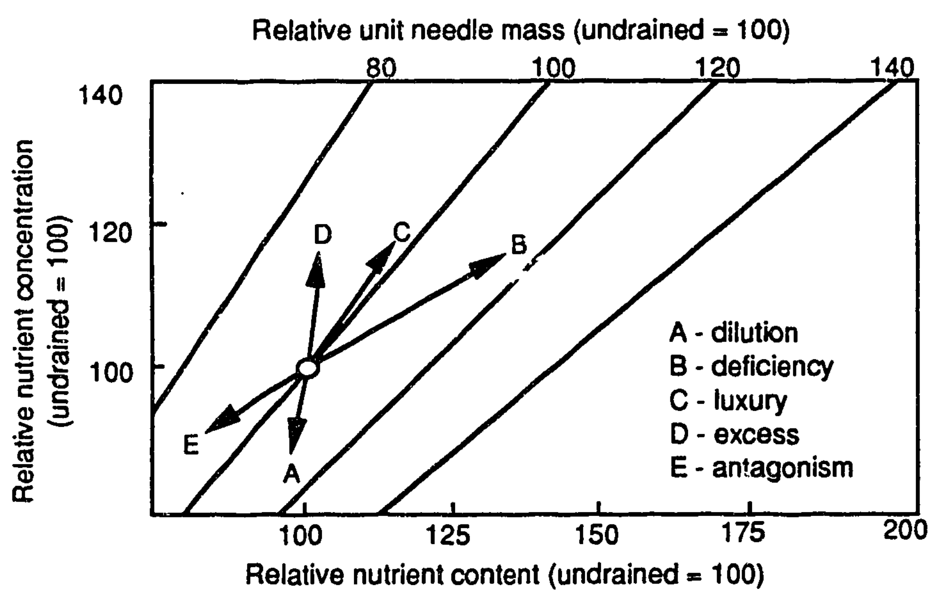


Fig. 4-1. Vector diagram response regions and diagnostic interpretations (Adapted from Timmer and Morrow 1984)

4.3 RESULTS

4.3.1 Foliar Responses to Drainage

Foliar mass increased significantly with drainage (Table 4-1 and Fig. 4-2) by 28% to 59% (Table 4-2). This necessitates the use of total nutrient content in place of concentration to accurately assess nutrient response to drainage.

Table 4-1. Summary for analysis of variance of current-year needle mass

SOURCE	DF	MS	F Ratio	P>F
D†	1	0.161	16.956	.054
L††	3	0.027	8.351	.109
S(L)§	2	0.003		
L*D	3	0.005	0.570	.687
D*S(L)	2	0.010		
error	48			

† D = drainage treatment (undrained and drained)
†† L = pH level (4.0, 5.2, 6.6, and 7.2)
§ S = individual sites within pH levels

One vector diagram was constructed for each site (Fig. 4-3) to provide a measure of relative response strengths among the nutrients measured. These relative response strengths are ranked and summarized in Table 4-3 to provide an overview of the apparent stress conditions among all sites.

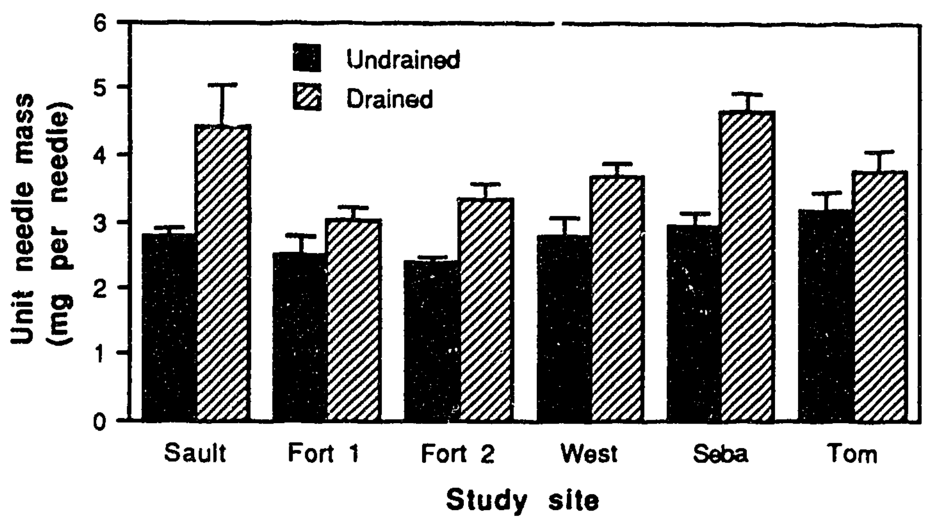


Fig. 4-2. Unit needle mass in undrained and drained areas of sites arrayed by peat pH (SE bars)

Table 4-2. Unit needle weight and nutrient concentrations of current year needles compared among site pH levels and drainage treatments

Treatment	pH	n	UNW†	N§	P	K	Ca	Mn	Zn¶	Cu
	7.2	5	2790	0.75 A††	0.12 M	0.44 S	0.29 S	336	22.0	1.17
	S.E.		114	0.03	0.01	0.04	0.04	27	3.4	0.17
	6.6	10	2460	0.90 M	0.13 M	0.47 S	0.47 L	556	44.6	1.94
Undrained			131	0.05	0.01	0.02	0.04	60	4.5	0.49
	5.2	5	2790	1.11 M	0.11 M	0.34 T	0.50 L	764	32.4	2.24
			243	0.05	0.00	0.02	0.03	56	1.9	0.21
	4.0	10	3050	1.06 M	0.12 M	0.46 S	0.29 S	759	28.6	2.05
			170	0.03	0.01	0.02	0.03	51	3.0	0.17
Overall		30	2770	0.97 M	0.12 M	0.44 S	0.37 S	622	33.5	1.90
	7.2	5	4430	1.10 M	0.15 T	0.48 S	0.43 L	333	35.3	2.47
			632	0.02	0.00	0.01	0.05	33	4.8	0.15
	6.6	10	3160	1.46 T	0.16 T	0.54 S	0.32 S	328	32.4	3.06
Drained			158	0.06	0.01	0.05	0.03	82	2.3	0.22
	5.2	5	3690	1.23 T	0.16 T	0.46 S	0.46 L	778	32.3	3.07
			169	0.02	0.01	0.01	0.02	53	2.0	0.08
	4.0	10	4220	1.14 M	0.13 M	0.41 S	0.32 S	367	28.1	2.40
			252	0.04	0.01	0.01	0.03	26	2.1	0.29
Overall		30	3810	1.25 T	0.15 T	0.47 S	0.36 S	417	31.5	2.74

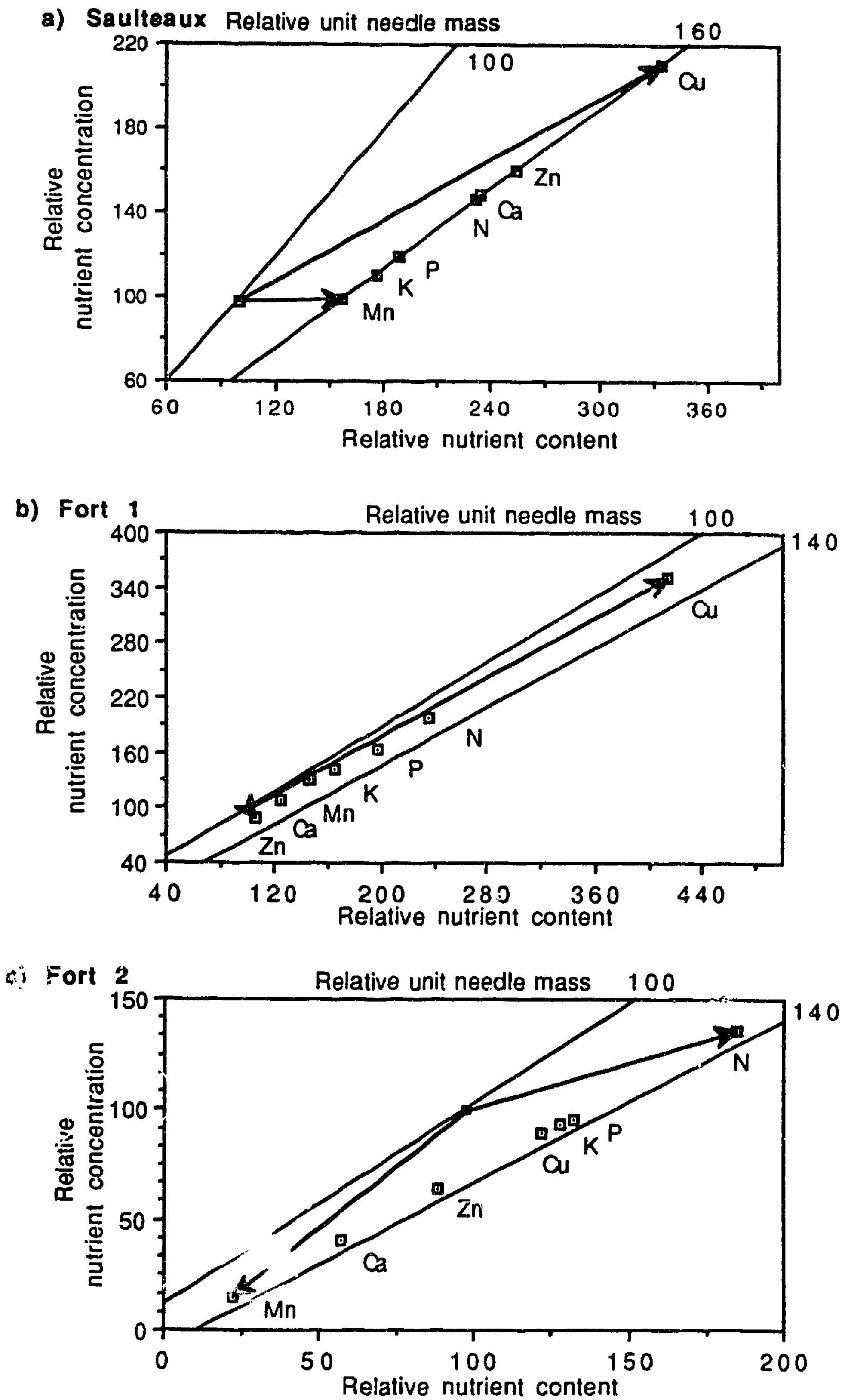
† UNW = unit needle weight expressed as ug/needle
§ Macronutrients (N, P, K, Ca) expressed as % dry weight
¶ Micronutrients (Mn, Zn, Cu) expressed as ug/g dry weight
†† Letters indicate foliar nutritional classes as defined by Swan (Appendix 4-1). A=acute deficiency, M=moderate deficiency, T=transitional, S=sufficient, L=luxury consumption

Table 4-3. Relative rankings of nutrient responses summarized from vector diagrams in Fig. 4-3†

Site	N	P	K	Ca	Mn	Zn	Cu
Sauiteaux	4	3	2	5	1	6	7
Fort 1	6	5	4	2	3	1	7
Fort 2	7	6	5	2	1	3	4
Westlock	4	7	5	1	3	2	6
Seba Beach	4	3	2	6	1	5	7
Tomahawk	6	7	5	2	1	3	4
Total	31	31	23	18	10	20	35

† Within each site the elemental responses, expressed as the calculated length of each vector as a hypotenuse in x-y units, were ranked from the greatest (7), to the least (1).

Scanning all six vector diagrams allows a quick assessment of the differences in foliar responses among sites. A relatively consistent pattern is found in the responses of N, P, and K. Four of the six sites had the same relative response ranking (N > P > K). With the exception of the Fort 2 and Tomahawk sites, where P and K, and N and K


a) Saulteaux
Relative unit needle mass
160
100
Relative nutrient concentration
Relative nutrient content
Cu
Zn
Ca
N
P
K
Mn
b) Fort 1
Relative unit needle mass
100
140
Relative nutrient concentration
Relative nutrient content
Cu
N
P
K
Mn
Ca
Zn
c) Fort 2
Relative unit needle mass
100
140
Relative nutrient concentration
Relative nutrient content
N
P
K
Cu
Zn
Ca
Mn

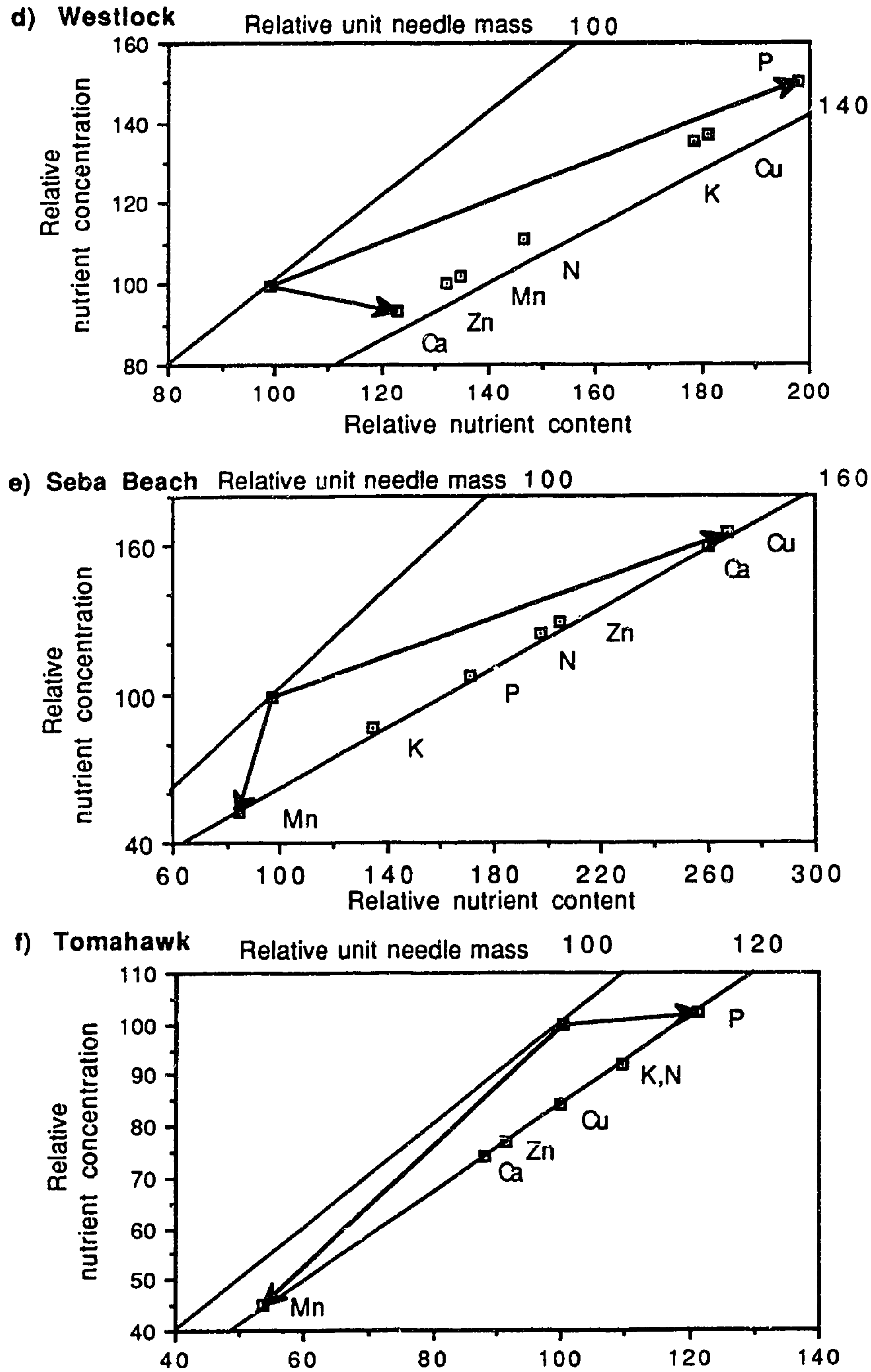


Fig. 4-3. Vector diagrams of foliar responses to drainage within sites

respectively were slightly diluted, all concentrations of these three macronutrients increased in drained areas. Based on its response ranking, Cu is the most deficient nutrient in the undrained peats. The Ca, Mn, and Zn responses were variable and didn't rank consistently with respect to the above elements.

Table 4-4 contains the analysis of variance summary for nitrogen given as an example of the statistical design used for all elements. Whereas changes in nutrient content provide a measure of responses to treatment, the nutrient concentrations following drainage provide a measure of the degree of deficiency still remaining after the treatment. The probability values for the tests of pH, drainage, and pH by drainage interaction effects are summarized for all nutrients in Table 4-5.

Significant (P<0.07) increases in needle content of N (76%), P (72%), and K (46%) were found in drained areas (Tables 4-2 and 4-5). These responses were consistent relative to each other (N > P > K) in 4 of the six sites (Table 4.3). Concentrations also increased (N 28%, P 25%, and K 6%) but not significantly (Tables 4-2 and 4-5).

No significant drainage responses of content or concentration of Ca, Mn, Zn, or Cu were found. Cu concentrations increased 44% while Ca, Mn, and Zn all decreased in drained areas by 3%, 33%, and 6% respectively (Tables 4-2 and 4-5).

Table 4-4. Summary of analysis of variance of N in current-year needles

Parameter	SOURCE	DF	MS	F Ratio	P>F
	pH level (L)	3	148.7	1.241	0.475
	S(L)	2	119.9		
N	drainage (D)	1	5649.3	13.500	0.067
Content	L*D	3	130.4	0.311	0.821
	S*D(L)	2	419.6		
	error	48	69.2		
	pH level (L)	3	1570700	10.607	0.087
	S(L)	2	1480400		
N	drainage (D)	1	101211000	6.197	0.131
Concentration	L*D	3	22453600	1.375	0.447
	S*D(L)	2	16332100		
	error	48	1072237		

Table 4-5. Probability values from analysis of variance of foliar nutrients

	Nutrient content			Nutrient concentration		
Element	pH Effect	Drg Effect	pH*Drg	pH Effect	Drg Effect	pH*Drg
N	0.475	0.067	0.821	0.087	0.131	0.447
P	0.258	0.042	0.703	0.561	0.237	0.793
K	0.141	0.031	0.432	0.285	0.422	0.642
Ca	0.155	0.306	0.628	0.010	0.950	0.737
Mn	0.082	0.945	0.465	0.060	0.424	0.480
Zn	0.999	0.181	0.650	0.679	0.986	0.756
Cu	0.412	0.134	0.938	0.235	0.328	0.948

4.3.2 Foliar Responses with pH Level

The pH effect on foliar concentration was significant only for Ca (P = 0.010), although N (P = 0.087) and Mn (P = 0.060) were bordering on significant (Table 4-5). Only Mn had a foliar content response to pH bordering on significant (P = 0.082). No significant pH by drainage interaction effects were found.

The listing of pre- and post-drainage concentrations by pH level in Table 4-2 allows inspection for deficiency and response differences among pH levels. The upper case letters in Table 4-2 designate classes for foliar nutrient status derived from Appendix 4-1 (black spruce in organic soils of central and eastern Canada). No deficiency classes are listed for the micronutrients as there is little information available regarding their stress levels. However, the ranking of elemental responses in the vector diagrams and the summary of those responses in Table 4-3 should indicate to what degree the micronutrients were deficient relative to the known deficiency levels of the macronutrients.

4.3.3 Correlation Between Foliar and Peat Nutrient Contents

The simple correlations between foliar nutrient contents per needle and elemental peat contents (m/v) in the upper 30 cm of peat below the lower limit of live green moss (Table 4-6) were determined (Table 4-7).

Table 4-6. Elemental nutrient contents in peat (m/v) in the upper 30 cm below the lower limit of live green moss (n=9) and black spruce foliar contents per needle (n=5) by site and drainage treatment

Variable and Treatment	Site	N	P	K	Ca	Mn	Zn	Cu
		ug/cm^3						
Peat Undrained	Salt	550	29.7	25.5	1990	32.00	0.89	0.105
	Fort 1	505	28.3	21.3	1260	34.80	2.14	0.171
	Fort 2	621	34.6	34.3	1040	25.80	1.37	0.164
	West	397	17.3	8.6	463	0.76	1.68	0.067
	Seba	406	22.4	17.7	200	2.99	2.42	0.120
	Tom	494	25.8	16.1	215	2.15	1.74	0.100
Peat Drained	Salt	921	44.1	32.5	2680	17.70	6.03	0.241
	Fort 1	1820	67.9	27.7	4540	40.80	1.99	0.473
	Fort 2	1720	86.6	78.2	4370	44.70	3.46	0.533
	West	1490	56.1	12.3	2960	10.00	2.10	0.377
	Seba	620	29.5	18.0	395	2.11	3.37	0.191
	Tom	651	32.8	15.7	258	3.38	2.03	0.150
		ug/100 needles						
Foliage Undrained	Salt	21.1	3.45	12.2	7.96	0.94	0.061	0.00323
	Fort 1	19.5	2.90	11.3	9.63	1.14	0.081	0.00260
	Fort 2	24.9	3.28	11.9	13.57	1.64	0.137	0.00691
	West	30.9	3.02	9.6	13.74	2.15	0.092	0.00621
	Seba	29.2	3.31	13.1	6.89	2.12	0.068	0.00488
	Tom	35.6	4.02	14.8	10.98	2.44	0.108	0.00771
Foliage Drained	Salt	49.1	6.52	21.2	19.00	1.49	0.154	0.01120
	Fort 1	45.9	5.71	18.5	12.10	1.66	0.085	0.01070
	Fort 2	46.1	4.31	15.2	7.73	0.35	0.120	0.00841
	West	45.5	5.95	16.8	16.80	2.83	0.118	0.01140
	Seba	57.8	5.66	17.8	17.90	1.80	0.141	0.01300
	Tom	38.8	4.86	16.1	9.86	1.33	0.099	0.00784

Table 4-7. Correlation coefficients and P values of black spruce foliar contents per needle with corresponding total nutrient contents in peat (m/v) in the upper 30 cm below live green moss

Foliar Element	Peat elements r	P>F
N†	.552	.063
P†	.491	.105
K††	.148	.644
Ca††	.055	.856
Zn††	.632	.027
Mn††	.709	.010
Cu††	.490	.106

† Determined by digestion in H_2O_2 and H_2SO_4 followed by colorometric analysis (Sections 3.2 and 4.2)

†† Determined by ashing at 495° C and dissolution in aqua-regia followed by analysis with ICP-AES (Sections 3.2 and 4.2)

4.4 DISCUSSION

4.4.1 Drainage Responses

The applicability of Swan's (1970) nutrient concentration classes to black spruce stands growing in Alberta is uncertain. However, the ranking of foliar vector responses (Table 4-3) matched well with the ranking of foliar concentration responses one would expect from the nutrient concentration classes found in undrained areas (Table 4-2). In all cases the vector responses to drainage of N, P, and K were consistent with the ranking of their concentration classes. Drainage resulted in N and P concentrations increasing from moderately deficient to transitional; whereas K and Ca, which were rated as sufficient before drainage, did not respond appreciably. These results supports the use of Swan's (1970) class limits in Alberta as well as the relative response rankings from vector analysis as diagnostic tools with respect to macronutrients.

Since the vector diagrams provide a ranking of micronutrient responses in relation to the macronutrient responses, the degree of micronutrient deficiency may be roughly estimated by comparing micronutrient responses with the responses of the macronutrients which are of a known nutritional status. However, this assumes that all nutrient availabilities increase by equal proportions following drainage such that differences in response to drainage are due only to differences in deficiency in undrained areas.

Ca concentration was in either the sufficiency or luxury consumption range in all undrained cases and responses to drainage were variable suggesting that the responses were related to some factor other than undrained concentration. Paarlahti et al. (1971) considered that Ca and Mg did not have physiological functions which would make them valuable in foliar analysis. Also, Ca concentration is known to rise dramatically as foliage ages (Lowry 1968), and this could introduce variability among sites which may have phenological differences due to geographical location.

Foliar Zn concentrations decreased 6% to 31.5 ug g^{-1} (Table 4-2) in drained areas but this was not significant (Table 4-5). The undrained foliar Zn concentration of 33.5 ug g^{-1} (Table 4-2) was comparable to the 38.3 ug g^{-1} found by Lowry (1972) in current-year needles of black spruce growing in 27 organic soil plots in continental regions of central and eastern Canada. For Scots pine Veijalainen (1977) recommended 40 ug cm^{-3} of Zn as a satisfactory content in organic soils whereas soils in this study had only 2.5 ug cm^{-3} (Appendix 4-2). Nevertheless, the overall drainage response did not indicate a deficiency condition. However on the sites with lowest foliar Zn concentration, Saulteaux (22.0 ug g^{-1}) and Seba, (23.6 ug g^{-1}) drainage resulted in concentration increases to 35.3 ug g^{-1} and 30.4 ug g^{-1} respectively (Appendix 4-1). At both sites the Zn response was slightly greater than the N response and the N concentrations were rated as acutely and moderately deficient and increased to moderately deficient to transitional following drainage. At Fort 2 where the undrained Zn was 57.0 ug g^{-1} drainage resulted in a decrease to 36.5 ug g^{-1} (Appendix 4-1). This response ranked between K which was classed as sufficient and Ca which was classed as luxury. The drained concentrations of K and Ca are classed as sufficient, suggesting that Zn is in the sufficient class at 36.5 ug g^{-1}. Based on these findings some approximate nutritional class limits are proposed for foliar Zn of sapling to pole-sized black spruce:

< 24 ug g^{-1} - acutely deficient

24-30 ug g^{-1} - moderate to transitional

> 30 ug g^{-1} - sufficient

Veijalainen (1977, Scots pine) and Lowry (1972, black spruce) indicated 0.04 % is a sufficient foliar Mn concentration indicating that foliar Mn in this study was sufficient in all areas except the Fort 2 drained area (Appendix 4-1). Foliar Mn concentration decreased by 24 % in drained areas (Table 4-2) but this change was not significant (Table 4-5). However, the foliar Mn content was correlated ($r = 0.709$, P=0.01) with its elemental peat content (m/v) in the upper 30 cm (Tables 4-6 and 4-7). Sims and Patrick (1978) found the percentages of micronutrients complexed with organic matter in Histosols increased in the order of Mn < Cu < Zn, and that Mn was markedly less complexed than the other micronutrients. The relatively weak binding of Mn by organic matter would allow Mn uptake to reflect Mn concentration in the peat and could explain the high r value. Foliar Mn was much lower in the drained areas of Fort 2 (pH 6.6) and of Seba and Tomahawk (pH 4.0) whereas Zn and Cu were similar among drainage treatments at these sites. At Seba and Tomahawk where the low pH and redox potential in undrained areas favor high Mn solubilities (Sims and Patrick 1978) the decrease in drained areas could be explained by a decrease in Mn solubility due to a presumed higher Eh following drainage. In the Fort 2 drained area only sapling size trees were available for sampling and the root systems may have not been developed enough to extract Mn from the 20-30 cm depth where more total Mn was present compared to the 0-10 cm depth. Peat elemental data (Appendix 4-2) indicate an increasing Mn concentration with depth. The lower Mn content in the peat and the presumed higher Eh following drainage would both act to decrease Mn uptake.

Copper was the most deficient of the nutrients measured (Table 4-3). At the three sites with the lowest undrained foliar Cu concentration the Cu response to drainage was the highest of the seven nutrients studied (Fig. 4-3 and Appendix 4-1). At these sites the Cu response was proportionally greater than the N response even though the N deficiency was rated as moderate at two of the sites and acute at the other (Table 4-2). Of these three sites the highest Cu concentration was 1.66 ug g^{-1}. This suggests Cu concentrations less than 1.7 ug g^{-1} represent an acute deficiency. Lowry (1972), reported 8.2 ug g^{-1} Cu in black spruce needles growing on organic soils. Veijalainen (1977) reported a Cu increase in Scots pine needles from 4.5 ug g-1 where the water table was at 10 cm to 6.5 ug g-1 where the water table was at 50 cm. Of all the areas included in this study the highest Cu concentration found was 3.6 ug g^{-1}. This was in the drained area of Fort 1 (Appendix 4-1) indicating that while drainage increases Cu availability, marked deficiencies may still exist after drainage. Using the same procedure as with Zn some approximate nutritional class limits are proposed for foliar Cu in sapling to pole-sized black spruce:

< 2.2 ug g^{-1}	- acute deficiency
2.2 - 2.9 ug g^{-1}	- moderate to transitional
2.9 - 6.5 ug g^{-1}	- no data from this study
6.5 - 8.2 ug g^{-1}	- sufficient (Lowry 1972, Veijalainen 1977)

Peat Cu contents (m/v) did not correlate with foliar content (r = 0.492, P=0.106, Tables 4-6 and 4-7), but in all site x drainage treatments (Table 4-2) the peat concentration (m/m) was less than 6% of the minimum value specified by Veijalainen (1977) for Scots pine. Foliar deficiencies in our study are likely related to scarcity of Cu in the peat.

4.4.2 pH Responses

Analysis of variance results (Table 4-5) indicated that N (P=0.087), Ca (P=0.010), and Mn (P=0.060) foliar concentrations varied among pH levels. The significance of the pH effects on foliar N and Ca is unclear as there was no consistent trend in N or Ca concentrations with pH (Table 4-2). Needle N content correlated (P=0.065) with peat N content (m/v) but no correlation was found for Ca (Tables 4-6 and 4-7).

The increase in foliar Mn concentration with decreasing pH contrasts with the absence of pH responses of Zn (P=0.679) and Cu (P=0.235) to pH level (Tables 4-5 and 4-5). This can be explained by the influence of pH and Eh on Mn, Zn, and Cu solubility in the presence of organic matter. Sims and Patrick (1978) found that low pH and Eh increased the solubilization of Mn, Zn and Cu but that subsequent association with the exchange complex or organic fraction caused variable effects on water-soluble concentrations. The net effects were that low pH decreased the water-soluble Zn and Cu but increased water-soluble Mn, and that low Eh decreased water soluble Zn but increased water-soluble Mn and Cu. Mn was more influenced than Zn or Cu.

No drainage by pH interaction occurred for any of the elements studied (Table 4-5). On this basis the null hypothesis that response to drainage would not be affected by pH must be accepted. This suggests that peat pH in the range 4.0 to 7.2 does not inhibit the ability of microbial decomposers to effect nutrient release from peat once the water table is lowered.

4.5 CONCLUSIONS

No significant foliar concentration increases occurred as a result of drainage. However, N, P, and K contents per needle all increased significantly following drainage. Ca did not change appreciably. Foliar Mn and Zn concentrations decreased in most drained areas. Although Cu concentrations increases were not significant, they were the highest of all elements suggesting it was the most deficient element studied. No pH by drainage interactions occurred for foliar nutrient contents suggesting peat pH does not affect foliar nutrient responses to drainage.

Vector diagrams facilitated comparison of magnitude of foliar response among elements at each site from which the relative deficiencies of each element could be inferred. The magnitude of foliar nutrient responses to drainage consistently paralleled the magnitude of undrained deficiency according to Swan's (1970) nutrient concentration classes suggesting these concentration classes are applicable to Alberta peatlands. Based on Swan's (1970) nutrient concentration classes, black spruce growing on these natural Alberta peatlands generally suffered from moderate to acute N and P deficiencies. Drainage resulted in the nutritional status being upgraded to transitional but not sufficient. K and Ca were present in sufficient concentrations and did not change concentration classes following drainage.

Vector diagrams allowed classes for foliar status of micronutrients to be estimated by displaying the magnitude of their responses relative to macronutrient responses for which classes were available. Sufficient variability of undrained foliar Zn concentrations and responses occurred to allow the proposal of approximate class limits by comparing Zn responses with macronutrient responses. Some class limits were also proposed for Cu but the Cu responses did not encompass the range of class limits as well as with the Zn data. Vector diagrams suggested Cu was the most deficient element overall and was acutely deficient at three sites. Foliar Cu was less than 25% of that reported by Lowry (1972) in a study of black spruce on organic soils in central Canada. The Cu deficiency was likely due to low peat Cu.

Correlations between foliar content per needle and peat contents (m/v) were significant for Mn, Zn, and N in order of decreasing r value.

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5. STEMWOOD GROWTH RESPONSES OF BLACK SPRUCE TO DRAINAGE OF FEN PEATLANDS COMPRISING A pH GRADIENT

5.1 INTRODUCTION

Few long term data exist regarding the effects of peatland drainage on black spruce growth in Alberta (Hillman 1987). The few studies in Alberta have shown the initial response to drainage of black spruce stands to be a depression of growth rates for a period of 2-3 years followed by a linearly increasing growth rate for a period of 13-19 years, followed by near-steady growth near the maximum rate (Lieffers and Macdonald 1990, Dang and Leiffers 1989). No studies assessed the effect of site pH on growth response of black spruce.

The simplest approach to assessing growth response is to compare growth rates in adjacent drained and undrained areas. Assessment of growth responses amongst sites with different peat pH levels is complicated by necessity of using several sites which may introduce undesired stand and climatic differences associated with widely located sites. This complication can be overcome by a relatively new analysis technique, developed by Salonius et al. (1982) and Ballard and Majid (1985), referred to as the ratio method in this paper. The ratio method utilizes growth trend data in an undrained area to calculate a presumed undrained growth rate for the paired drained area during the post-ditching period. The method was recently adapted to evaluate black spruce growth response to drainage by Dang and Lieffers (1989).

The objectives were to: *i)* assess the growth response of black spruce to wetland drainage, *ii)* to compare growth responses amongst sites with different peat pH levels, and *iii)* to compare analysis of covariance and the ratio method as alternative growth analysis methods.

5.2 MATERIALS AND METHODS

5.2.1 Sampling Design

The study sites met several criteria as outlined in section 2-1. Sites were distributed over a few hundred kilometers (Fig. 2-1), and ditching dates spanned a 27-year interval thus giving rise to possible climatic and phenological differences which could have influenced post-drainage growth.

At each site trees were sampled in early to mid-August 1987 along two transects 100 m in length and parallel to the drainage ditch (Fig. 2-2). The drained transects were 3-5 m from the drainage ditch, while the undrained transects were 30-35 m from the ditch, sufficient distance to be considered away from the ditch's main influence based on ditch spacings used in Finnish drainage operations (Jeglum 1985). Along each 10 m segment of the 100 m transect one dominant or codominant sample tree was randomly selected.

From each sample tree a cross-section of bole was collected from 30 cm height for diameter growth analysis. These discs were air dried, trimmed with a band saw, then sanded in preparation for annual ring measurement. The longest axis through the disc was located, and the average length of the four radii at 45° to that axis was determined. Two radii, originating from the centre ring (pith) on the disc, which matched this average radius were located and marked. Allual increments along these two radii were measured and recorded using a computerized ring counting device (Clyde and Titus 1987).

The MGLH module in the Systat software package (Systat Inc. 1986) was used for the two analysis approaches, analysis of covariance and ratio method. Firstly, the raw radial increment data was analyzed to test the null hypotheses that drainage and/or pH level had no effect on growth rates, and that pH level did not have an effect on growth response in the first 11 years following ditching. In the sampling design used, sites were nested within pH levels and sites were split into drainage treatments. The statistical model of the sampling design used (Chapter 2) is:

$$Y_{ijkl} = \mu + \tau_i + \beta_{j(i)} + \gamma_k + \tau\gamma_{ik} + \beta\gamma_{j(i)k} + \delta(x_{ijkl} - \bar{x}_{....}) + \varepsilon_{(ijk)l} \quad \begin{cases} i=1...4 \\ j=1...2 \\ k=1...2 \\ l=1...3 \end{cases}$$

Where τ_i is the effect of the 'i'th pH level, $\beta_{j(i)}$ is the effect of the 'j'th site within the 'i'th pH level, and γ_k is the effect of the 'k'th drainage treatment. Stem radius at time of drainage (INIT) may have influenced post-drainage growth increments. Therefore, INIT was tested for suitability as a covariate. No significant interaction was found between INIT and pH level or drainage treatment (Appendix 5-1), thus INIT was included in the statistical model (Woolons and Whyte 1988); δ is the regression coefficient of the covariate INIT.

Secondly, the ratio method was used to adjust the radial growth data to eliminate possible growth trend effects arising from influences other than the drainage treatment. The method employed pre- and post-drainage radial increments from the undrained area to estimate the projected undrained increments in the drained area (Ballard and Majid 1985). The adaptation by Dang and Lieffers (1989), the ring index method, was attempted. However, in our application some sample trees in drained areas had as few as five years radial increment after the maximum from which to project post-drainage growth trends. Consequently, the annual radial increments used for projection were decreasing rapidly and long-term projections were suspected of deviating from the true undrained growth trend. Thus, ring indices were calculated in undrained areas using the procedure of Dang and Lieffers (1989) to check for deviations in the growth projections. T-tests indicated that the projected growth trends for the undrained trees were significantly lower ($P < 0.01$) than the true growth trends in over 90 percent of the sample trees. The ring index method was thus abandoned in favor of the ratio method.

The purported advantage of the ring index method over the ratio method is that it utilizes the pre-drainage growth data from the drained sample trees to project a growth trend for the post-drainage period, whereas the ratio method assumes the growth trend found in the undrained areas can be applied to the drained areas as well.

In application of the ratio method, the pre-drainage growth rate used was the mean of the immediate three pre-drainage years. The derived growth response values were subtracted from the actual radial increments to derive a presumed undrained growth value. This presumed undrained growth increment was used as the denominator to determine the percent growth increase due to drainage ('adjusted growth response'). The adjusted growth response was analyzed by analysis of variance to test for pH effects. The statistical model of the sampling design used (Chapter 2) is:

$$Y_{ijkl} = \mu + \tau_i + \beta_{j(i)} + \varepsilon_{(ij)k} \qquad \begin{cases} i=1...4 \\ j=1...2 \\ k=1...3 \end{cases}$$

Where τ_i is the effect of the 'i'th pH level, and $\beta_{j(i)}$ is the effect of the 'j'th site within the 'i'th pH level.

5.3 RESULTS

The Neerlandia site was not included for reasons discussed in Section 2-1. The bole samples (n=10 per site x drainage area) indicated the ages of the stands averaged between 8 and 60 at the time of ditching (Table 5-1). Annual radial increments (Fig. 5-1) and annual basal area increments in selected years following ditching (Table 5-2) display the magnitude of growth response to ditching.

Table 5-1. Mean ages (yr) of sample trees at time of ditching†

	pH	7.2	6.6		5.2		4.0	
Treatment	Site	Salt	Fort 1	Fort 2	West	Niton	Seba	Tom
Undrained	Age	29	16	21	10	21	60	65
	SD	2.2	0.0	2.2	1.0	1.5	3.3	1.8
Drained	Age	16	11	21	6	21	46	56
	SD	4.2	0.8	2.4	4.4	3.0	5.5	3.5

†ring count at 30 cm bole height (n=10)

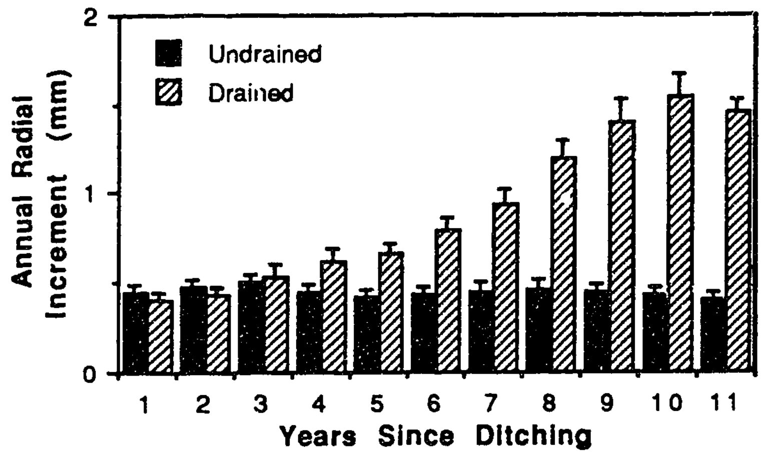

Fig. 5-1. Composite average for all seven sites of annual radial increments at 30 cm bole height for undrained and drained areas (SE bars)

Table 5-2. Initial basal area and annual basal area increments in selected years following ditching compared among drainage treatments (n=70)

Treatment		Period (yr) since ditching					
		1	3	5	7	9	11
	Initial BA	Annual BA increment					
	mm^2	mm^2					
Undrained	932	41.5	45.5	40.4	43.1	44.9	45.9
Drained	601	33.4	60.8	88.5	146	192	229
		% Response					
		-19.6	33.6	119	238	327	399

Results of the analysis of covariance using both annual radial increment and adjusted growth response are displayed for year seven only (Table 5-3). Since the pH 7.2 level had only one site (Table 5-1), only 3 degrees of freedom were available in the error terms used to test ditching effects. The same analysis procedure was used for the first 11 years following ditching; the results are summarized in Table 5-4. In both statistical models the sites within pH term, S(L), was the error term used to test the pH effect. The growth response model did not include drainage effects as the input data were adjusted growth responses only.

Table 5-3. Summary of analysis of covariance of annual radial increment and adjusted growth response (ratio method) for year seven after ditching

Input Data	SOURCE	DF	MS	F Ratio	P>F
	INIT	1	0.907	4.455	0.037
	pH level (L)	3	0.724	0.555	0.680
Annual	S(L)	3	1.306		
Radial	drainage (D)	1	23.300	7.833	0.068
Increment	L*D	3	1.429	0.480	0.719
	S*D(L)	3	2.975		
	error	121	0.204		
Adjusted	pH level (L)	3	395740	0.671	0.624
% Growth	S(L)	3	589472		
Response	error	60	24434		

Table 5-4. Summary of analysis of covariance of annual radial increment (ARI)† and of analysis of variance of adjusted % growth response (ratio method; RM) to test peat pH and drainage effects on black spruce radial increment at 30 cm bole height

Years since	Correlation†† coefficients		P>F INIT	P>F D§	P>F L§§		P>F L*D
Drainage	ARI	RM	ARI	ARI	ARI	RM	ARI
1	.575	.528	0.659	0.552	0.084	0.529	0.327
2	.613	.667	0.752	0.519	0.346	0.728	0.647
3	.677	.764	0.757	0.210	0.541	0.820	0.757
4	.631	.653	0.447	0.087	0.794	0.877	0.868
5	.723	.683	0.563	0.056	0.739	0.772	0.718
6	.756	.718	0.198	0.054	0.653	0.595	0.706
7	.849	.814	0.037	0.068	0.680	0.624	0.719
8	.875	.795	0.145	0.043	0.696	0.696	0.802
9	.897	.819	0.102	0.031	0.683	0.654	0.773
10	.862	.746	0.058	0.018	0.822	0.614	0.669
11	.897	.784	0.179	0.013	0.822	0.503	0.735

† Basal area at time of ditching (INIT) used as a covariate

†† Multiple R from analysis of variance

§ Drainage effect

§§ pH effect

Table 5-5. Growth response variables based on annual radial increment following year of ditching

	pH Level and Site						
	7.2	6.6		5.2		4.0	
	Sault	Fort 1	Fort 2	West	Niton	Seba §	Tom §
Year of statistically greater growth†	11	6	10	12+	12	7	6
Years to Maximum¶	18	9	19	30	12	11+	7+

† - year following ditching in which the cumulative drained radial increment exceeded the undrained increment at 95% confidence

¶ - year following ditching in which the annual radial increment reached a maximum in the drained area.

§ - maximum growth rate not yet achieved at sampling time

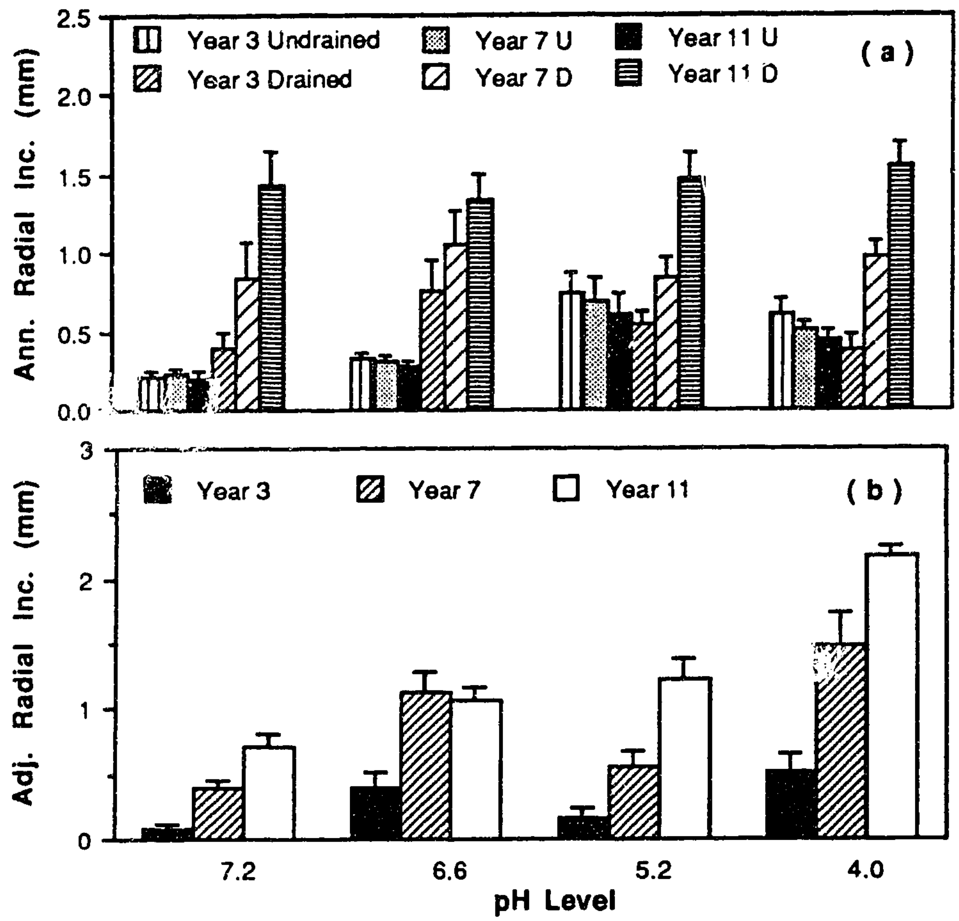

Fig. 5-2. Comparison for black spruce stemwood of a) annual radial increments and b) radial increments adjusted by the ratio method in selected years following ditching at 4 pH levels (SE bars)

5.4 DISCUSSION

Cumulative radial increment data indicate drainage resulted in an initial growth depression lasting 1 to 8 years (Appendix 5-2) followed by a growth increase which become significant 6 to more than 12 years after ditching (Table 5-5). The initial growth depression and response lag (Fig. 5-1) have been attributed to a combination of loss of contact of the shallow root systems with the water table leading to water stress (Strong and La Roi 1983, Lieffers and Rothwell 1987) and a greater photosynthate sink in the root systems as they expand in response to the lowered water table while still utilizing the same photosynthetic leaf area as in pre-drainage growth (Dang and Leiffers 1989).

The period from ditching to maximum annual radial increment ranged from 9 to 30 years (Table 5-5); more variable than the 13 to 19 years reported by Dang and Lieffers (1989). No pH effect was evident in the period until maximum post-ditching radial increment. The variability of the initial response period could be due to some inaccuracy in initial drainage dates. Ditching dates were estimated from county records of road building activity (Saulteaux, Fort 2, Westlock, Niton, and Tomahawk) and the exact year in which construction activity effected water table heights is uncertain. The variability in period to maximum post-ditching growth may be related to the variable climate among widely located sites, or variability in the stands' ages at the time of ditching.

The covariate, basal area at time of ditching, had a significant effect on radial increment only in years seven and ten following drainage though years eight, nine, and 11 were nearly significant (Table 5-4). The drainage treatment had significant effects in all years after year five (Table 5-4). Covariance can not be used in conjunction with the ratio method because the ratio method uses difference response (i.e., drained growth minus undrained growth) which can not be paired with individual basal area values. Also, the ratio method does not predict a growth trend from the pre-drainage period in the drained area. Hence, it is assumed the same trend would take place on drained and undrained areas provided drainage had not occurred. In this regard the ratio method is inferior to the ring index method. However, the ratio method should provide a more accurate estimate of drainage response than a simple analysis of the raw radial increment by providing a more accurate estimate of the presumed drained growth (Fig. 5-2). The responses derived with the ratio method were converted to percent responses of the presumed growth in drained areas to make responses more comparable amongst sites. The comparison amongst sites is valid only if drainage is similar at all sites.

Neither analysis method revealed any statistical difference in growth response amongst pH levels up to eleven years following drainage (Table 5-4).

5.5 CONCLUSIONS

Analysis of covariance was successfully used to show that annual radial growth of pole-sized black spruce in wetlands in Alberta was significantly greater in drained versus undrained areas starting at year five after ditching. The covariate, basal area at time of ditching, was a significant or nearly significant factor in the statistical model starting at year seven after ditching (Table 5-4). The ratio method provided a presumably more accurate measure of the post-ditching radial increment in drained areas than the raw radial increment data but does not an error term for a significance test of the drainage effect.

Analysis of covariance of radial increments and analysis of variance of the adjusted growth response (ratio method) indicated peat pH had no effect on growth response to drainage (Table 5-4). The ratio method was useful for testing the pH effect on black spruce radial growth response to drainage because it adjusted the drained increments for differences in climate during the post-ditching period (Fig. 5-2) which was necessitated by the use of widely located sites ditched in different calendar years.

The approach used in this study, one of utilizing sites with incidental drainage due to right-of-way ditch construction, resulted in variability in the depth of drainage amongst sites. No long term data is available for the changes in water table height over time and hence the effect of this variability on long term growth responses can not be eliminated from the analysis.

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6. SYNTHESIS

The nutrient status of seven fens in Alberta's boreal forest was assessed directly and indirectly through measurement of N mineralization, foliar and peat elemental analysis, and black spruce growth response analysis. The main objective of the study was to enhance understanding of the impacts of lowering the water table through ditching. By examining sites with a range of pH levels, which correlate with mire types differing in surface water chemistry (Sjörs, 1952), the effects of drainage were compared across the range of pH levels encountered in peatlands of the Boreal Wetland region in Alberta. Nitrate production in drained areas was examined in order to address environmental concerns.

6.1 SOIL MINERAL N, FOLIAR N AND BLACK SPRUCE GROWTH RELATIONS

Though mineral N g^{-1} C decreased at some sites and increased at others following drainage, foliar N concentration increased at all sites following drainage. A significant correlation (P=0.061) existed between mineral N (m/v) and foliar N content per needle (Table 6-1 and Fig. 6-1). The greater foliar N content in drained areas may be

Table 6-1. Simple correlation coefficients for† black spruce basal area increment, foliar nitrogen, and peat properties (n=12)

	FN	Db	MinN	N	P	K¶
BAI††	0.776***	0.436	0.609**	0.343	0.186	-0.245
FN§		0.637**	0.555*	0.548*	0.482	0.163
Db§§			0.397	0.966***	0.923***	0.503*
MinN¶				0.326	0.125	-0.398
N¶					0.962***	0.518*
P¶						0.728***

† *,**,***, denote significance at, respectively, the 90, 95, and 99% levels of confidence

†† BAI: basal area increment during last 3 years, 30 cm bole height

§ FN: foliar nitrogen content per needle

§§ Bulk density of peat (Mg m^{-3})

¶ Concentration in peat (m/v)

attributed to greater mineral N concentration (m/v), deeper roots of black spruce (Lieffers and Rothwell 1987) with lowered water table, and the cumulative effects of both over time such that retranslocated N to current-year needles is increased (Nambiar and Fife 1987).

At sites where increased Db resulted in increased θ despite a lower water table, the lower water table may still have provided an increased available rooting volume than in undrained areas. This is because the presumably smaller pore size distribution could have caused a more gradual transition in θ above the water table. Another interesting result of the more gradual transition in θ is that the tree's root system could occupy a thicker layer above the water table (Lieffers and Rothwell 1987) which would make it more able to withstand changes in water table height. The correlation between stemwood growth and foliar N is shown in Fig. 6-2 and Table 6-1.

The significant correlations found between mineral N (m/v), foliar N per needle, and radial stemwood growth (Figs. 6-1, 6-2, 6-3, and Table 6-1) suggest that N may be the limiting factor to black spruce growth in the Boreal Wetland region of Alberta. Also, NPK fertilization of an Alberta peatland indicated N was the most limiting nutrient (Mugasha et al. 1991). Furthermore, N was the only foliar macronutrient which was correlated with peat contents (Table 4-7), or with black spruce basal area increments (Table 6-1). Foliar analysis results (Chapter 4) indicated that drainage alleviates the N deficiency. Figures 6-1, 6-2, and 6-3 provide additional evidence that drainage increases black spruce growth in Alberta peatlands by alleviating N deficiency.

6.2 LIMITATIONS OF SAMPLING DESIGN

Ideal study sites were difficult to find, especially as regards pH levels. The pH, drainage, soil, and stand criteria left few options in site selection and consequently sites were accepted which introduced unavoidable variability with respect to geographic location, calendar year of drainage, initial water table depth, and depth of drainage

(Chapter 2). These sources of variability could have obscured treatments effects in all the experiments. In particular, the variability within study areas in N mineralization was already high (CV ≈ 133%) and the added variability among site undoubtedly made the N mineralization experiment fairly insensitive to treatment eff· :ts.

Comparison of stem growth responses between sites was ha red by the same site differences associated with mineralization and foliar analysis. ˜l .e ring index method of analysis could not be applied as the sample trees were too young at time of drainage. The ratio method was used and allowed comparison between sites though assumptions of homogeneity of growth trends were required. A clear growth increase was measured over the first eleven years following drainage.

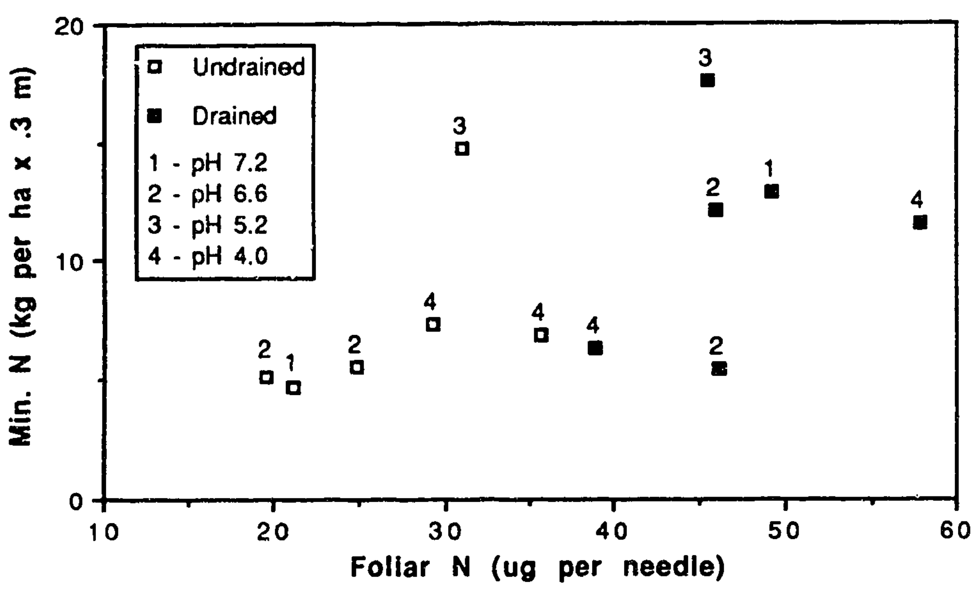

Fig. 6-1. Relationship between mineral N (m/v) from in-situ incubation and foliar N content of current-year needles of black spruce

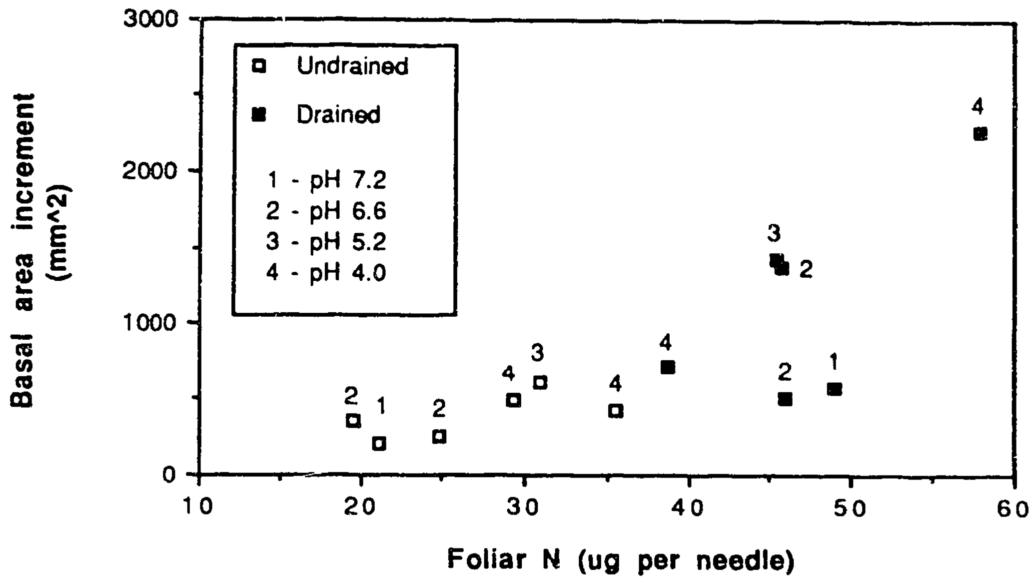

Fig. 6-2. Correlation between annual stemwood growth of black spruce (measured at 30 cm height)and foliar N content per current-year needle

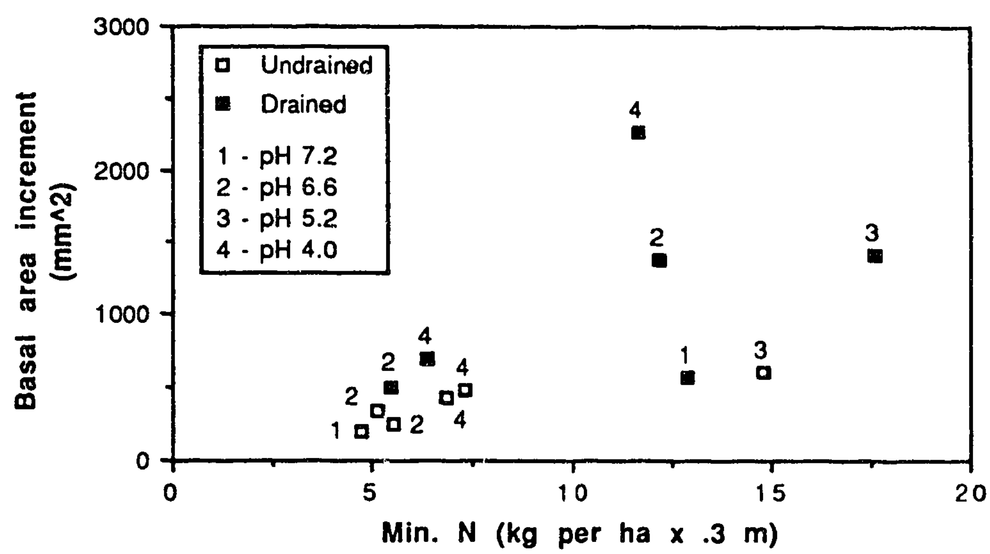

Fig. 6-3. Correlation between annual stemwood growth of black spruce (measured at 30 cm height) and mineral N from in situ incubation in the upper 30 cm of peat.

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Appendix 2-1. Species cover by site and drainage treatment†

Species	Sault		Fort 1		Fort 2		West		Niton		Seba		Tom	
	U††	D	U	D	U	D	U	D	U	D	U	D	U	D
Moss Layer														
Aulacomium palustre	3	23	3	20	3	7	13	23	T	20	3		T	7
Campylium stelatum	T			17	20									
Calliergon spp.	T	T							T					
Drepanocladus spp.				3					T				T	T
Hylocomium splendens	10		3		3	20	30		33	17		20		7
Pleurozium schreberi	23	7	3	10	30	27	50	27	13	30	43	27	7	23
Polytrichum strictum	T	17	3		3	T		20	T		T	23	T	T
Ptilium crista-castrensis							T	T	T	7	3	7		T
Sphagnum angustifolium			3		7	T	T	7	23				40	47
Sphagnum fuscum	30	13	33					13	10		37	3	3	7
Sphagnum magellanicum									20				50	10
Sphagnum nemoreum		3	3					3						
Tomenthypnum nitens	17	13	36	10	T	27			T	20		13		
Cladina spp.			3		27	20	7	T			3	3		
Cladonia spp.		T	3		T	T	T	T			6	6		
Mnium spp.			3	T				T						
Peltigera spp.			T		3	T								
Herb and Shrub Layer														
Adenocaulen bicolor			T											
Andromeda pol		3												
Caltha palustris			T											
Epilobium spp.				10										
Equisetum fluviatile			27	20	3	6								
Galium labradoricum				T										
Grass spp.	3	20		20	T	T			T	7				
Ledum groenlandicum	27	23	37	13	53	53	87	23	60	10	80	80	17	47
Linneae borealis				T										
Petasites vitae			T	3										
Ribes spp.				T										
Rubus chamaemorus			T		T	T	T	T	10	T			13	7
Smilicana spp.	T	T						T						
Vaccinium vitis-ideae	20	20	23	13	20	7	7	13	17	17	17	20	3	7
Vaccinium oxycoccus	10	10	3	T	T	7					T	T		
Vaccinium myrtilloides			3	7	3	7								
Tree Layer														
Betula papyrifera			T	T										
Betula pumila	T		T	T					T	T				
Larix laricina	6			3	T	T	3		7	7	T	3		
Picea mariana	40	70	53	43	60	57	53	63	63	57	47	47	67	73
Populus tremuloides				10				T						
Salix spp.		10	T	27	7	7		7	T					

† Species abundance was determined by ocular estimation and reported in coverage classes. Coverage classes were: T (trace): ≤5%, 10%: >5 - 15%, 20%: >15 - 25% .....100%: >95 - 100%. Tabulated data represents means of 3 plots. Moss layer and shrub and herb layer plots were 1 m in diameter and tree layer plots were 10 m in diameter.

†† n=3 for undrained (U) and drained (D) areas

Appendix 2-2. Field determined stage of peat humification according to von Post and Granlund (1925)

		Drainage Treatment					
		Undrained			Drained		
Site	Depth	†1	2	3	1	2	3
	(cm)	††					
Saulteaux	0-10	2	1	1	1	2	1
	10-20	3	1	1	3	4	2
	20-30	4	2	4	3	4	2
Fort 1	0-10	2	2	1	4	5	4
	10-20	4	2	2	5	4	4
	20-30	6	2	3	6	4	5
Fort 2	0-10	2	3	3	3	2	2
	10-20	5	3	3	3	3	5
	20-30	5	7	4	6	4	5
Westlock	0-10	2	2	1	2	1	1
	10-20	2	2	1	2	2	2
	20-30	2	2	2	3	3	3
Niton	0-10	1	2	2	1	1	1
	10-20	2	3	3	3	3	4
	20-30	2	4	3	3	3	4
Seba	0-10	3	2	1	3	2	2
	10-20	3	3	3	3	2	2
	20-30	3	3	3	3	3	2
Tomahawk	0-10	2	3	4	3	4	4
	10-20	4	3	3	3	3	3
	20-30	4	3	3	4	3	3

† Numbers 1, 2 and 3 represent the three replicate cores sampled in each site x drainage area.

†† Data represent humification class; 1= completely unhumified, 10= completely humified (von Post and Granlund 1925)

Appendix 2-3. Preparation of peat for KCL extraction of mineral N

Preliminary results from analysis of mineral N in subsamples bulked from a few randomly picked subsubsamples of undisturbed field-fresh peat had poor reproducibility (CVs ca 30%). Lack of homogenization prior to subsampling was suspected to be a source of the variability as our experience indicated inadequate homogenization can result in inaccurate dry mass estimates and variability in the mineral N contents of subsamples. Homogenization of field-fresh peat can not always be performed with the grinding equipment used for mineral soils because of the high water contents. Homogenization by hand may be adequate but is tedious. A household meat grinder was considered as a possible alternative to hand homogenization.

For mineral N extraction the period required for equilibration of a peat sample with 1 M KCl may be greater than the 60 minute shaking period recommended for mineral soils (Keeney and Nelson 1982). In preliminary work, a contact period of a week before filtration yielded significantly greater results for NH_4-N and NO_3-N than a similar sample that was filtered immediately after shaking with KCl. The euqilibration period may also be affected by the stage of decomposition of the peat as the more decomposed peat may contain slowly exchangeable NH_4-N.

A three-factor experiment was conducted that compared the effects of two peat sources, three standing periods, and two methods of peat homogenization on the quantity and reproducibility of mineral N in KCl extracts.

Materials and Methods

Field-moist peat from two sites (Table 1) was sampled with a box sampler and transported/stored as described previously (Section 3.2). Each peat was homogenized by hand breaking into pieces of approximately 1-2 cm length or by forcing through a 4 mm aperature of a household meat grinder. Subsamples were dried at 105 °C for 24 hrs for water determination. Mineral N was extracted from moist subsamples equivalent to

6 grams oven dry weight with 180 mL of KCl solution equivalent to 1 M after dilution by peat water. Suspensions were shaken for 1 hour and left standing at 5° C for zero, one, or seven days prior to filtering through Whatman No. 1 filter paper. Extracts were frozen until analysis for NH_4-N and NO_3-N individually by steam distillation (Bremner and Shaw 1955). Concentration of H_2SO_4 titrant was .005 N. Reproducibility of water content and mineral N determinations were compared amongst homogenization methods and analysis of variance was used to determine if homogenization methods and/or standing periods affected KCl-extractable mineral N.

Table 1. Peat materials for mineral N extraction

Site†	Microsite	Depth (cm)	pH††	Humification§
Fort 1	drained hummocks	10-30	6.6	H6
Seba	undrained hollows	20-40	4.0	H2

† Site description in Chapter 2
†† measured from expressed peat water
§ according to von Post and Granlund (1925)

Results

Coefficient of variation (CV) for water content was reduced from 2.7% to 0.3% when the peat was ground before subsampling compared to hand mixed (Table 2). Similarly, the mean of the CVs for NH_4-N was reduced from 9.5% to 2.8% by grinding before subsampling (Table 3). The mean of the CVs of NO_3-N was not affected by preparation method. Grinding increased NH_4-N ($P<0.001$, Table 4) by 8-10 ug/g in both peats; NO_3-N was not affected (Figure 1).

Table 2. Means and CVs of peat water determinations following two homogenization methods (n=3)

Homog. Method	Peat Source	H_2O % wt.	CV%
Hand Mixed	Seba	632	5.3
	Fort 2	426	1.1
Ground	Seba	648	0.3
	Fort 2	439	0.4

Table 3. Means and CVs of mineral N extracted following two homogenization methods and three standing times (n=3)

Homog. Method	Peat Source	Standing Period	— NH_4-N —		— NO_3-N —	
		days	ug/g	CV(%)	ug/g	CV(%)
Hand Mixed	Fort	0	5.5	34.4	24.0	7.2
		1	5.1	8.2	23.0	6.4
		7	6.8	3.1	21.5	8.0
	Seba	0	55.3	3.5	4.9	65.0
		1	49.8	3.6	4.6	24.7
		7	61.1	4.0	9.6	33.9
Ground	Fort	0	13.3	2.3	24.4	10.1
		1	13.1	8.1	21.9	16.2
		7	16.1	3.3	23.1	9.3
	Seba	0	62.8	0.1	6.5	19.3
		1	64.1	1.4	5.9	40.2
		7	68.0	1.4	7.6	54.5

Standing period resulted in small but significant ($P<0.001$) increases in NH_4-N for the 7 day standing period compared to immediate extraction (Figure 2). The differences between zero standing time and one day standing time were insignificant (Figure 2). However, significant peat x period interactions occurred for NH_4-N and NO_3-N.

Table 4. Summary of analysis of variance of the effects of two peat sources, three standing periods and two homogenization methods on the concentration of NH_4-N and NO_3-N in KCl extracts

		NH_4-N			NO_3-N		
SOURCE	DF	MS	F-RATIO	P>F	MS	F-RATIO	P>F
Peat	1	22732.1	8367.6	<0.001	2437.7	373.8	<0.001
Period	2	80.7	29.7	<0.001	8.5	1.3	0.289
Homog	1	725.5	267.1	<0.001	1.0	0.3	0.695
Peat* Period	2	21.3	7.8	0.002	18.2	2.8	0.080
Peat* Homog	1	3.5	1.2	0.277	0.0	0.0	0.996
Period* Homog	2	10.8	4.0	0.031	1.2	0.2	0.836
Error	26	2.7			6.5		

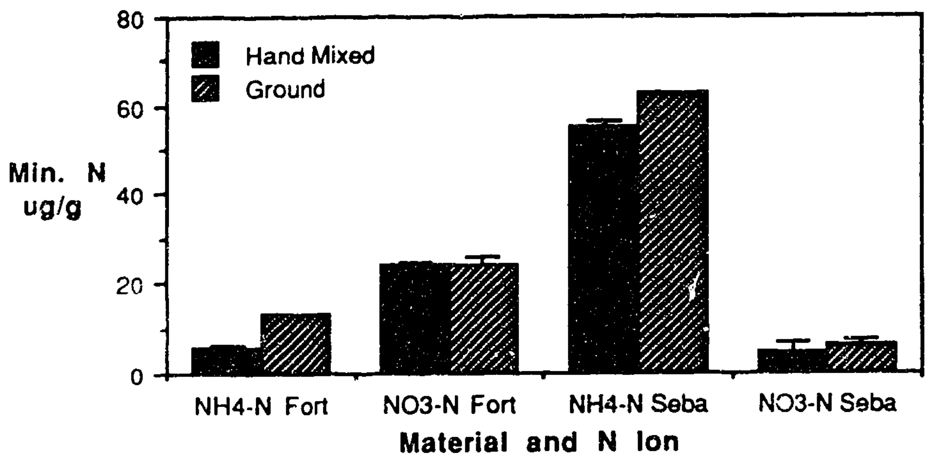

Fig. 1. Effects of two homogenization methods on KCl extractable N in peat (n=3, SE bars)

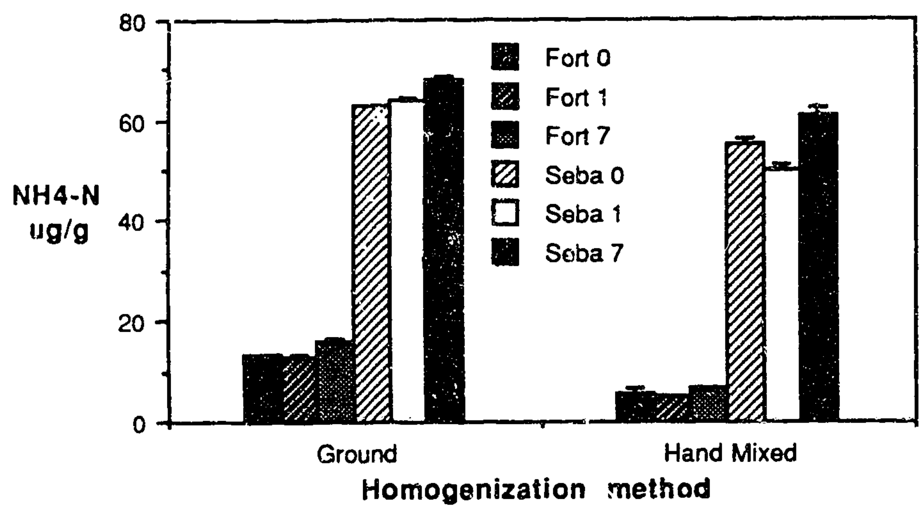

Fig. 2. Effects of three standing periods (0, 1, and 7 days) and two homogenization methods on KCl extractable mineral N in peat (n=3, S.E. bars)

Discussion

Grinding before subsampling is preferred from the standpoint of decreased variability in dry weight equivalents mineral N concentrations among subsamples but is unacceptable because it results in substantially higher NH_4-N determinations than in undisturbed samples which are more representative of the field condition under study. The variability in NH_4-N includes sources introduced in all the analysis steps: *i)* subsampling for moisture determination and *ii)* for KCl extraction, and *iii)* steam distillation. The CV for NH_4-N of 9.5% found amongst subsamples in this experiment was low compared to the NH_4-N CVs (approximately 133%) found amongst samples collected within site by drainage areas (Chapter 3). If the sampling design (Chapter 2) can detect differences between drainage areas despite this high spatial variablility, the variability of 9.5% introduced at the preparation and analysis stages is unlikely to prevent detection of differences amongst field areas. Thus the hand mixing method is acceptable and preferred over the grinding method. The interaction between peat and standing period indicates one hour may not be ideal for all peats. Two peat types is an insufficient sample for a general recommendation regarding standing period.

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APPENDIX 3-1. Bulk density, ash, and volumetric water content

Table 1: Bulk density (Db), ash, and volumetric water content (θ) of peat in samples adjacent to samples incubated in-situ for N mineralization, compared across sites and drainage and depth levels

Treatment	n=	Db		Ash †		θ	
		Undrained	Drained	Undrained	Drained	Undrained	Drained
		Mg m^{-3}	Mg m^{-3}	% wt.	% wt.	m^3 m^{-3}	m^3 m^{-3}
pH 7.2	9	0.056	0.075	11.6	16.2	58.8	37.0
pH 6.6	18	0.046	0.131	10.9	13.7	39.0	57.3
pH 5.6	9	0.052	0.129	3.7	8.5	36.6	79.3
pH 4.0	18	0.050	0.068	3.6	3.9	56.2	48.6
0-10 cm	18	0.039	0.081	6.9	10.7	30.8	34.7
10-20 cm	18	0.045	0.103	6.8	10.9	48.2	57.1
20-30 cm	18	0.066	0.117	8.0	10.4	64.0	72.3
Undrained	54	0.050		7.3		47.6	
Drained	54	0.101		10.7		54.7	

† Ash contents are weighted means obtained by weighting Ash cell means with corresponding Db cell means (each cell equals one 'site x drainage x depth' combination, n=3).

Table 2: Volumetric water content (θ) of peat in samples adjacent to samples incubated in-situ for N mineralization compared across sites and drainage and depth levels

Area	Site	0-10 cm	10-20 cm	20-30 cm	0-30 cm
		m^3 m^{-3}			
Undrained	Salt	48	49	40	46
	Fort 1	21	39	70	43
	Fort 2	23	37	42	34
	West	19	36	55	37
	Seba	25	45	68	46
	Tom	47	60	82	63
Drained	Salt	19	48	53	40
	Fort 1	40	55	64	53
	Fort 2	41	78	73	64
	West	63	74	91	76
	Seba	20	34	47	34
	Tom	25	57	90	58

Table 3: Carbon content, ash, and bulk density (Db), of peat in samples adjacent to samples incubated in-situ for N mineralization compared across sites and drainage and depth levels

Property	Area	Site	0-10 cm	10-20 cm	20-30 cm	0-30 cm
C (% wt.)	Undrained	Salt	47.9	46.1	46.4	46.7†
		Fort 1	50.1	48.8	48.5	48.9
		Fort 2	46.3	49.0	50.0	48.4
		West	49.9	49.8	49.8	49.8
		Seba	49.4	46.4	49.0	48.4
		Tom	47.7	50.0	49.1	49.1
	Drained	Salt	44.2	45.3	44.7	44.8
		Fort 1	49.8	49 3	49.4	49.5
		Fort 2	44.6	51.0	50.1	48.9
		West	49.5	51.6	50.1	50.4
		Seba	47.7	47.6	49.8	48.5
		Tom	48.9	49.1	49.8	49.4
Ash (% wt.)	Undrained	Salt	5.2	14.0	13.2	11.6†
		Fort 1	4.4	9.7	12.9	10.4
		Fort 2	15.3	7.5	10.4	11.3
		West	3.0	3.5	4.6	3.7
		Seba	4.1	2.6	2.7	3.1
		Tom	6.9	3.9	3.1	4.2
	Drained	Salt	11.8	18.6	16.4	16.2
		Fort 1	12.3	14.6	15.2	14.2
		Fort 2	16.4	11.4	12.8	13.3
		West	9.2	7.4	8.7	8.5
		Seba	3.4	4.4	2.9	3.5
		Tom	4.9	5.2	3.5	4.3
Db (Mg m^{-3})	Undrained	Salt	0.038	0.051	0.079	0.056
		Fort 1	0.025	0.034	0.070	0.043
		Fort 2	0.051	0.041	0.053	0.048
		West	0.048	0.049	0.058	0.052
		Seba	0.039	0.044	0.066	0.050
		Tom	0.032	0.049	0.071	0.051
	Drained	Salt	0.050	0.088	0.086	0.075
		Fort 1	0.096	0.130	0.144	0.123
		Fort 2	0.113	0.151	0.153	0.139
		West	0.123	0.124	0.139	0.129
		Seba	0.060	0.069	0.090	0.073
		Tom	0.041	0.057	0.093	0.064

† Carbon and ash contents for 0-30 cm are weighted means obtained by weighting Ash cell means for each depth with corresponding Db cell means (each cell equals one 'site x drainage x depth' combination, n=3).

Appendix 3-2. Means (n=3) of NH_4-N, NO_3-N, and total mineral N for samples incubated in-situ, compared across sites and drainage and depth levels

Variable	Tmt	Site	0-10 cm	10-20 cm	20-30 cm	0-30 cm†
NH_4-N ug g^{-1} C	Undrained	Sault	129.5	30.9	50.4	62.5
		Fort 1	78.6	141.3	43.4	76.3
		Fort 2	94.7	85.2	28.6	68.0
		West	444.9	124.5	33.5	189.4
		Seba	199.3	-123.4	136.1	76.0
		Tom	38.2	72.4	144.6	98.8
	Drained	Sault	228.8	111.8	90.1	129.8
		Fort 1	83.0	36.7	19.2	41.9
		Fort 2	-78.0	9.5	34.7	-5.1
		West	193.0	38.3	20.8	81.3
		Seba	190.[illegible]	20.3	86.9	94.6
		Tom	199.[illegible]	-10.9	42.9	60.4
NO_3-N ug g^{-1} C	Undrained	Sault	5.0	6.6	12.4	9.0
		Fort 1	3.0	0.3	5.2	3.5
		Fort 2	6.5	6.6	6.7	6.6
		West	4.6	3.4	6.1	4.8
		Seba	21.3	12.7	11.8	14.6
		Tom	9.2	[illegible].5	6.2	6.9
	Drained	Sault	6.2	[illegible].9	12.3	9.6
		Fort 1	31.8	[illegible]	16.0	19.1
		Fort 2	41.5	14.[illegible]	25.7	25.8
		West	7.1	4.[illegible]	9.3	7.1
		Seba	8.7	6.[illegible]	4.4	6.1
		Tom	9.4	3.9	12.3	9.2
Total Min. N ug g^{-1} C	Undrained	Sault	134.5	37.5	62.8	71.5
		Fort 1	81.6	141.7	48.6	79.8
		Fort 2	101.2	91.8	35.3	74.6
		West	449.5	127.9	39.7	194.2
		Seba	220.7	-110.7	147.9	90.6
		Tom	47.3	78.9	150.8	105.7
	Drained	Sault	235.0	120.7	102.4	139.4
		Fort 1	114.9	49.8	35.2	61.0
		Fort 2	-36.5	23.6	60.4	20.7
		West	200.1	43.0	30.0	88.4
		Seba	199.5	26.3	91.3	100.7
		Tom	208.6	-7.0	55.3	69.6

Variable	Tmt	n	0-10 cm	10-20	20-30
			ug/g C		
NH_4-N	Undrained	18	180.4	52.6	74.9
	Drained	18	111.7	34.8	43.3
NO_3-N	Undrained	18	8.3	6.2	8.2
	Drained	18	20.4	9.4	14.4
Total Min. N	Undrained	18	188.7	58.8	83.1
	Drained	18	132.1	44.2	57.7

† Weighted means were obtained by multiplying mineral N cell means by corresponding Db cell means (each cell equals one 'site x drainage x depth' combination; n=3) then dividing by the overall Db mean of the current treatment level.

APPENDIX 3-3. Analysis of variance summary for concentration of Mineral N per gram C, NO_3-N per gram C, and Mineral N per gram N from in-situ incubation using a model with log10(θ) as a covariate.

Variable	SOURCE†	DF	MS	F Ratio	P>F
Mineral N g^{-1} C	L	3	32052	7.38	0.122
	error S(L)	2	4343		
	D	1	8819	3.96	0.185
	L*D	3	11176	5.02	0.171
	error S*D(L)	2	2227		
	R(L*S*D)	24	10501		
	P	2	54107	6.41	0.057
	L*P	6	45081	5.34	0.063
	error S*P(L)	4	8435		
	D*P	2	751	0.05	0.954
	L*D*P	6	11758	0.75	0.641
	error S*D*P(L)	4	15639		
	log10(θ)	1	386		
NO_3-N g^{-1} C	L	3	355.9	1.85	0.369
	error S(L)	2	192.0		
	D	1	447.3	7.02	0.118
	L*D	3	621.7	9.76	0.094
	error S*D(L)	2	63.7		
	R(L*S*D)	24	123.0		
	P	2	258.8	8.50	0.063
	L*P	6	114.6	3.77	0.110
	error S*P(L)	4	30.4		
	D*P	2	79.8	2.25	0.222
	L*D*P	6	93.0	2.62	0.186
	error S*D*P(L)	4	35.5		
	log10(θ)	1	110.1		
Mineral N g^{-1} N	L	3	144008	14.96	0.063
	error S(L)	2	9627		
	D	1	100678	12.14	0.073
	L*D	3	51434	6.20	0.142
	error S*D(L)	2	8295		
	R(L*S*D)	24	31099		
	P	2	175569	5.21	0.077
	L*P	6	127470	3.78	0.109
	error S*P(L)	4	33726		
	D*P	2	7762	0.25	0.791
	L*D*P	6	46508	1.49	0.364
	error S*D*P(L)	4	31209		
	log10(θ)	1	136		

† Where:
L = peat pH level (7.2, 6.6, 5.2, 4.0)
S = sites within pH levels (1 or 2)
D = drainage treatment (undrained or drained)
P = depth level (0-10 cm, 10-20 cm, and 20-30 cm below live moss)

APPENDIX 3-4. Total elemental P† and K†† and C:N Ratios for peat samples adjacent to samples incubated in-situ, compared across sites and drainage and depth levels

Variable	Tmt	Site	0-10 cm	10-20 cm	20-30 cm	0-30 cm§
P ug g-1 C	Undrained	Sault	1005	1347	1165	1184
		Fort 1	1070	1461	1603	1463
		Fort 2	1634	1701	1688	1673
		West	1066	529	494	682
		Seba	1169	1020	735	934
		Tom	1539	1208	609	998
	Drained	Sault	1076	1806	1362	1472
		Fort 1	1436	1268	1062	1231
		Fort 2	1340	1366	1339	1349
		West	1257	885	657	922
		Seba	1057	811	680	825
		Tom	1281	1190	661	953
K ug g-1 C	Undrained	Sault	1735	1110	494	965
		Fort 1	1586	1248	700	1017
		Fort 2	2199	1439	835	1488
		West	854	164	49	334
		Seba	1425	830	253	732
		Tom	1434	916	107	648
	Drained	Sault	1732	978	530	975
		Fort 1	818	274	371	452
		Fort 2	2004	1029	691	1170
		West	543	83	-21	192
		Seba	1216	472	75	514
		Tom	1170	669	79	490
C:N Ratio	Undrained	Sault	63.8	56.6	47.4	53.9
		Fort 1	65.0	42.8	37.0	43.9
		Fort 2	42.9	39.8	34.2	38.8
		West	53.8	77.6	70.5	67.6
		Seba	64.1	58.0	59.3	60.2
		Tom	41.9	44.9	61.7	52.1
	Drained	Sault	55.1	35.2	37.3	40.5
		Fort 1	36.1	31.0	35.5	34.1
		Fort 2	49.9	37.5	37.6	40.9
		West	40.4	43.2	54.0	46.2
		Seba	62.3	65.0	53.1	59.4
		Tom	43.9	42.3	58.8	50.6

† Determined by digestion in H2O2 and H2SO4 followed by colometric analysis (Sections 3.2 and 4.2)

†† Determined by ashing at 495° C and dissolution in aqua-regia followed by analysis with ICP-AES (Sections 3.2 and 4.2)

§ Weighted means were obtained by multiplying mineral N cell means by corresponding Db cell means (each cell equals one 'site x drainage x depth' combination; n=3) then dividing by the overall Db mean of the site x drainage treatment (n=9).

Appendix 3-5. Properties of peat samples incubated in-situ or adjacent to incubated samples (individual cases)

Site	Depth	Db	Porosity	Ash	H_2O	C	NH_4-N	NO_3-N	Min N
†	††	Mg/m^3	% Vol.§	% Wt	Mg/m^3	%Wt	——	ug/g C	——
Sault	1	0.035	97.7	5.3	0.25	49.7	78.9	7.8	87
U	1	0.028	98.1	7.8	0.55	47.7	304.5	5.2	310
	1	0.052	96.6	2.5	0.69	46.3	5.0	2.0	7
	2	0.035	97.7	16.4	0.45	47.7	85.4	4.9	90
	2	0.035	97.7	14.6	0.44	46.7	30.6	5.9	15
	2	0.084	94.5	11.0	0.83	44.1	-23.3	9.1	-14
	3	0.040	97.4	15.9	0.58	47.5	22.5	23.3	46
	3	0.045	97.0	10.9	0.38	46.0	71.3	4.1	75
	3	0.151	90.1	12.8	1.00	45.8	57.3	10.0	67
Sault	1	0.038	97.5	17.3	0.11	40.4	450.1	4.8	455
D	1	0.067	95.6	11.8	0.24	45.6	152.7	7.3	160
	1	0.046	97.0	6.3	0.15	46.8	83.6	6.7	90
	2	0.058	96.2	15.7	0.24	47.8	209.7	12.2	222
	2	0.088	94.2	15.0	0.45	46.6	42.1	6.6	49
	2	0.117	92.3	25.2	0.63	41.5	83.6	7.9	92
	3	0.062	95.9	14.8	0.31	46.5	51.7	18.6	70
	3	0.105	93.1	14.4	0.80	45.7	104.0	13.9	118
	3	0.091	94.0	19.9	0.40	41.9	114.7	4.2	119
Fort 1	1	0.025	98.4	3.1	0.20	51.7	50.4	1.4	52
U	1	0.023	98.5	5.1	0.27	47.2	139.1	0.9	140
	1	0.027	98.2	5.1	0.19	51.5	46.2	6.7	53
	2	0.044	97.1	11 4	0.53	48.7	146.3	-3.5	143
	2	0.036	97.6	10.5	0.33	49.2	213.2	-5.8	207
	2	0.023	98.5	7.3	0.26	48.5	64.5	10.4	75
	3	0.070	95.4	13.9	0.57	50.2	32.7	11.1	44
	3	0.065	95.7	11.8	0.58	49.3	33.8	-1.5	32
	3	0.075	95.1	13.0	0.91	46.0	63.7	5.9	70
Fort 1	1	0.103	93.2	13.2	0.41	52.3	128.0	23.4	151
D	1	0.085	94.4	10.8	0.36	47.5	-191.0	17.9	-173
	1	0.099	93.5	12.7	0.28	49.8	312.1	54.2	366
	2	0.112	92.6	13.3	0.54	49.4	23.5	18.3	42
	2	0.138	90.9	12.1	0.62	50.1	48.5	8.0	56
	2	0.141	90.7	18.3	0.44	48.4	38.1	13.0	51
	3	0.184	87.9	16.7	0.94	49.7	35.1	19.9	55
	3	0.102	93.3	16.7	0.45	47.9	40.6	8.8	49
	3	0.144	90.5	12.1	0.57	50.5	-18.2	19.3	1

† U=undrained area
D=drained area

†† 1=0-10 cm, 2=10-20 cm, 3=20-30 cm; 3 samples of each

§ Calculated from Db and an assumed particle density of 1.52 Mg m^{-3}.

Appendix 3-5. Peat properties (continued)

Site	Depth	Db	Porosity	Ash	H_2O	C	NH_4-N	NO_3-N	Min N
†	††	Mg/m^3	% Vol.§	% Wt	Mg/m^3	%Wt	——	ug/g C	——
Fort 2	1	0.054	96.4	8.6	0.17	49.2	228.5	7.6	236
U	1	0.049	96.7	13.1	0.33	49.6	4.0	7.8	12
	1	0.050	96.7	24.2	0.18	40.2	51.6	4.1	56
	2	0.050	96.7	7.8	0.46	49.6	184.7	5.1	190
	2	0.038	97.5	7.8	0.54	49.6	-0.5	6.3	6
	2	0.034	97.7	6.8	0.28	48.0	71.4	8.4	80
	3	0.059	96.1	10.4	0.38	50.4	35.3	-0.4	35
	3	0.054	96.5	10.6	0.54	50.5	44.8	7.8	53
	3	0.045	97.0	10.2	0.31	49.2	5.7	12.6	16
Fort 2	1	0.119	92.2	9.2	0.52	48.0	-98.7	67.5	-18
D	1	0.142	90.7	13.9	0.57	46.3	-39.7	3.3	-36
	1	0.079	94.8	26.0	0.28	39.4	-95.7	53.8	-30
	2	0.159	89.5	9.8	0.87	52.1	73.4	30.9	104
	2	0.158	89.6	13.0	0.79	51.4	18.5	3.7	22
	2	0.137	91.0	11.4	0.72	49.4	-63.3	7.6	-56
	3	0.155	89.8	12.9	0.61	49.9	36.9	8.3	43
	3	0.142	90.6	14.0	0.77	50.2	12.5	23.0	36
	3	0.161	89.4	11.5	0.57	50.3	54.6	45.7	100
West	1	0.044	97.1	3.8	0.14	50.8	344.1	11.0	355
U	1	0.045	97.1	2.3	0.17	49.9	726.4	0.3	727
	1	0.055	96.4	2.7	0.28	49.1	264.1	2.4	267
	2	0.053	96.5	4.7	0.44	50.0	96.9	4.9	102
	2	0.040	97.4	2.6	0.26	49.7	117.9	3.1	121
	2	0.054	96.5	3.4	0.37	49.5	158.7	2.1	169
	3	0.043	97.2	6.4	0.31	51.3	37.2	2.1	39
	3	0.065	95.7	3.4	0.67	48.6	53.8	9.9	64
	3	0.067	95.6	3.9	0.66	49.6	9.5	6.5	16
West	1	0.107	93.0	11.4	0.62	47.0	95.0	8.4	103
D	1	0.143	90.6	7.9	0.85	49.9	234.9	5.4	240
	1	0.120	92.1	8.3	0.43	51.5	249.1	7.4	256
	2	0.154	89.8	8.6	0.81	52.5	20.0	9.7	30
	2	0.115	92.5	7.2	0.65	51.4	64.2	0.4	65
	2	0.104	93.2	6.4	0.76	50.8	30.8	3.7	35
	3	0.188	87.6	13.6	1.00	49.1	22.4	10.2	33
	3	0.133	91.2	6.8	0.92	49.5	22.4	13.4	36
	3	0.096	93.7	5.8	1.00	51.7	17.4	4.3	22

† U=undrained area
D=drained area

†† 1=0-10 cm, 2=10-20 cm, 3=20-30 cm; 3 replicates of each

§ Calculated from Db and an assumed particle density of 1.52 Mg m^{-3}.

Appendix 3-5. Peat properties (continued)

Site	Depth	Db	Porosity	Ash	H_2O	C	NH_4-N	NO_3-N	Min N
†	††	Mg/m^3	% Vol.§	% Wt	Mg/m^3	%Wt		ug/g C	
Seba	1	0.047	96.9	5.3	0.34	51.7	126.3	24.5	151
U	1	0.023	98.5	4.3	0.14	47.6	227.9	11.4	239
	1	0.048	96.8	2.9	0.32	49.0	243.8	28.1	272
	2	0.039	97.4	2.5	0.46	46.9	21.4	5.4	27
	2	0.053	96.5	2.4	0.67	45.6	-385.1	17.9	-367
	2	0.040	97.4	2.9	0.50	46.8	-6.6	14.9	8
	3	0.051	96.6	3.2	0.68	49.7	25.3	4.2	30
	3	0.082	94.6	2.7	1.00	50.0	365.6	23.1	389
	3	0.064	95.8	2.3	0.73	47.4	17.4	8.2	26
Seba	1	0.059	96.1	2.8	0.26	47.5	186.4	11.2	198
D	1	0.073	95.	4.0	0.18	48.3	310.2	8.1	318
	1	0.049	96.8	3.4	0.26	47.1	75.9	6.8	83
	2	0.056	96.3	7.8	0.33	45.5	22.8	7.8	31
	2	0.071	95.4	3.0	0.20	48.0	-25.8	5.0	-21
	2	0.080	94.7	2.5	0.34	49.2	63.9	5.4	69
	3	0.070	95.4	3.8	0.39	50.9	26.6	6.6	33
	3	0.098	93.6	2.7	0.57	48.3	62.6	3.2	66
	3	0.103	93.2	2.2	0.47	50.2	171.4	3.4	175
Tom	1	0.034	97.8	12.0	0.32	45.0	.	.	.
U	1	0.022	98.6	4.1	0.23	49.6	51.7	6.0	58
	1	0.041	97.3	4.7	0.78	48.5	24.7	12.3	37
	2	0.034	97.7	2.9	0.35	51.0	28.2	4.4	33
	2	0.052	96.6	4.2	0.79	49.0	74.9	2.3	77
	2	0.063	95.9	4.5	0.74	49.9	114.0	12.8	127
	3	0.038	97.5	3.6	0.36	48.4	364.9	4.3	369
	3	0.085	94.4	3.1	0.79	49.6	6.1	8.6	15
	3	0.090	94.1	2.7	0.83	49.4	62.9	5.6	69
Tom	1	0.048	96.9	5.8	0.17	49.4	136.4	2.1	139
D	1	0.038	97.5	3.8	0.32	48.7	85.5	8.2	94
	1	0.038	97.5	5.0	0.23	48.6	375.7	17.8	393
	2	0.059	96.1	6.8	0.71	49.5	-64.0	-0.4	-64
	2	0.054	96.5	3.7	0.60	49.0	-8.1	6.7	-26
	2	0.059	96.1	5.1	0.56	48.7	39.3	5.5	45
	3	0.087	94.3	3.4	0.82	49.4	-34.6	0.9	-35
	3	0.092	94.0	3.1	0.96	50.7	21.8	-0.5	21
	3	0.099	93.5	4.0	1.00	49.3	141.6	36.6	180

† U=undrained area
D=drained area
†† 1=0-10 cm, 2=10-20 cm, 3=20-30 cm; 3 samples of each
§ Calculated from Db and an assumed particle density of 1.52 Mg m^{-3}.

APPENDIX 4-1. Foliar class limits and site foliar nutrient data

Table 1: Suggested class limits† for foliar nutrient assessment of black spruce needles (from Swan (1970) in Lowry (1972).

Element	Acute Deficiency (A)	Moderate Deficiency (M)	Transitional (T)	Sufficient (S)	Luxury (L)
	%wt.				
N	< 0.80	0.80-1.20	1.21-1.50	1.51-2.50	> 2.50
P	< 0.11	0.11-0.14	0.15-0.18	0.19-0.30	> 0.30
K	< 0.19	0.19-0.30	0.31-0.40	0.41-0.80	> 0.80
Ca	< 0.05	0.05-0.10	0.11-0.15	0.16-0.40	> 0.40

† Foliar concentrations of current year needles collected in the fall

Table 2: Nutrient concentrations and deficiency classes of current-year black spruce needles by site and drainage (n=5)

Treatment	Site	N		P		K		Ca		Zn	Mn	Cu
		% wt.								ug g^{-1}		
Undrained	Sault	0.751	A	0.123	M	0.436	S	0.289	S	22.0	336	1.17
	Fort 1	0.769	A	0.118	M	0.443	S	0.372	S	32.3	429	1.02
	Fort 2	1.027	M	0.136	M	0.494	S	0.567	L	57.0	683	2.87
	West	1.108	M	0.108	A	0.340	T	0.495	L	32.4	764	2.24
	Seba	0.998	M	0.113	M	0.443	S	0.242	S	23.6	735	1.66
	Tom	1.126	M	0.128	M	0.468	S	0.348	S	33.7	783	2.45
Drained	Sault	1.099	M	0.146	T	0.485	S	0.426	L	35.3	333	2.47
	Fort 1	1.520	S	0.192	S	0.623	S	0.401	L	28.4	552	3.57
	Fort 2	1.394	T	0.13	M	0.457	S	0.232	S	36.5	104	2.54
	West	1.231	T	0.162	T	0.458	S	0.458	L	32.3	778	3.07
	Seba	1.239	T	0.121	M	0.381	T	0.385	S	30.4	381	2.74
	Tom	1.032	M	0.131	M	0.430	S	0.257	S	25.8	353	2.06

Appendix 4-2. Means (n=3) and coefficients of variation of total volumetric peat nutrient contents by site, drainage, depth and element

Drainage Treatment	Site	N g m^{-3} 0-10 cm	N 10-20 cm	N 20-30 cm	Org. P g m^{-3} 0-10 cm	Org. P 10-20 cm	Org. P 20-30 cm	K g m^{-3} 0-10 cm	K 10-20 cm	K 20-30 cm
Undrained	Salt	296	433	717	16.7	25.3	39.4	32.2	25.4	25.5
	C.V.	17	20	59	23	19	75	38	46	137
	Fort 1	195	412	916	12.5	23.4	49.4	19.9	20.2	23.3
		21	40	4	16	39	10	23	67	66
	Fort 2	558	528	777	34.0	29.8	39.4	50.8	28.0	21.0
		20	32	16	10	33	19	30	25	75
	West	457	315	407	25.1	12.5	14.5	20.9	3.7	1.7
		22	21	11	25	24	22	43	44	238
	Seba	304	352	550	22.1	20.7	22.9	28.6	15.7	7.5
		37	14	23	29	5	16	48	78	34
	Tom	364	554	575	22.9	32.0	22.7	19.9	24.7	3.4
		31	29	45	25	41	43	70	98	50
Drained	Salt	423	1169	1106	25.2	59.6	48.4	40.0	38.9	19.3
	C.V.	43	30	39	59	45	31	45	36	75
	Fort 1	1369	2112	2005	62.6	75.0	67.7	38.9	18.5	24.5
		27	23	31	22	7	55	25	121	51
	Fort 2	1069	2089	2048	64.8	96.4	97.1	91.6	77.3	55.6
		46	20	10	41	19	19	45	37	149
	West	1521	1657	1419	73.1	52.9	45.4	32.2	5.4	-1.8
		13	56	59	33	46	62	35	46	-248
	Seba	470	545	845	30.7	25.1	31.8	34.2	15.6	3.1
		30	43	9	12	29	4	7	38	54
	Tom	474	670	804	29.8	34.4	33.3	24.2	18.9	3.6
		31	14	23	38	40	32	53	29	25

Footnotes for conversions:

1. mass of nutrient 'A' m^{-2} in 0-30 cm layer:

$$A\ g\ m^{-2}{}_{(0\text{-}30\ cm)} = \left(A\ g\ m^{-3}{}_{(0\text{-}10\ cm)} + A\ g\ m^{-3}{}_{(10\text{-}20\ cm)} + A\ g\ m^{-3}{}_{(20\text{-}30\ cm)}\right) + 10$$

2. Kmol 'A' m^{-2} in 0-30 cm layer:

$$= A\ g\ m^{-2}{}_{(0\text{-}30\ cm)} + (A\ \text{mol. wt.} \times 1000)$$

Appendix 4-2: continued

Drainage Treatment	Site	Ca g m^{-3} 0-10 cm	10-20 cm	20-30 cm	[illegible] g m^{-3} 0-10 cm	10-20 cm	20-30 cm	Mn g m^{-3} 0-10 cm	10-20 cm	20-30 cm
Undrained	Salt	267	1801	3401	0.83	0.77	1.47	2.4	16.0	120.9
	C.V.	48	16	76	91	93	111	53	76	161
	Fort 1	204	966	2632	1.60	2.09	2.81	1.9	12.4	89.7
		55	45	15	55	44	16	60	90	40
	Fort 2	671	900	1607	1.2[illegible]	1.27	1.72	7.7	7.9	60.8
		27	42	23	4	44	62	33	64	37
	West	246	434	658	1.54	1.95	1.45	0.9	0.5	0.8
		23	54	35	20	37	32	12	46	12
	Seba	87	183	328	2.24	2.12	2.53	3.5	2.5	2.2
		37	27	24	32	17	29	33	33	15
	Tom	108	181	351	1.41	2.08	1.90	1.4	1.9	3.0
		36	31	36	45	61	77	53	62	30
Drained	Salt	1111	3057	3790	1.13	19.37	1.12	21.0	25.7	9.4
	C.V.	80	21	37	47	163	7	141	71	34
	Fort 1	3288	4736	5696	1.88	2.06	2.05	84.2	21.1	22.5
		20	10	38	45	21	56	107	86	134
	Fort 2	2654	4003	6365	2.62	5.45	2.03	14.8	55.2	61.3
		34	10	10	21	55	62	60	79	53
	West	1940	2634	4815	2.98	1.88	1.41	8.7	3.7	19.0
		8	41	86	43	33	16	102	67	89
	Seba	248	476	416	2.64	3.05	4.15	2.6	1.7	1.9
		56	52	34	25	23	38	25	63	79
	Tom	165	207	402	2.80	1.27	2.07	4.2	2.3	3.5
		25	12	7	68	27	19	66	17	24

Footnotes for conversions:

1. mass of nutrient 'A' m^{-2} in 0-30 cm layer:

$$A\ g\ m^{-2}{}_{(0\text{-}30\ cm)} = \left(A\ g\ m^{-3}{}_{(0\text{-}10\ cm)} + A\ g\ m^{-3}{}_{(10\text{-}20\ cm)} + A\ g\ m^{-3}{}_{(20\text{-}30\ cm)}\right) + 10$$

2. Kmol 'A' m^{-2} in 0-30 cm layer:

$$= A\ g\ m^{-2}{}_{(0\text{-}30\ cm)} + (A\ \text{mol. wt.} \times 1000)$$

Appendix 4-2: continued

Drainage Treatment	Site	Cu g m^{-3} 0-10 cm	10-20 cm	20-30 cm
Undrained	Salt	0.07	0.09	0.16
	C.V.	44	59	90
	Fort 1	0.05	0.11	0.36
		42	40	18
	Fort 2	0.19	0.12	0.17
		18	13	9
	West	0.07	0.05	0.09
		33	27	38
	Seba	0.10	0.09	0.17
		46	33	30
	Tom	0.07	0.10	0.11
		25	41	39
Drained	Salt	0.14	0.38	0.24
	C.V.	24	93	66
	Fort 1	0.37	0.49	0.59
		30	15	61
	Fort 2	0.48	0.58	0.50
		23	16	16
	West	0.25	0.58	0.28
		14	109	43
	Seba	0.19	0.21	0.18
		44	50	27
	Tom	0.12	0.12	0.21
		30	9	10

Footnotes for conversions:

1. mass of nutrient 'A' m^{-2} in 0-30 cm layer:

$$A\ g\ m^{-2}{}_{(0\text{-}30\ cm)} = \left(A\ g\ m^{-3}{}_{(0\text{-}10\ cm)} + A\ g\ m^{-3}{}_{(10\text{-}20\ cm)} + A\ g\ m^{-3}{}_{(20\text{-}30\ cm)}\right) \div 10$$

2. Kmol 'A' m^{-2} in 0-30 cm layer:

$$= A\ g\ m^{-2}{}_{(0\text{-}30\ cm)} \div (A\ mol.\ wt. \times 1000)$$

APPENDIX 5-1. Test of validity of initial basal area as a covariate

Analysis of variance was performed on stem growth data to test the interaction effect of initial stem radius by pH on post drainage radial growth. The input data was the cumulative radial growth increment to year seven following drianage. The analysis (Table 1) indicated neither the pH level (L) nor the drainage treatment (D) had any significant interaction with initial stem radius (INIT) indicating the assumption of equality of slopes amongst pH levels is plausible and the use of initial stem radius as a covariate is valid. The analysis including INIT as a covariate is in Table 2.

Table 1. Analysis of variance to test for interactions between initial stem radius and pH or drainage

Source	SS	DF	MS	F-Ratio	P>F
L	0.719	3	0.240	2.065	0.117
S(2)	1.051	1	1.051	9.051	0.004
S(3)	0.689	1	0.689	5.934	0.019
S(4)	0.019	1	0.019	0.163	0.688
DRG	0.562	1	0.562	4.844	0.033
L*DRG	0.897	3	0.299	2.574	0.065
DRG*S(2)	0.375	1	0.375	3.227	0.079
DRG*S(3)	0.146	1	0.146	1.253	0.269
DRG*S(4)	0.002	1	0.002	0.013	0.910
INIT	0.600	1	0.600	5.171	0.027
L*INIT	.598	3	0.199	1.718	0.176
DRG*INIT	0.101	1	0.101	0.874	0.355
ERROR	5.574	48	0.116		

Table 2. Analysis of covariance to test for effects of initial stem radius on post-drainage radial growth measured at 30 cm bole height

Source	SS	DF	MS	F-Ratio	P>F
INIT	0.139	1	0.139	1.149	0.289
L	0.468	3	0.156	1.293	0.287
S(2)	1.201	1	1.201	9.946	0.003
S(3)	1.354	1	1.354	11.213	0.002
S(4)	0.038	1	0.038	0.314	0.578
DRG	3.607	1	3.607	29.870	0.000
L*DRG	1.062	3	0.354	2.932	0.042
DRG*S(2)	0.454	1	0.454	3.764	0.058
DRG*S(3)	0.052	1	0.052	0.432	0.514
DRG*S(4)	0.094	1	0.094	0.780	0.381
ERROR	6.279	52	0.121		

APPENDIX 5-2. Annual radial increment (mm) of black spruce at 30 cm height for alternate years during the post-drainage period

Site	Area	Year 1	Year 3	Year 5	Year 7	Year 9	Year 11
Saulteaux	Undrained	0.214†	0.220	0.213	0.226	0.240	0.202
	Drained	.415	.392	.487	.842	1.060	1.230
	Response††	0.201	0.172	0.274	0.616	0.820	1.228
Fort 1	Undrained	0.419	0.333	0.291	0.394	0.352	0.324
	Drained	0.590	1.225	1.076	1.439	2.634	1.719
	Response	0.171	0.892	0.785	1.045	2.282	1.395
Fort 2	Undrained	0.375	0.316	0.232	0.215	0.218	0.234
	Drained	0.295	0.277	0.479	0.665	0.892	0.955
	Response	-0.080	-0.039	0.257	0.450	0.674	0.721
Westlock	Undrained	0.655	1.011	0.803	1.110	1.087	0.955
	Drained	0.397	0.683	0.835	1.100	1.498	1.598
	Response	-0.258	-0.328	0.032	-0.010	0.411	0.643
Niton Junction	Undrained	0.643	0.589	0.445	0.447	0.474	0.414
	Drained	0.438	0.444	0.531	0.616	0.948	1.365
	Response	-0.205	-0.145	0.086	0.169	0.474	0.951
Seba Beach	Undrained	0.370	0.498	0.541	0.451	0.421	0.349
	Drained	0.209	0.163	0.524	1.035	1.598	1.787
	Response	-0.161	-0.335	-0.017	0.584	1.177	1.438
Tomahawk	Undrained	0.575	0.736	0.565	0.553		
	Drained	0.512	0.603	0.678	0.918		
	Response	-0.063	-0.133	0.113	0.365		

† Number of observations (n)=10

†† Radial increment for the drained area minus that for the undrained area