

# Water and peat chemistry comparisons of natural and post-harvested peatlands across Canada and their relevance to peatland restoration

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Received 16 February 1995; revised 2 April 1996; accepted 2 April 1996

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## Abstract

Water and peat chemistry comparisons of four post-harvested and neighboring, undisturbed peatlands across Canada show that harvesting alters chemical conditions. Commercial harvesting removes the surface peat and exposes layers farther down the peat deposit. The newly exposed peat layers that were formed in earlier developmental stages of the peatland can be more minerotrophic and/or more variable in chemical composition than undisturbed bog peat. All the harvested sites were originally bogs. Only one site, which had minimal peat removed, presently has chemical conditions somewhat similar to the original surface, with low elemental levels typical of bogs. Two sites are now chemically similar to poor fens and one site is similar to a moderate-rich fen. Levels of sodium, potassium, calcium, magnesium, sulphate and chloride in three of the harvested sites are higher than normal values found in natural, unharvested bogs, and result from the exposure of fen peat. Higher levels of ammonium-nitrogen and nitrate-nitrogen in the peat and water of all the harvested sites are present, with higher ammonium associated with wetter sites and higher nitrate levels associated with drier sites.

**Keywords:** Restoration; Nitrogen enrichment; Peatland reclamation; Biogeochemistry; Bog succession

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## 1. Introduction

Peatlands, with their large carbon deposits, are a useful source of peat which can be used as a soil amendment, a fuel source and as absorbent material. In Canada, horticultural use of peat consumes an average of 750 metric tons of peat annually (Keys,

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1992). Vacuum harvesting is now the most common harvesting method and affects large areas over long periods of time. Removal of peat layers during commercial harvesting exposes peat layers formed during earlier successional stages of the fen to bog successional gradient and affects the chemical and hydrological conditions of the peatland surface. The development of peatlands normally proceeds along a nutrient gradient from mesotrophic rich fens, to *Sphagnum*-dominated poor fens, to oligotrophic bogs (Kuhry et al., 1993). Potential revegetation of sites after abandonment is expected to be affected by these new conditions.

Peat removal with harvesting changes not only the chemical characteristics, but also removes much of the viable seed bank (Salonen, 1987). Due to the usual large size of the affected areas, diaspores (seeds, plant fragments) are not always nearby to allow natural recolonization of the site once harvesting activities have ceased (Nilsson et al., 1990). Water levels are low and wind erosion is high, further hindering recolonization of peatland plants (Famous et al., 1989). Left alone, these sites are often barren for decades after harvesting (Nilsson et al., 1990). Intervention is necessary to aid in the re-establishment of peatland species on post-harvested sites.

Examination of how chemical conditions in post-harvested peatlands compare to natural peatlands has not been carried out in North America. Analysis of the peat and water chemistry of harvested and neighboring undisturbed peatlands allows the changes in nutrient status, element levels and successional peatland type to be determined. Knowledge of the chemistry of the post-harvested sites is critical to restoration efforts, as plant species that can be potentially used in revegetation have distinct tolerances to surrounding chemical and hydrologic factors (Sjörs, 1950, 1952; Gignac et al., 1991a). Thus appropriate peatland plant species can be chosen for restoration. In addition, chemical studies would indicate if any ameliorative measures such as fertilization are necessary. These studies also indicate the potential effects of stopping harvesting at different peat depths.

In this paper, we compare the chemistry of post-harvested and associated natural peatlands of four sites across Canada, reflecting the provinces most active in horticultural peat harvesting (Alberta, Québec and New Brunswick), in order to determine the effects of peat harvesting.

## 2. Site descriptions

Before harvesting procedures commenced, the four post-harvested sites surveyed in this study were bogs. The sites are located along an east–west transect across Canada (Fig. 1). Tree cover increases from the east coast to the western interior in the natural, undisturbed peatlands. The yearly temperature curves are similar among the four sites, while the amount of precipitation varies. The sites in Québec and New Brunswick receive more precipitation. The two Québec sites have precipitation more evenly distributed throughout the year (Fig. 2).

### 2.1. New Brunswick – Maisonnette

The Maisonnette peatland is located on the Acadian Peninsula, near Caraquet (47°49' N, 65°02' W; Fig. 1). This wetland is classified as a maritime Atlantic boreal peatland

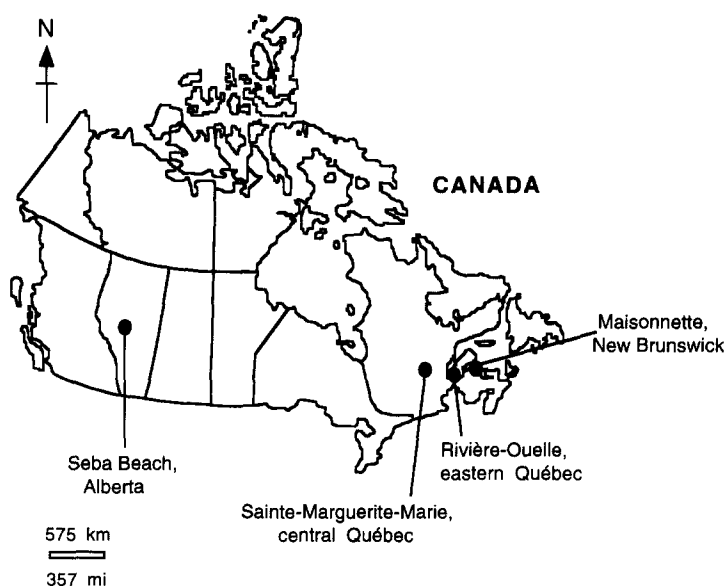


Fig. 1. Locations of study sites across Canada. One site in Alberta, Seba Beach. Two sites in Québec, Sainte-Marguerite-Marie and Rivière-Ouelle. One site in New Brunswick, Maisonnnette.

(National Wetlands Working Group, 1986). The mean annual temperature for the area is 3.3°C, with total annual precipitation of 722 mm, of which approximately 50% falls as rain (Fig. 2). This coastal raised bog has dimensions of 3.9 km by 2.0 km (541 ha). Originally, the bog was covered by ericaceous shrubs and *Sphagnum*, with *Picea mariana* (black spruce) and *Larix laricina* (larch) occurring near the margins (nomenclature follows Anderson (1990) for *Sphagnum* mosses and Scoggan (1978) for vascular plants).

Approximately 339 ha have been prepared for horticultural peat production by Fisons-Western (currently Sun Gro Horticulture Canada) using the vacuum harvesting method. Harvesting of the site ceased in 1992, just prior to restoration work. The restoration site covers an area approximately 2.16 ha, or 0.6% of the area in production. A peat depth of 0.4 to 1.2 m was left on the site after harvesting. To recharge the site with water, the main perimeter ditch was filled with bulldozed peat, as were four secondary channels in August 1992.

## 2.2. Eastern Québec – Rivière-Ouelle

The Rivière-Ouelle peatland is located approximately 150 km northeast of Québec City (47°27' N, 69°56' W; Fig. 1). Harvested for horticultural peat by Tourbières Lambert, this peatland is 1535 ha in area. This eastern Québec peatland is an Atlantic boreal wetland (National Wetlands Working Group, 1986). The area surrounding this peatland has a mean annual temperature and precipitation of 4.2°C and 967.4 mm, respectively (Fig. 2). Of the precipitation, 66% occurs as rainfall. Peat harvesting of this

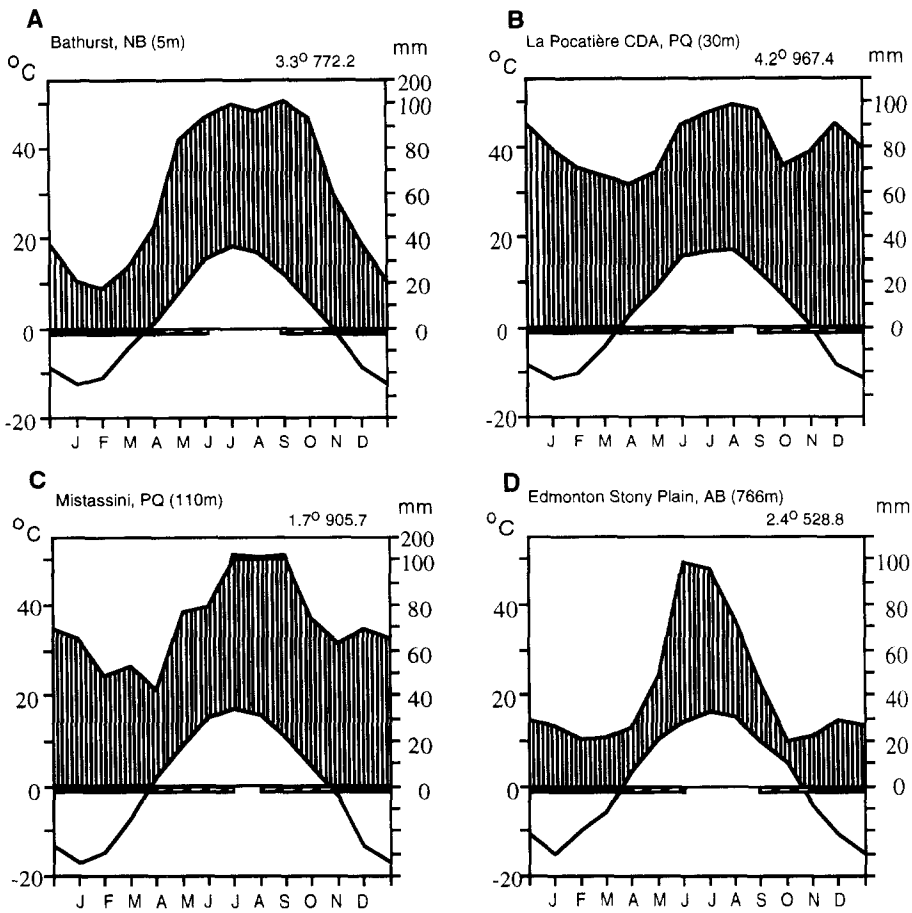


Fig. 2. Climate diagrams of the study sites, after Walter and Leith (1960). (A) New Brunswick: Maissonnette peatland area. Mean annual temperature: 3.3°C; mean annual precipitation: 772.2 mm; height above sea level: 5 m. (B) Eastern Québec: Rivière-Ouelle peatland area. Mean annual temperature: 4.2°C; mean annual precipitation: 967.4 mm; height above sea level: 30 m. (C) Central Québec: Sainte-Marguerite-Marie peatland area. Mean annual temperature: 1.7°C; mean annual precipitation: 905.7 mm; height above sea level: 110 m. (D) Alberta: Seba Beach peatland area. Mean annual temperature: 2.4°C; mean annual precipitation: 528.8 mm; height above sea level: 766 m. For all the graphs: the upper line is precipitation, the lower line is temperature, the solid bar is months with mean monthly temperature < 0°C, the diagonally hatched bar is months with absolute minimum temperature < 0°C.

bog was started in the 1930s using the block-cut method. Today, nearly half of the peatland surface is being extracted for horticultural peat with the vacuum harvesting method.

Restoration experiments at the Rivière-Ouelle peatland began in the summer of 1993 and took place on three vacuum harvested bays, 3 ha in total, that were abandoned approximately 10 years ago. A depth of 1 m of peat remains at the restoration site. The peat substrate has only been sparsely colonized by plants, with plant cover of less than

10%, consisting mainly of small *Betula papyrifera* and *Eriophorum* spp. To rewet the site, all secondary ditches adjacent to the restoration bays were blocked.

### 2.3. Central Québec – Sainte-Marguerite-Marie

The Sainte-Marguerite-Marie peatland is located in central Québec near Lac Saint-Jean (48°47' N, 72°10' W; Fig. 1). This peatland is classified as a low boreal peatland (National Wetlands Working Group, 1986). This area has a mean annual temperature of 1.7°C, with annual precipitation of 905.7 mm, of which 71% falls as rain (Fig. 2). The total area of the peatland is 4312 ha. The undisturbed ombrotrophic areas are dominated by *Sphagnum angustifolium*, *S. capillifolium*, *S. fuscum* and *S. magellanicum*, ericaceous shrubs and some interspersed *Eriophorum angustifolium*, *Picea mariana* and *Larix laricina*.

The experimental site is located on a series of bays within an area of 60 hectares, where peat harvesting stopped in 1991. The peat was extracted by a block cutting method by Fafard et Frères Ltée for the production of *Sphagnum* based absorbent board. A peat depth of 2.5–3 m remains on the site and the surface is fibric–mesic peat. The secondary drainage channels of the experimental bays were blocked in late April 1992 to allow rewetting of the surface.

### 2.4. Alberta – Seba Beach

The Seba Beach peatland is located about 130 km west of Edmonton (53°33' N, 114°44' W; Fig. 1). This peatland is classified as a continental mid-boreal peatland (National Wetlands Working Group, 1986). The area has a mean annual temperature of 2.4°C and annual precipitation of 528.8 mm, considerably less than the three eastern sites (Fig. 2).

Originally this peatland was covered by bog and poor fen vegetation dominated by *Picea mariana*, *Sphagnum fuscum* and scattered *Larix laricina*. This site was first opened in 1975 to harvesting by dredging. In 1980, another peat harvesting company, now Sun Gro Horticulture Canada, leveled, drained and then vacuum harvested the area. The restoration site is approximately 16 hectares in area, 0.02% of the area presently being harvested. Surface height of the peat is highest in the northeastern corner sloping to the southwest corner, with drainage southwestward. Peat depth ranges from 0.73 m at the northern end, deepening at the southern end to over 4 m.

In order to raise the water level, a dam was constructed in the southwest corner in the fall of 1991, when peat harvesting ceased. In early 1992, the lower areas of the southern end of the field were flooded, with the northern end of the site staying relatively dry. Beginning in 1992, *Carex* spp. and meadow-annuals invaded the wetter areas while much of the drier areas remained vegetation free.

## 3. Methods

### 3.1. Water chemistry

Water samples were collected from various locations within the post-harvested fields and from the neighboring undisturbed peatlands for comparative measures. Surface

water pH was measured in the field or in the lab, from samples obtained from pools, ditches, or from within water level pipes. Surface water samples, with the exception of the Alberta site, were first filtered using a 0.45  $\mu\text{m}$  cellulose acetate filter, then measured for conductivity values with corrections for temperature at 20°C and hydrogen ions (Sjörs, 1952). Surface water nutrients were analyzed by the Department of Zoology at the University of Alberta, the Peat Research and Development Centre in Shippagan, New Brunswick, or the Centre de Recherches minérales, Ministère de l'Énergie et des Ressources (Gouvernement du Québec), in Sainte-Foy, Québec. Water samples were stored in 1-litre Nalgene polyethylene bottles for  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ , total phosphorus (TP) and  $\text{NO}_3^-$ -N analyses. Water samples for  $\text{NH}_4^+$ -N analyses were stored in 250 ml polystyrene flasks or polyethylene bottles. Samples for  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  were filtered through a prewashed Whatman GF/C filter, stored at 4°C and analyzed on an atomic absorption spectrometer (Perkin-Elmer, model 3300 or Varian 1475). Analyses of  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  were conducted by ion chromatography with a Waters chromatographic system. Samples for TP were filtered under low pressure (–50 kPa), through a 250  $\mu\text{m}$  Nitex net and transferred to culture tubes (Prepas and Rigler,

Table 1

Means (and ranges) of water chemistry data of the natural areas of the four sites

	New Brunswick 1992/1993	Eastern Québec 1993	Central Québec 1993	Alberta 1993
<i>n</i>	8	1	3	2
pH	3.9 (3.8–4.0)	3.7	3.7 <sup>a</sup> (3.6–3.8)	3.7 (3.7)
Corrected conductivity ( $\mu\text{S}/\text{cm}$ )	30 (0–70)	97	58 <sup>b</sup> (0–115)	0 (0)
P total (mg/l)	< 0.1 ( < 0.0– < 0.1)	0.0	0.0 (0.0–0.2)	0.1 (0.0–0.1)
$\text{NH}_4^+$ -N (mg/l)	1.6 (0.4–2.8)	< 0.1	0.2 <sup>a</sup> (0–1.4)	0.1 (0.1–0.1)
$\text{NO}_3^-$ -N (mg/l)	< 0.1 ( < 0.1– < 0.1)	0.06	< 0.1 <sup>a</sup> (0– < 0.1)	0.0 (0.0–0.0)
$\text{Na}^+$ (mg/l)	4.1 (2.2–8.0)	16.5	0.3 (0.1–0.5)	1.0 (0.9–1.1)
$\text{K}^+$ (mg/l)	0.3 (0.2–0.4)	< 0.4	0.2 (0.2–0.3)	0.2 (0.2–0.3)
$\text{Ca}^{2+}$ (mg/l)	0.4 (0.2–0.6)	4.6	0.6 (0.5–0.8)	3 (2.8–3.2)
$\text{Mg}^{2+}$ (mg/l)	0.5 (0.3–0.6)	3.1	0.3 (0.2–0.3)	1.1 (1.1–1.1)
$\text{SO}_4^{2-}$ (mg/l)	1.9 (1.1–2.9)	9.6	2.6 <sup>b</sup> (0.7–3.5)	2.4 (1.9–2.9)
$\text{Cl}^-$ (mg/l)	5.0 (3.1–9.8)	3.4	0.1 <sup>b</sup> (0.1–0.2)	0.5 (0.4–0.5)

<sup>a</sup> *n* = 5.<sup>b</sup> *n* = 2.

1982). These samples were analyzed colorimetrically on a Milton Roy Spectronic Spectrometer or a UV/vis LKB Urtrospec II. After filtration through a prewashed 0.45  $\mu\text{m}$  HAWP Millipore membrane filter, nitrate was determined by the cadmium–copper reduction method of Stainton et al. (1977) or using ionic chromatography with a Waters chromatographic system. Ammonium samples were analyzed by the phenolhypochlorite method of Solorzano (1969) as modified by Prepas and Trew (1983) or by steam distillation with a Kjeltect 1002 distillation system.

### 3.2. Peat chemistry

Peat samples were collected from 0–5 and 1–5 cm profiles from the harvested peat surfaces and from 1–5 and 10–15 cm profiles in the natural areas. Samples were stored in polyethylene bags at a cool temperature until analysis. Peat pH was analyzed using a 2:1 or 10:1 ratio of distilled water and fresh peat using methods from the Department of Soil Science, University of Alberta (1990), or measuring mixtures of 3 g of air dried peat with 50 ml of 0.1 mol/l  $\text{CaCl}_2$ . Peat conductivity analyses were conducted using the same ratios or the samples were saturated with distilled water, filtered on an eight micron filter and conductivity measurements were obtained from the filtrate. Peat conductivity measurements were corrected for temperature to 20°C and for pH according to Sjörs (1952). Surface peat samples were analyzed for the elements P, S, Mg, Na, K and Ca by one of three ways: (1) by following methods by Kalra and Maynard (1991) and analyzed with an inductively coupled plasma-atomic emission spectroscopy spec-

Table 2  
Means (and ranges) of peat chemistry data of the natural areas of the four sites

	Eastern Québec 1993	Central Québec 1992/1993	Alberta 1992/1993
<i>n</i>	1	1	2
pH	2.71	2.85	4.15 <sup>a</sup>
Corrected conductivity ( $\mu\text{S}/\text{cm}$ )	0	0	10 <sup>a</sup>
P total (mg/kg)			406.3 (387.7–424.9)
$\text{NH}_4\text{-N}$ (mg/kg)		690	112.0 (80.2–143.8)
$\text{NO}_3\text{-N}$ (mg/kg)			1.4 (0–2.7)
Na (mg/kg)	260	400	110.2 (106.1–114.2)
K (mg/kg)	800	830	241.6 (114.8–368.3)
Ca (mg/kg)	1500	1100	6236.0 (5615–6856)
Mg (mg/kg)	830	390	855.7 (705.3–1006)
S (mg/kg)			1529 (974.3–2083)

<sup>a</sup> *n* = 1.

trometer, (2) by displacing the cations by agitating the sample in a solution of 1 M ammonium acetate ( $\text{CH}_3\text{COONH}_4$ ) at pH 7 and then analyzing the filtrate by atomic absorption spectrophotometry, or (3) by measuring the filtrate of a one hour hot water extraction with 2 M HCl at  $85^\circ\text{C}$ , using atomic absorption spectrophotometry. Available nitrate and ammonia were extracted by one of two ways: (1) by methods outlined by Day et al. (1979) and analyzed using a technicon autoanalyzer and the Industrial Methods 158-71 W/B, December 1972, and 696-82W, April 1983, respectively, or (2)

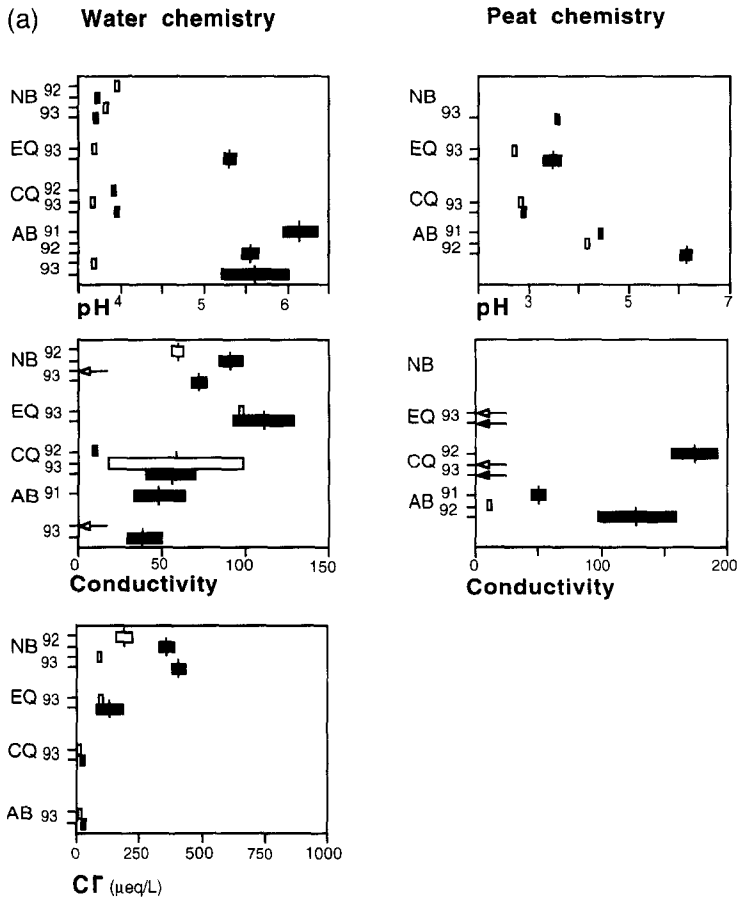


Fig. 3. (a) Annual means  $\pm$  standard errors of water and peat chemistry of harvested and undisturbed peatlands for pH, corrected conductivity ( $\mu\text{S}$  at  $20^\circ\text{C}$ , corrected for pH) and  $\text{Cl}^-$ . NB = New Brunswick. EQ = Eastern Québec. CQ = Central Québec. AB = Alberta. The white bar represents undisturbed peatland values, the solid bar represents post-harvested peatland values. Arrows indicate values below 35.7. Narrow bars, ■ □, indicate standard errors below 25 for water values and 39 for peat values. (b) Annual means  $\pm$  standard errors of water and peat chemistry of harvested and undisturbed peatlands for cations (Na, K, Ca and Mg). Legend the same as in a. (c) Annual means  $\pm$  standard errors of water and peat chemistry of harvested and undisturbed peatlands for nutrients (total P, P,  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ ,  $\text{SO}_4$  and S). Valence for total P was set at 3. Legend the same as in a.

by measuring nitrate with ion chromatography on the filtrate of a one hour hot water extraction with 2 M HCl at 85°C, and measuring ammonia by steam distillation of 10 g samples placed in 100 ml of double distilled water. Samples were analyzed by the authors, the Department of Zoology at the University of Alberta, the Peat Research and Development Centre, or the Centre de Recherches minérales, Gouvernement du Québec, Ministère de l'Énergie et des Ressources.

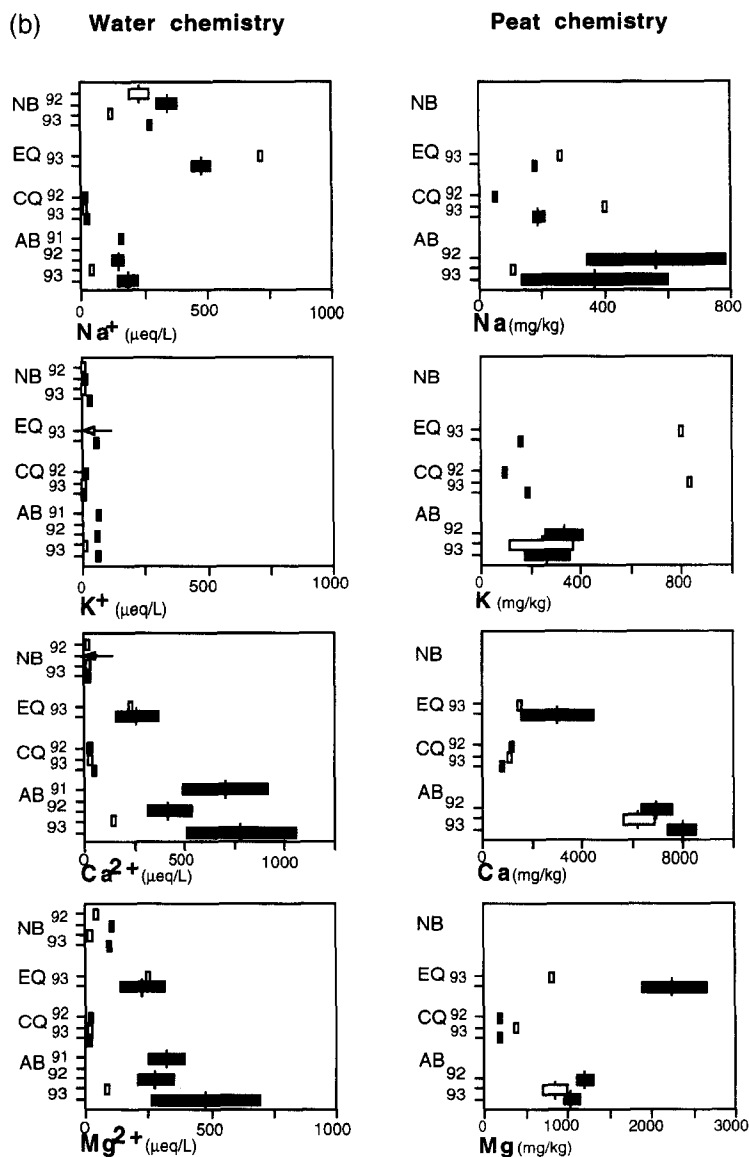


Fig. 3 (continued).

Although different methods were used for peat chemistry analyses for the New Brunswick, Québec and Alberta sites, all analyses done at an individual site were similar. Conclusions are mostly based on intra-site differences, not inter-site comparisons.

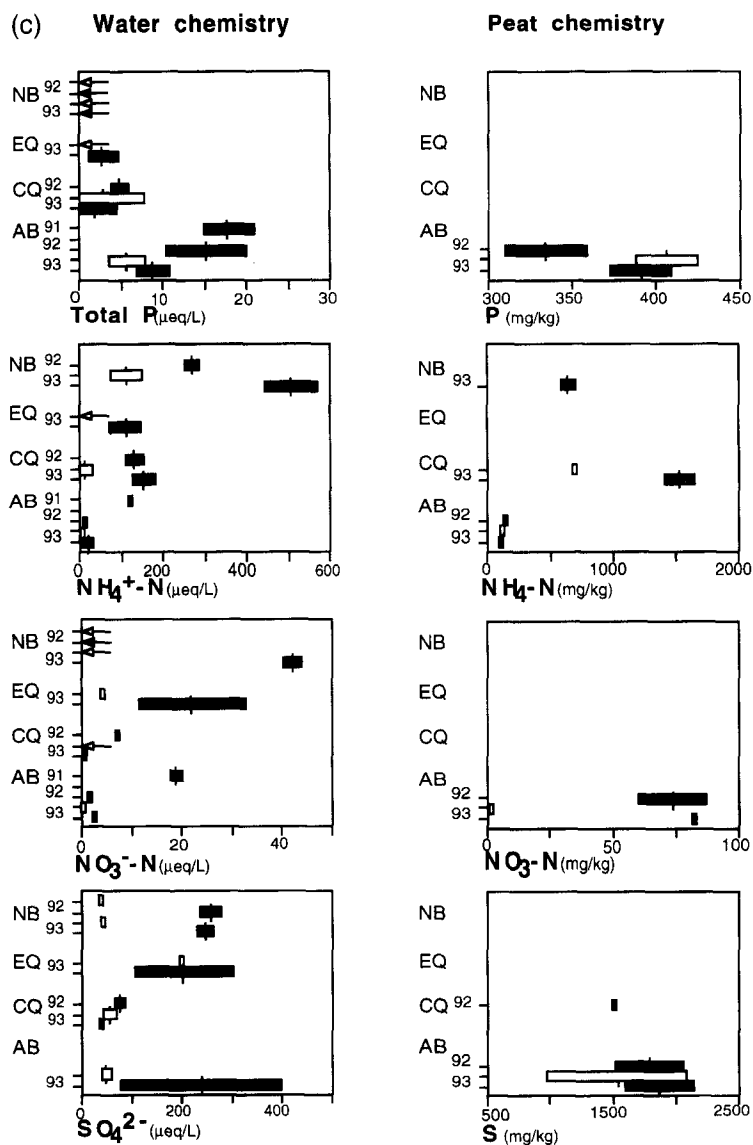


Fig. 3 (continued).

## 4. Results

### 4.1. Natural areas – water and peat chemistry

Hydrochemical analyses of the natural areas showed a general trend of lower element levels with less variation than the harvested site values (Tables 1 and 2). The natural areas had pH values of the surface water ranging from 3.6–4.0 (Fig. 3a, white bars). Total phosphorus,  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$ , had mean annual ranges of  $< 0.15\text{--}5.7\text{ }\mu\text{eq/l}$ ,  $< 3.6\text{--}112.1\text{ }\mu\text{eq/l}$  and  $< 3.6\text{--}4.3\text{ }\mu\text{eq/l}$ , respectively (Fig. 3c, white bars). Sodium and  $\text{Cl}^-$  increased in concentration in the surface waters toward the coast with the

Table 3

Means (and ranges) of water chemistry data of the harvested areas of the four sites

	New Brunswick 1992/1993	Eastern Québec 1993	Central Québec 1992/1993	Alberta 1991/ 1992/1993
<i>n</i>	38	3	25	20
pH	3.7 (3.4–4.0)	5.3 (5.2–5.4)	4.0 <sup>a</sup> (3.7–4.4)	5.6 <sup>f</sup> (4.8–8.7)
Corrected conductivity ( $\mu\text{S/cm}$ )	82 (32–164)	110 (90–143)	33 <sup>b</sup> (0–119)	57 <sup>g</sup> (20–253)
P total (mg/l)	$< 0.1$ ( $< 0.0\text{--}0.4$ )	0.0 ( $< 0.6\text{--}< 0.6$ )	0.1 (0.0–0.2)	0.4 (0.1–1.1)
$\text{NH}_4^+\text{-N}$ (mg/l)	5.4 (1.8–15.8)	1.6 (1.6–1.6)	2.0 <sup>c</sup> (0.0–5.7)	3.6 (0.1–9.4)
$\text{NO}_3^-\text{-N}$ (mg/l)	0.1 ( $< 0.1\text{--}0.9$ )	0.3 (0.0–0.6)	0.1 <sup>d</sup> ( $< 0.1\text{--}0.2$ )	0.2 (0.0–2.7)
$\text{Na}^+$ (mg/l)	7.2 (3.2–21.9)	11.0 (9.4–12.3)	0.5 (0.2–1.0)	6.1 (1.8–13.9)
$\text{K}^+$ (mg/l)	0.9 (0.3–4.2)	2.2 (2.1–2.5)	0.4 (0.1–0.8)	2.6 (1.5–3.8)
$\text{Ca}^{2+}$ (mg/l)	0.3 ( $< 0.1\text{--}1.4$ )	5.3 (1.2–8.3)	0.9 (0.2–2.3)	12.6 (2.3–28.7)
$\text{Mg}^{2+}$ (mg/l)	1.3 (0.4–4.9)	2.8 (0.8–4.4)	0.3 (0.0–1.8)	4.1 (0.8–11.9)
$\text{SO}_4^{2-}$ (mg/l)	12.1 (6.1–25.1)	9.7 (1.2–17.4)	2.7 <sup>b</sup> ( $< 0.1\text{--}7.6$ )	8.6 <sup>h</sup> (1.3–26.7)
$\text{Cl}^-$ (mg/l)	13.5 (6.9–26.2)	4.6 (1.2–7.2)	0.6 <sup>e</sup> (0.1–1.5)	1.0 <sup>h</sup> (0.6–1.6)

<sup>a</sup> *n* = 37.<sup>b</sup> *n* = 31.<sup>c</sup> *n* = 29.<sup>d</sup> *n* = 36.<sup>e</sup> *n* = 16.<sup>f</sup> *n* = 54.<sup>g</sup> *n* = 29.<sup>h</sup> *n* = 13.

continental areas of central Québec and Alberta having 13–34  $\mu\text{eq/l}$  and 3–13  $\mu\text{eq/l}$ , respectively, compared to New Brunswick and eastern Québec with 122–718  $\mu\text{eq/l}$  for  $\text{Na}^+$  and 91–190  $\mu\text{eq/l}$  for  $\text{Cl}^-$  (Fig. 3a,b). Potassium had a very narrow range of 5–7  $\mu\text{eq/l}$  in the natural areas, while  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{SO}_4^{2-}$  had somewhat wider ranges, without apparent geographic trends (Fig. 3b).

Although data for peat chemistry are less complete than that for water chemistry, some trends are apparent. The surface peat was acidic with mean annual pH ranging from 2.7–4.2 (Fig. 3a, white bars). Total phosphorus and  $\text{NH}_4\text{-N}$  levels were higher than the low values for  $\text{NO}_3\text{-N}$ . The maritime influence on Na levels in the peat was not as obvious as in the water, although the eastern sites had higher levels than the site in Alberta (Fig. 3a,b, white bars). Higher levels of K were also present in the East, while the western site had higher levels of Ca than the eastern sites. No consistent trends were found for Mg and S in the surface peat of the natural areas (Fig. 3b).

Table 4

Means (and ranges) of peat chemistry data of the harvested areas of the four sites

	New Brunswick 1993	Eastern Québec 1993	Central Québec 1992/1993	Alberta 1991/1992/1993
<i>n</i>	6	4	16	62
pH	3.6 (3.4–3.9)	3.5 (3.2–4.0)	2.9 <sup>a</sup> (2.8–3.0)	5.3 <sup>d</sup> (3.8–8.0)
Corrected conductivity ( $\mu\text{S/cm}$ )	1 900 000 (1 200 000–3 300 000)	0 (0)	103 <sup>b</sup> (0–256)	66 <sup>d</sup> (0–600.4)
P total (mg/kg)				362.7 (176.2–624.0)
$\text{NH}_4\text{-N}$ (mg/kg)	640 (500–900)		1533 <sup>a</sup> (930–1900)	121.1 <sup>c</sup> (13.5–711.6)
$\text{NO}_3\text{-N}$ (mg/kg)				78.1 <sup>c</sup> (0–433.0)
Na (mg/kg)		180 (170–210)	112 (19–250)	466.1 (51.2–9393)
K (mg/kg)		160 (150–190)	138 (36–260)	297.2 (56.7–3096)
Ca (mg/kg)		3000 (290–7000)	1007 (700–1833)	7433 (2261–16 220)
Mg (mg/kg)		2280 (1800–3400)	197 (136–253)	1135 (407–3269)
S (mg/kg)			1500 <sup>c</sup> (1200–2000)	1820 (570–11 740)

<sup>a</sup> *n* = 7.

<sup>b</sup> *n* = 34.

<sup>c</sup> *n* = 9.

<sup>d</sup> *n* = 139.

<sup>e</sup> *n* = 88.

#### 4.2. Harvested areas – water and peat chemistry

Although some geographical variation in chemistry was present in the natural areas, most elements had limited variation across the four sites. The four harvested areas had more variation than the natural areas for every element in both surface water and peat (Tables 3 and 4 and Fig. 3a–c). Mean annual surface water pH varied from 3.7–6.2, with levels being higher than pH 4 in eastern Québec and Alberta (Fig. 3a, solid bars). Mean annual total phosphorus ranged from < 1.9–17.9  $\mu\text{eq/l}$ , with the Alberta sites

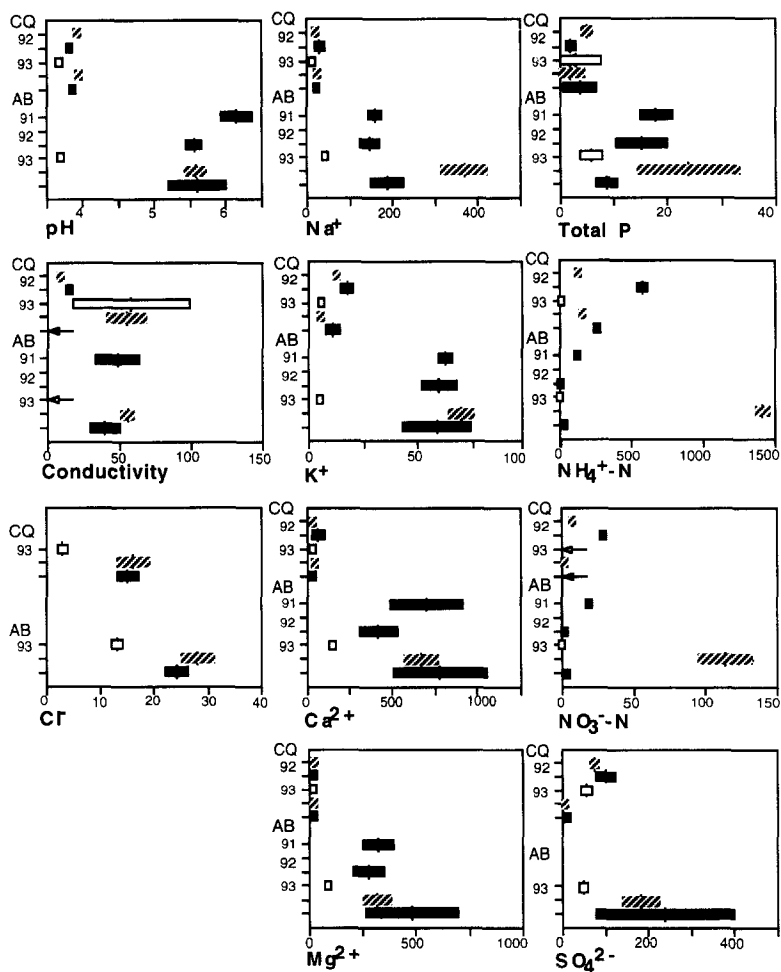


Fig. 4. Annual water chemistry means ( $\pm$  standard errors) from Sainte-Marguerite-Marie, central Quebec (CQ) and Seba Beach, Alberta (AB). Corrected conductivity ( $\mu\text{S}$  at  $20^\circ\text{C}$ , corrected for pH). The white bar represents the undisturbed peatland values; the hatched bar represents the harvested area, surface pit or water level pipe; the solid bar represents the harvested area ditch. All units are  $\mu\text{eq/l}$  except pH and conductivity ( $\mu\text{S}$  at  $20^\circ\text{C}$ , corrected for pH). Arrows represent values below 3.6. Narrow bars (open, hatched, closed) indicate standard errors below 26.7.

having the highest levels (Fig. 3c, solid bars). Ammonia-nitrogen ranged from 13.5 to 505.7  $\mu\text{eq/l}$ , with the highest values occurring in New Brunswick, while  $\text{NO}_3^-$ -N ranged from 0.7 to 42.1  $\mu\text{eq/l}$  (Fig. 3c).

As in the natural areas, annual means of  $\text{Na}^+$  and  $\text{Cl}^-$  were higher in the harvested areas of New Brunswick and eastern Québec than in the more continental sites. Most of the  $\text{Na}^+$  means and all of the  $\text{Cl}^-$  means were higher in the harvested areas than the corresponding natural areas. In New Brunswick and eastern Québec, annual means for  $\text{Na}^+$  and  $\text{Cl}^-$  ranged from 281–479  $\mu\text{eq/l}$  and 131–404  $\mu\text{eq/l}$ , respectively, while the lower levels in central Québec and Alberta ranged from 18–211  $\mu\text{eq/l}$  and 16–29  $\mu\text{eq/l}$ , respectively (Fig. 3a,b, solid bars).

The harvested areas had greater variation in K compared to the narrow ranges present in the natural areas. Calcium,  $\text{Mg}^{2+}$  and  $\text{SO}_4^{2-}$  had wider ranges than  $\text{K}^+$ . The Alberta harvested site had the highest annual means for Ca and Mg, while central Québec had the lowest  $\text{SO}_4^{2-}$  and the other harvested sites had means between 202–257  $\mu\text{eq/l}$  (Fig. 3b,c, solid bars).

Comparisons of water samples collected from ditches in harvested fields and water samples from surface hollows or from within water level pipes were made at two of the harvested sites. Although the central Québec ditches and surface hollows varied only slightly, the water from the Alberta harvested site showed large differences. Water from pipes had higher levels of  $\text{Na}^+$ ,  $\text{NH}_4^+$ -N,  $\text{NO}_3^-$ -N and total P, than that taken from the ditches (Fig. 4).

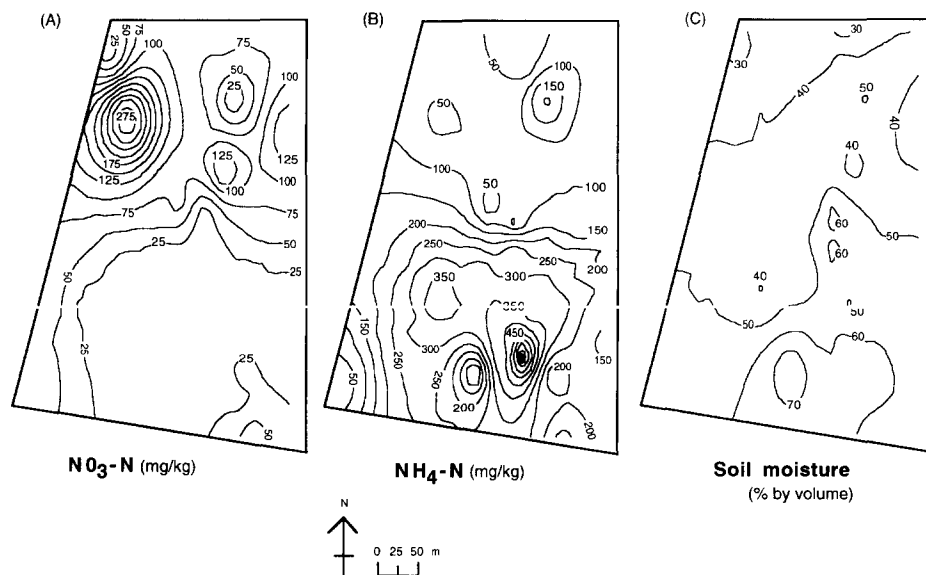


Fig. 5. Nutrient availability at Seba Beach, Alberta. (A) Available nitrate-nitrogen, (B) available ammonia-nitrogen (mg/kg), (C) Soil moisture (% by volume). 1992 values.

Table 5

Surface water nitrogen content from undisturbed peatlands in Canada

Peatland type	Region (B = boreal, C = continental, M = maritime)	Mean $\text{NO}_3^-$ -N (mg/l)	Mean $\text{NH}_4^+$ -N (mg/l)	Reference
Bog	B-Alberta	0.002	0.020	Nicholson, 1987
Bog	B-Alberta	0.002	0.004	Vitt et al., 1995
Bog	B-Alberta	0.002	0.023	Thormann, 1995
Bog	C-Québec and New Brunswick	0.018	0.179	Rocheft, unpublished
Bog	M-Québec and New Brunswick	0.002	0.124	Rocheft, unpublished
Poor fen	B-Alberta	0.001	0.013	Vitt and Chee, 1990
Poor fen	B-Alberta	0.002	0.011	Vitt et al., 1995
Poor fen	C-Québec and New Brunswick	0.002	0.124	Rocheft, unpublished
Poor fen	M-Québec and New Brunswick	0.001	0.001	Rocheft, unpublished
Poor fen	northwest Ontario	< 0.001		Bayley et al., 1987
Moderate-rich fen	B-Alberta	0.001	0.054	Vitt and Chee, 1990
Moderate-rich fen (open)	B-Alberta	0.001	0.028	Thormann, 1995
Moderate-rich fen (open)	B-Alberta	0.002	0.007	Vitt et al., 1995
Moderate-rich fen (forested)	B-Alberta	0.002	0.011	Vitt et al., 1995
Extreme-rich fen	B-Alberta	0.002	0.010	Vitt and Chee, 1990
Extreme-rich fen	B-Alberta	0.001	0.025	Thormann, 1995
Extreme-rich fen	B-Alberta	0.015	0.022	Rocheft, unpublished
Extreme-rich fen	C-Québec and New Brunswick	0.001	0.001	Rocheft, unpublished

Surface peat chemistry of the harvested areas had similar trends to that found in the natural areas. The harvested sites had higher peat pH, with annual means ranging from 2.9 to 6.4, with the highest values present in Alberta (Fig. 3a, solid bars). The maritime influence of high Na levels in the eastern sites was not apparent in the harvested peat, as the Alberta site had the highest Na levels (Fig. 3b, solid bars). Potassium ranged from 95 to 332 mg/kg, with Alberta having the highest annual means (over 250 mg/kg). In the harvested areas, Ca annual means ranged from 780 to 7952 mg/kg, with the highest values in Alberta, and similar to those of the natural areas. As in the natural areas, Mg and S in the peat did not show any consistent trends. Total phosphorus annual means of peat were similar to those of the natural areas, while  $\text{NO}_3^-$ -N annual means of peat were higher in the harvested areas and  $\text{NH}_4^+$ -N annual means were similar or higher than values in the natural areas. In Alberta, nitrogen levels appear to be related to moisture levels, as wetter areas of the harvested site had higher  $\text{NH}_4^+$ -N levels and lower  $\text{NO}_3^-$ -N levels, while drier areas had higher  $\text{NO}_3^-$ -N levels and lower  $\text{NH}_4^+$ -N levels (Fig. 5).

## 5. Discussion

### 5.1. Water chemistry

Removal of the peat surface with harvesting affected the water chemistry of the harvested sites with the exposure of the underlying peat layers. Harvested areas had 2 to 20 times the variation in chemical characteristics compared to the natural peatlands. In the New Brunswick and eastern Québec harvested peatlands, higher levels of aqueous  $K^+$ ,  $Mg^{2+}$  and  $SO_4^{2-}$  indicate that these sites most resemble poor fen chemical conditions and are presently not typical of bogs. Water from the harvested area in Alberta was more similar to a poor or moderate-rich fen (Vitt and Chee, 1990), with higher levels of pH,  $Ca^{2+}$ ,  $Mg^{2+}$  and  $K^+$  than the other three harvested, eastern peatlands. The central Québec harvested site had the least amount of surface peat removed and chemical levels in the water that most closely resemble the chemical conditions of natural North American bogs (Gorham et al., 1985).

The water chemistry of the central Québec harvested site was similar to that of a bog, while the other three harvested sites had fen chemistry characteristics. Yet all of the harvested sites had nutrient levels of  $NH_4^+-N$  and  $NO_3^--N$  higher than neighboring natural areas and higher than values recorded from other undisturbed peatlands (Fig. 3b and Table 5). Possible reasons why the aqueous  $NH_4^+-N$  and  $NO_3^--N$  values were higher in the post-harvested sites include: (1) Values of pH were higher in three of the post-harvested sites than in the natural peatlands and may allow more nitrifying bacteria to grow (Dickinson, 1983). (2) Drier conditions in harvested areas during the sampling periods may have favored more biological activity of aerobic microbes (Lähde, 1969) and higher numbers of nitrifying bacteria (Waksman and Stevens, 1928; Zimenko and Misnik, 1970; Dunican and Rosswall, 1974), thus more organic nitrogen could be mineralized (Heikkinen, 1990). (3) The low (or nonexistent) vegetation cover on the harvested fields may have permitted higher nitrogen levels to remain available, due to lack of nitrogen consumption.

Nutrient levels of aqueous  $NH_4^+-N$ ,  $NO_3^--N$  and total P in the Alberta harvested area ditches decreased in 1992 and 1993 from the high 1991 levels first recorded. The ditches in the Alberta site have increased in vegetation and algal cover since harvesting ceased in 1991, while the areas around the water level pipes on the harvesting bays still have little vegetation cover. The subsequent lower nutrient levels of  $NH_4^+-N$ ,  $NO_3^--N$  and total P in the ditches may be a result of vegetation consumption of these nutrients, while these nutrients are not consumed in the harvested expanses. The ditch nutrient levels perhaps suggest how revegetation may affect nutrient chemistry. The comparisons between the ditch and surface pit samples from central Québec showed little difference; however, this site had low vegetation cover on the harvested bays as well as in the ditches.

### 5.2. Peat chemistry

Peat researchers, such as Mörsjö (1968), Lähde (1969), Sillanpää (1972), Damman (1978), Hemond (1980) and Clymo (1983, overview), have outlined the vertical distribution of elements in undisturbed bogs. Biological activity of *Sphagnum* causes

larger concentrations of K and P in the surface layer, with decreasing concentrations with increasing depth (Mörnsjö, 1968; Lähde, 1969; Damman, 1978; Hemond, 1980). Levels of K in the surface peat were higher in the natural areas of eastern and central Québec than the corresponding harvested areas. The lower levels in the harvested areas in the east (poor fens) indicate that the higher concentrations of these elements in the original surface peat were removed with harvesting and were not replenished due to the lack of biological activity. In Alberta, the levels of K were similar in both harvested and natural areas, suggesting a higher nutrient status of the now exposed moderate-rich fen peat in the harvested area (Vitt and Chee, 1990).

Magnesium and Ca decrease with increasing depth, possibly due to changes in the ion capacity of the peat and humidification (Lähde, 1969; Hemond, 1980), although Damman (1978) recorded an increase in Mg levels with increasing depth. For the harvested site that is most similar to bog chemical characteristics (central Québec), levels of Mg were lower than the neighboring natural area while Ca values were similar in both areas. For the fen-like harvested peatlands of eastern Québec and Alberta, Mg and Ca were higher in the harvested than the natural areas and this is probably due to the exposure of more ion rich fen peat with harvesting.

Sodium has the highest concentration in the top 15 cm, and is leached from the top layers of a peat deposit (Damman, 1978; Clymo, 1983). Lower levels of Na in the harvested peat of eastern and central Québec indicate that the higher levels of sodium, normally found at the surface of undisturbed peatlands, were removed with harvesting. The levels of Na in the Alberta harvested site were higher than the natural area levels, probably due to the exposure of moderate-rich fen peat (Vitt and Chee, 1990).

Levels of pH and conductivity have been shown to increase with increasing depth in a peat deposit (Mörnsjö, 1968). Levels of peat pH and conductivity were higher in all four harvested areas. The less extensive peat removal in central Québec resulted in only a minor increase in peat pH, while the removal of the bog peat with harvesting at the other three sites revealed the more element rich and less acidic fen peat. The peat pH of the harvested field in Alberta changed from 4.5 to 6.1 over the years 1991 and 1992 and was the result of increased moisture on the site, after rewetting measures were started in the fall of 1991.

Nitrogen levels have been documented to remain low throughout bog peat profiles (Damman, 1978, 1988), yet harvested sites had higher than usual levels of  $\text{NH}_4\text{-N}$  and  $\text{NO}_3\text{-N}$  in the surface peat and more variation in values (Fig. 3c and Table 6). While Salonen (1994) documented ranges of 3–58 mg/kg for  $\text{NO}_3\text{-N}$  and 3–45 mg/kg for  $\text{NH}_4\text{-N}$  of harvested peatlands in Finland, our Canadian sites had more variation with

Table 6  
Surface peat nitrogen content from undisturbed peatlands in boreal Alberta, Canada (Harkonen, 1985)

Peatland type	Mean $\text{NO}_3\text{-N}$ (mg/kg)	Mean $\text{NH}_4\text{-N}$ (mg/kg)
Bog	0.9	53.7
Poor fen	1.4	64.6
Moderate-rich fen	1.4	108.1
Extreme-rich fen	1.1	68.4

14–1900 mg/kg  $\text{NO}_3\text{-N}$  and 0–900 mg/kg  $\text{NH}_4\text{-N}$ . As suggested above, these higher levels of  $\text{NO}_3\text{-N}$  and  $\text{NH}_4\text{-N}$  in the post-harvested peat may be due to a variety of factors including increased pH, aeration, microbial activity and low vegetation cover. Evidence that moisture levels affect nitrogen levels was present in Alberta, where wetter areas of the harvested site had higher  $\text{NH}_4\text{-N}$  levels and lower  $\text{NO}_3\text{-N}$  levels, while drier areas had higher  $\text{NO}_3\text{-N}$  levels and lower  $\text{NH}_4\text{-N}$  levels. Zimenko and Misnik (1970) noted this same trend, in which field sites with lower water levels had higher levels of nitrate and nitrifying bacteria, and lower levels of ammonia and ammonifying bacteria. Salonen (1994) noted a correlation between particle size and the prominent form of nitrogen in harvested peatlands. Higher  $\text{NO}_3\text{-N}$  levels were found in peats with larger particle size, while higher  $\text{NH}_4\text{-N}$  soils had smaller particle size. Other laboratory research (Koerselman et al., 1993) showed that higher water levels resulted in higher levels of ammonium release in peat soils, while nitrate release was not significantly affected by a water level 10 cm below the surface. The Alberta results do not corroborate findings from another rewetted peatland of which Meade (1992) documented higher levels of  $\text{NO}_3$  and lower levels of  $\text{NH}_4$  in wetter areas compared to drier areas.

Sulfur increases in concentration with depth in the peat profile, possibly due to changes in solubility and/or increasing humidification and decomposition of the other peat elements (Zoltai and Johnson, 1985). Similar levels of sulfur were recorded in the surface peat of the harvested and natural areas of the Alberta site. With the drier conditions on the harvested site, reduced sulfur compounds may have been reoxidized in the peat and transferred to the water (Bayley et al., 1986).

## 6. Conclusions and implications for restoration

The removal of surface bog peat for peat harvesting activities has altered the peat and water chemistry of the four post-harvested peatlands, moving them back in the fen to bog succession time sequence. All the harvested sites had raised nutrient conditions of nitrate and ammonia, and all had more variation in elemental levels when compared to the natural areas. Natural, undisturbed bogs have fairly narrow ranges of elemental levels in water and peat. Harvested peatlands have more variation due to more varied conditions, including the extent to which fen peat is exposed, differing moisture levels and amount of vegetation cover.

Although the central Québec harvested site still has bog chemical conditions, the New Brunswick and eastern Québec harvested sites are now more similar to poor fens, while the Alberta harvested site is similar to a moderate-rich fen. The exposed fen peat resulted in higher levels  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{SO}_4^{2-}$  and  $\text{Cl}^-$  in the water. Higher levels of nitrate-nitrogen and ammonium-nitrogen in the water and the peat of the post-harvested sites may be explained by a variety of possible factors. Increased aeration and higher pH levels may have allowed more aerobic and nitrifying bacteria to grow, and more organic nitrogen to be mineralized. The lack of vegetation may have allowed the high nitrogen levels to remain intact.

The information obtained from this research characterizes post-harvested peatland conditions. This characterization identifies the differences between natural and harvested peatlands in order to further understand peatland processes and develop restoration measures for these and other post-harvested sites. In particular, high nutrient values, increased element contents and large variation in chemistry indicate that harvested surfaces differ considerably from the original, natural surface.

Since most peatland plants have narrow tolerances to chemical conditions, and are largely limited in their distribution by chemical properties (Sjörs, 1950, 1952; Gignac et al., 1991a), chemical characterization of harvested peatlands is critical for restoration procedures. Selection of appropriate species for restoration must take these factors into consideration. This research should be used in conjunction with predictive models (such as the response surface model (Gignac et al., 1991a,b)) which predict appropriate peatland bryophyte species for given variables of water pH, height above water level and climate.

Chemistry analyses also indicate the limitations of restoration of a particular post-harvested peatland. Bogs that have been harvested to moderate-rich fen surface layers are not likely to be appropriate for ombrotrophic bog plants. Fen species are a better choice for restoration, with emphasis on transitional *Sphagnum* species to help acidify the system. For example, although the chemical conditions are more similar to those of a moderate-rich fen at the Alberta site, *Sphagnum angustifolium* regenerates well if the moisture levels are sufficient, and may help to acidify the site.

Although it has been shown that *Sphagnum* in natural peatlands has increased growth rates with nitrogen additions in some locations (Rocheffort et al., 1990; Aerts et al., 1992), post-harvested peatlands have levels much higher than undisturbed peatlands; thus nitrogen fertilizer additions are not necessary for the restoration of these sites.

Finally, this study indicates that initial site characterization as well as periodic monitoring of site chemistry is necessary in order to provide sufficient data for successful restoration of harvested peatland sites.

## Acknowledgements

Funding for this research has been gratefully received through a NSERC Strategic grant to D.H.V., and a Province of Alberta Graduate Scholarship, a Tri-Council EcoResearch Fellowship, Award number 927-93-0280 and a Walter H. Johns Graduate Fellowship to H.W.M. Money was provided by the Alberta Forestry, Lands and Wildlife, Public Lands Division, the Ministry of Natural Resources and Energy of New Brunswick and a partnership between several public and private organizations from Québec: mainly the Ministère de l'Environnement et de la Faune du Québec, the Centre Québécois de Valorisation de la Biomasse, the Canadian Sphagnum Peat Moss Association, the Association québécoise des producteurs de tourbe, Fafard and Frères Ltée, Tourbières Lambert and Premier Peat Moss. Logistic support was provided by Sun Gro Horticulture Canada. We appreciated the technical assistance in the field that we received from Sade Abiola, Suzanne Campeau, Trevor Coleman, Chantal Ferland, Linda Halsey, Pat Hardy, Yenhung Li, Tracey Mattock, François Quinty, Allison Scott and

Christine Vogel, and lab assistance from Gerdie Hutchinson. Useful comments were given on an earlier draft of this paper by Claude Lavoie.

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