

## COMPARISONS OF WATER AND PEAT CHEMISTRIES OF A POST-HARVESTED AND UNDISTURBED PEATLAND WITH RELEVANCE TO RESTORATION

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**Abstract:** Peat harvesting has altered site water and peat chemistry at the Seba Beach peatland through removal of surface bog peat, moving the site back in the fen-to-bog succession time sequence. The post-harvested site is more similar to a moderate-rich fen in water and peat chemistry than the bog that it was originally. The exposure of fen peat has resulted in significantly higher concentrations for almost all water and peat chemical components compared to the neighboring natural bog. During five years of sampling this study found no significant differences between years in the water and peat chemistry within the natural area. A few significant yearly differences were found in the harvested area water chemistry, while the harvested area peat chemistry had many significant yearly differences. Several patterns were noted in the nitrogen concentrations in the harvested field. First, the harvested site had significantly higher concentrations of aqueous  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$ , as well as available  $\text{NO}_3^-\text{-N}$  in the peat, compared to the neighboring natural area. A variety of possible factors, such as increased aeration, high pH values, and low vegetation cover may account for these high nitrogen concentrations. Second, peat nitrogen concentrations seem to be affected by soil moisture. Harvested areas with high soil moisture had high concentrations of available  $\text{NH}_4^+\text{-N}$  and lower available  $\text{NO}_3^-\text{-N}$  concentrations, while drier areas had high concentrations of available  $\text{NO}_3^-\text{-N}$  and lower available  $\text{NH}_4^+\text{-N}$  concentrations. Third, the concentrations of these nutrients in the harvested area did not remain static over the years. In the peat, available  $\text{NO}_3^-\text{-N}$  concentrations were significantly reduced in 1995, and in the well samples,  $\text{NH}_4^+\text{-N}$  was significantly reduced in 1994 and 1995 compared to earlier years. This research shows that the chemistry of the harvested site has significantly changed from the original bog ecosystem. As the site is more similar to a moderate-rich fen, ombrotrophic bog species are unlikely to thrive on this site.

**Key Words:** peatland, peat harvesting, restoration, reclamation, water chemistry, peat chemistry

### INTRODUCTION

Peatlands are important ecosystems in Canada, where they cover 170 million ha, more than in any other country (Gorham 1990). A very small portion of this area is harvested for horticultural peat moss. Vacuum harvesting is the most common harvesting method in Canada. With this method, drains are installed in large areas, surface peatland vegetation is removed, and the fibric, high-*Sphagnum*-content peat is slowly harvested over years to decades. When layers of sub-quality peat are reached in the peat deposit, harvesting is stopped. Restoration measures are necessary to return the site to a functioning peatland because abandoned, harvested sites generally do not recover quickly (Lavoie and Rochefort 1996, Bugnon et al. 1997, Ferland and Rochefort 1997), as water levels are

low (Famous et al. 1991, Larose et al. 1997) and wind erosion is high (Campeau and Rochefort 1996)

One necessary step in the restoration process is to assess the chemical state of the post-harvested peatland. By comparing harvested with undisturbed peatlands, changes in elemental concentrations, nutrient status, successional pathways, and peatland type can be determined. As site chemistry influences type and growth of peatland vegetation, this information is necessary to develop a site-specific restoration plan.

Wind-Mulder et al. (1996) examined spatial variability in water and peat chemistry of four post-harvested and associated natural peatlands across Canada. This paper differs from Wind-Mulder et al. (1996), which focuses on the temporal variability of one post-harvested and one neighboring natural peatland in Seba Beach, Alberta. Data from five years of research

are analyzed. The objectives of this paper are to determine chemical differences between the harvested site and natural peatland and to determine the extent of chemical change that results from peat removal.

#### SITE DESCRIPTION

The Seba Beach peatland is located about 130 km west of Edmonton, Alberta, Canada (53° 33' N, 114° 44' W). This peatland is classified as a Continental Mid-Boreal peatland (NWWG 1988), typical of ombrotrophic bogs in the southern boreal forest of continental western Canada. The area has a mean annual temperature of 2.4° C, with a mean January temperature of -15° C and mean July temperature of 16° C. Average annual precipitation for the area is 528.8 mm, with a quarter of the total precipitation falling as snow (Environment Canada 1982a, 1982b).

Originally, this peatland was covered by bog and poor fen vegetation dominated by *Picea mariana* (Mill.) BSP., *Sphagnum fuscum* (Schimp.) Klinggr., *S. magellanicum* Brid., *S. angustifolium* C. Jens. ex Russ., and a few scattered *Larix laricina* (Du Roi) K. Koch. This site was first opened to harvesting by dredging in 1975. In 1980, Fisons Horticulture Inc., now Sun Gro Horticulture Canada Ltd., acquired the site and 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 by Sun Gro. The peat surface is highest in the northeastern corner, sloping downward to the southwest corner, with drainage southwestward. Drainage ditches run east/west, dividing the field into 20 harvesting bays and ranges in width from approximately 15 to 50 m. In general, the lower elevation bays in the south were wetter than the higher elevation bays in the north, with the hydraulic gradient roughly paralleling ditch orientation (Wind-Mulder 1998). The perimeter ditch runs along the western edge. Peat depth ranges from 0.73 m at the northern end to more than 4 m at the southern end.

To raise the water level, a dam was constructed in the southwestern corner in the fall of 1991, following the cessation of peat harvesting. Over the years 1992 to 1995, water levels increased, although conditions were quite varied across the field, ranging from dry to flooded (Wind-Mulder 1998).

The natural peatland is located over 200 m from the western edge of the harvested site. Over a four-year monitoring period from 1992 to 1995, water-level fluctuations and depths did not deviate in the natural peatland from typical values of other bogs in continental western Canada (Wind-Mulder 1998, Vitt unpublished data), indicating that drainage from the harvested site had not impacted the water level of the natural peat-

land at this location. The vegetation is mainly composed of *Picea mariana*, *Ledum groenlandicum* Oeder., *Andromeda polifolia* L., and *Sphagnum* mosses such as *Sphagnum fuscum*, *S. magellanicum*, and *S. angustifolium* typical of bog vegetation in Alberta (Belland and Vitt 1995). A site description of a section of the natural area is outlined in Li and Vitt (1997).

#### METHODS

##### Water Chemistry

Surface water samples were obtained from pools, ditches, or from within water-level wells. On the harvested site, ditches were first sampled randomly but approximately equally along the western quarter. With the installation of water-level wells, additional water samples were obtained from the surface water within the well, either by immersing the sample bottle in the well or by drawing water up by suction with a syringe and rubber hose. Water-level wells ranged from 1 to 25 m from the closest ditch to ensure that the chemical variability across the harvested surface was sampled. In the natural area, water samples were obtained within the well and from nearby shallow pools. Water samples were collected in July and August 1991, June and August 1992, August 1993, September 1994, and July 1995. Sample size for ditch water samples ranged from 2 to 15 from 1991 to 1995 (see Wind-Mulder 1998 for details). In the years 1993 to 1995, ten yearly water samples were collected from the wells in the harvested area, and two yearly water samples were collected in the natural area.

Surface water pH was measured digitally in the field or in the lab following Stainton et al. (1977). Surface water samples were measured for conductivity values with corrections for temperature at 20° C and hydrogen ions (Sjörs 1952). The Department of Zoology analyzed surface water nutrients at the University of Alberta. Water samples were stored in 1-L Nalgene polyethylene bottles for Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>, Mg<sup>2+</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, total phosphorus (TP), and NO<sub>3</sub>-N analyses. Water samples for NH<sub>4</sub><sup>+</sup>-N analyses were stored in 250 ml polystyrene flasks. Samples for Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>, and Mg<sup>2+</sup> were filtered through a prewashed Whatman GF/C filter, stored at 4° C, and analyzed on an atomic absorption spectrometer (Perkin-Elmer, model 3300). Analyses of Cl<sup>-</sup> and SO<sub>4</sub><sup>2-</sup> were conducted by ion chromatography with a Waters chromatographic system. Samples for TP were filtered under low pressure (-50 kPa) through a 250-µm Nitex net and transferred to culture tubes (Prepas and Rigler 1982, modified from Menzel and Corwin 1965). These samples were analyzed colorimetrically on a Milton Roy Spectronic Spectrometer. After filtration through a prewashed

0.45- $\mu\text{m}$  HAWP Millipore membrane filter, nitrate was determined on the technicon by the cadmium-copper reduction method of Stainton et al. (1977). Ammonium samples were analyzed on the technicon by Solorzano's (1969) phenylhypochlorite method as modified by Prepas and Trew (1983).

#### Peat Chemistry

Peat samples were collected from 0 to 5 cm profiles from the harvested peat surfaces and from 1 to 5 cm profiles in the natural area using a TJ-10.5 corer, a tomato juice can with one edge cut to form a handle and the other cut and filed to form a sharp cutting edge, with an opening diameter of 10.5 cm. In the natural area, two random samples were gathered within the vicinity of the natural area well (with the occasional exception, see Wind-Mulder 1998 for details). In the harvested area, peat sampling varied between years. In July 1991, the harvested field was sampled for peat pH and conductivity by dividing the field into 70-m sections along the bays and randomly collecting samples within each section ( $n=86$ ). In July and August 1992, the sampling design was altered to reduce the sample size for financial considerations. Each harvesting bay was divided in half, perpendicular to the hydraulic gradient, and was randomly sampled within each section ( $n=40$ ). As the bays were divided perpendicular to the hydraulic gradient no sampling bias for wetter or drier regions was encountered. In 1993 to 1995, peat samples collected along the western quarter were randomly placed near selected revegetation plots, while the rest of the site was divided into 4 to 8 sections and randomly sampled within each section. In September 1993, 40 peat samples were collected and in September 1994 and July 1995, 20 peat samples were analyzed. Samples were stored in polyethylene bags at a cool temperature until analysis.

Peat pH was analyzed using a 1:2 ratio of fresh peat and distilled water using methods from the Department of Soil Science at the University of Alberta (1990). Peat conductivity analyses were conducted using the same ratios. Peat conductivity measurements were corrected for temperature to 20° C and for pH according to Sjörs (1952). Bulk density was analyzed by oven drying peat samples of known volumes at 60° C.

Soil peat samples were analyzed for the elements Ca, K, Mg, Na, P, and S by dry ashing methods. Peat samples were oven-dried at 60° C, and then ground to 1/2 mm or less. Subsamples of 0.3 to 0.4 g were dry ashed at 470 °C and acid-digested with 6 ml 1.5 N HCl and 1 ml concentrated HNO<sub>3</sub>. Digested samples were filtered through Whatman #42 filter paper and analyzed by inductively coupled plasma spectrophotometry. Available nitrate and ammonia were extracted

by using a 1:20 ratio of air-dry ground peat and 2N KCl, mechanically shaken for 30 minutes and analyzing the filtrate using a technicon autoanalyzer and the Industrial Methods 158-71 W/B, December 1972, and 696-82W, April 1983, respectively. Samples were analyzed by the Department of Zoology at the University of Alberta (available NO<sub>3</sub>-N and available NH<sub>3</sub>-N samples) and by Forestry Canada, Northern Forestry Centre (Ca, K, Mg, Na, P, and S samples).

#### Statistical Analyses

Yearly chemistry data were grouped according to sampling sources. Peat chemistry data were either from the harvested field or the neighboring natural area. Water chemistry data were grouped into three source categories: natural area, harvested site ditches, and harvested site wells. The chemistry data were not normally distributed, and variances were not homogeneous. Spread versus level graphs and power of transformation values were generated, and transformations to normalize the data were attempted. Transformations could not fully normalize the data and homogenize the variances. Thus, nonparametric tests were used, with an alpha value consistently set at 0.05. For the water chemistry analyses Kruskal-Wallis one-way analysis of variance tests determined differences between years within sampling sources. Tukey Type Multiple Comparisons tests resolved distributions of significant differences. Since there were few significance differences between years within the sampling source categories, the yearly results were combined and differences between source categories were analyzed by Kruskal-Wallis one-way analysis of variance tests, followed by Tukey Type Multiple Comparisons tests.

For the peat chemistry analyses, testing was similar except that many chemical elements had significant differences between years. Therefore, Mann-Whitney U-Wilcoxon Rank Sum W tests were used to determine differences within years between the natural and harvested area. The computer package SPSS was used for all these statistical tests (SPSS 1995), with the exception of the Tukey Type Multiple Comparisons tests, which were manually calculated.

In addition to these statistical tests, the yearly variation of each sampling source was calculated as a coefficient of variation for each chemical component for both water and peat chemistry. These yearly coefficients of variation were averaged for each component, then components of similar unit-based measurements were ranked in order of increasing variation and compared. These calculations make it possible to compare relative variability of the chemical factors for each sampling source, as both mean and standard deviation (dispersion) are taken into account.

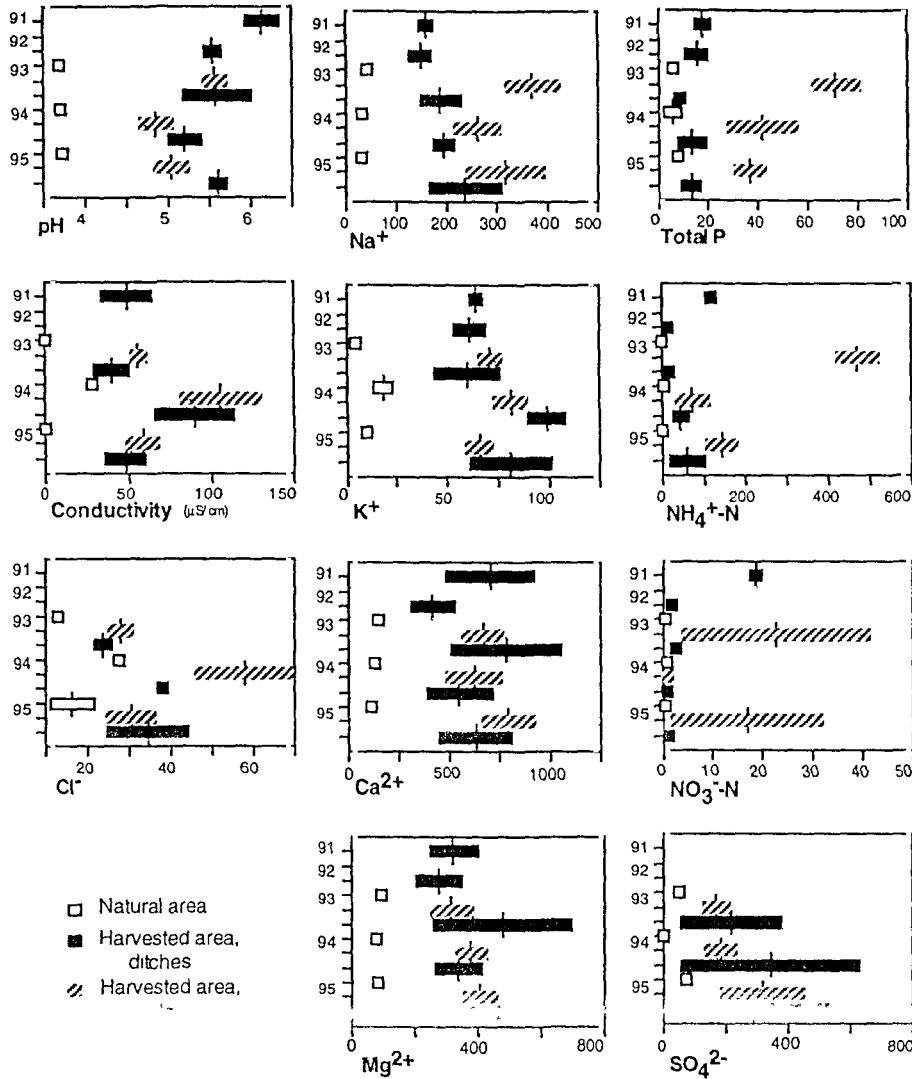


Figure 1. Annual mean water chemistry (in µeq/L, ± Standard Error), 1991–1995 values

RESULTS

Natural Area Water Chemistry

Generally, the water chemistry of the natural area had lower concentrations and less variation than did the harvested site (Figures 1 and 2). Mean annual pH in the surface water of the natural area was consistently 3.7, while mean annual conductivity ranged from 0 to 28 µS/cm (Figure 1, white bars). Cation concentrations (Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>, and Mg<sup>2+</sup>) were lower than those of the harvested site (Figure 1, white bars). In decreasing order of concentration, total phosphorus, NH<sub>4</sub><sup>+</sup>-N, and NO<sub>3</sub><sup>-</sup>-N in the natural area had mean annual ranges of 5.7 to 7.8 µeq/L, 3.2 to 5.5 µeq/L, and 0.4 to 0.8 µeq/L, respectively (Figure 1,

white bars). The natural area had consistent chemical concentrations over the years, with no significant differences between years. Mean coefficients of variation in the natural area were ranked according to increasing variability in the following order: Ca<sup>2+</sup> < Mg<sup>2+</sup> < Na<sup>+</sup> < NO<sub>3</sub><sup>-</sup>-N < Cl<sup>-</sup> < SO<sub>4</sub><sup>2-</sup> < K<sup>+</sup> < NH<sub>4</sub><sup>+</sup> - N < TP (Figure 2).

Natural Area Peat Chemistry

Peat chemistry values in the undisturbed area tended to be lower than in the harvested site (Figures 3 and 4). Mean annual peat pH ranged from 4.1 to 4.3, and mean annual conductivity ranged from 5 to 10 µS/cm (Figure 3, white bars). The elements Ca, Mg, Na, and

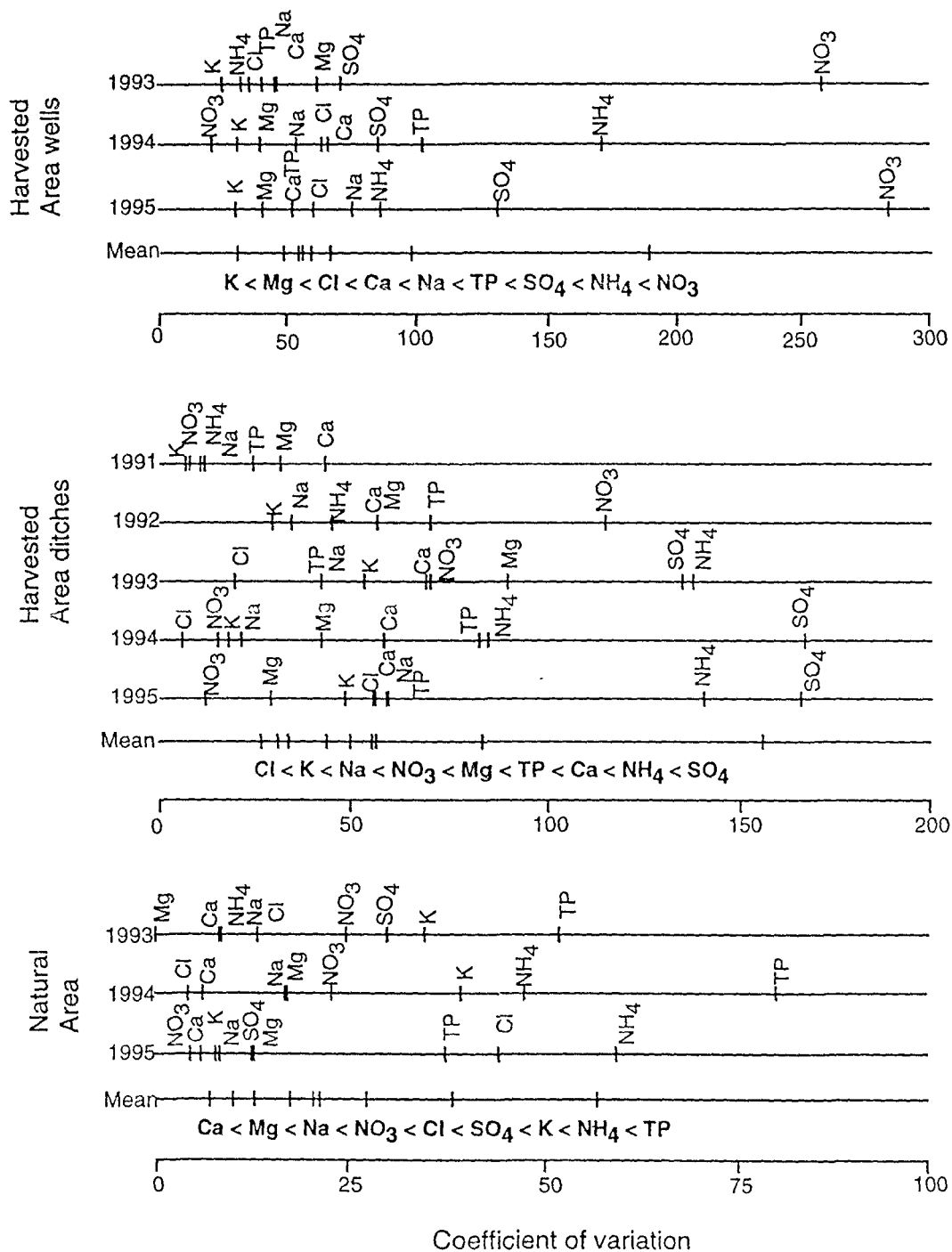


Figure 2 Coefficients of variation for water chemistry components for natural and harvested areas. Annual and total mean annual values outlined. Abbreviations: Ca = Ca<sup>2+</sup>, Cl = Cl<sup>-</sup>, K = K<sup>+</sup>, Mg = Mg<sup>2+</sup>, Na = Na<sup>+</sup>, NH<sub>4</sub> = NH<sub>4</sub><sup>+</sup>-N, NO<sub>3</sub> = NO<sub>3</sub><sup>-</sup>-N, SO<sub>4</sub> = SO<sub>4</sub><sup>2-</sup>, TP = total phosphorus.

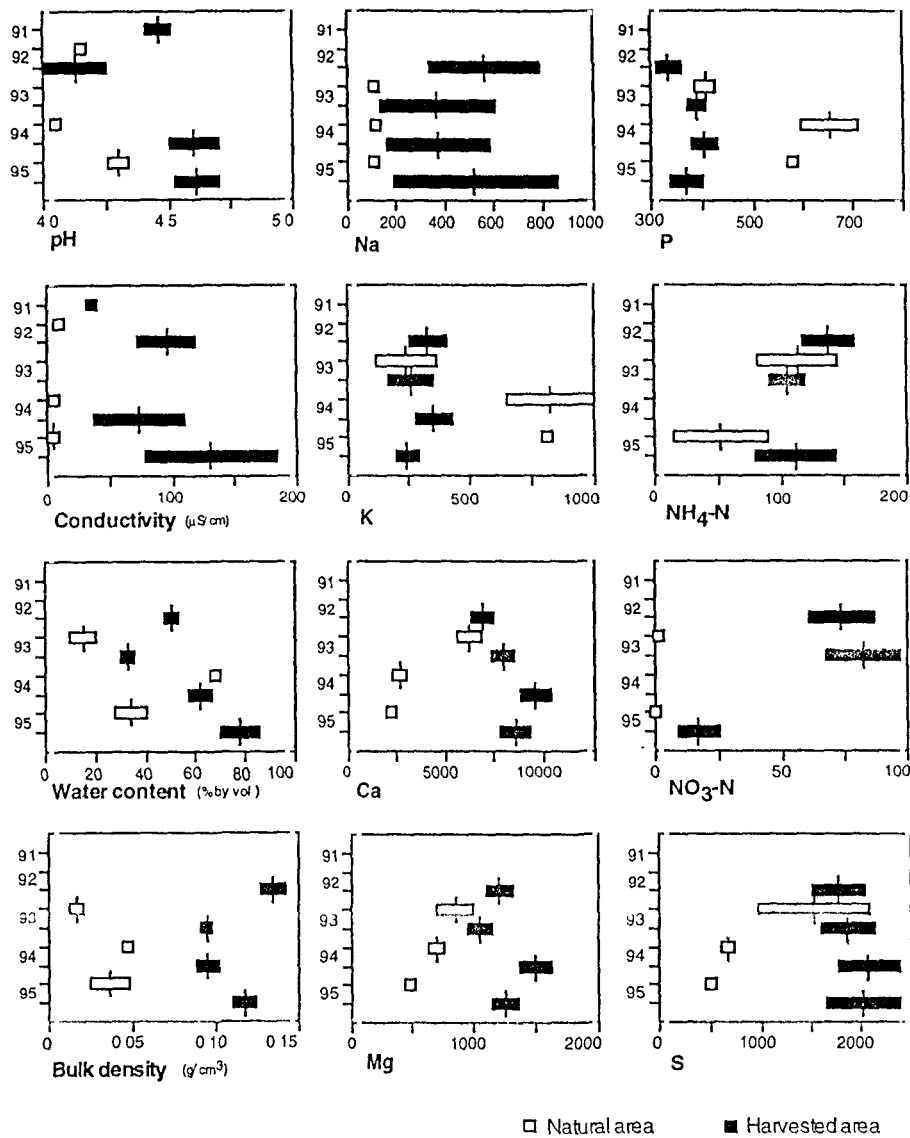


Figure 3 Annual mean peat chemistry (in mg/kg, unless otherwise noted,  $\pm$  Standard Error), to 5 cm depth, 1991–1995 values

S all had lower concentrations in the natural area (Figure 3, white bars). Phosphorus and potassium were the only chemical elements that had higher means in the natural area than in the harvested field (Figure 3). Phosphorus had a mean annual range of 406 to 653 mg/kg. The available nutrients  $\text{NH}_4\text{-N}$  and  $\text{NO}_3\text{-N}$  had mean annual ranges of 51.8 to 112.0 mg/kg and 0.1 to 1.4 mg/kg (Figure 3, white bars). No significant differences between years were found for peat chemistry within the natural area. Mean coefficients of variation for the natural area peat chemistry increased in variability in the following order:  $\text{Na} < \text{P} < \text{Ca} < \text{Mg} < \text{S} < \text{K} < \text{NH}_4\text{-N} < \text{NO}_3\text{-N}$  (Figure 4).

#### Harvested Area Water Chemistry

Generally, the surface water chemistry from both the ditches and from within the wells had higher concentrations of constituents than the natural site. In the wells, mean annual surface water pH ranged from 4.9 to 5.6 and mean annual conductivity ranged from 56 to 106  $\mu\text{S}/\text{cm}$ , while the ditch samples had a slightly higher pH and slightly lower conductivity range of 5.2 to 6.2 and 40 to 90  $\mu\text{S}/\text{cm}$ , respectively. The ditches had lower or similar annual means as the well category for the cations  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ , and  $\text{Mg}^{2+}$ . Generally, the water from within the wells had higher nutrient

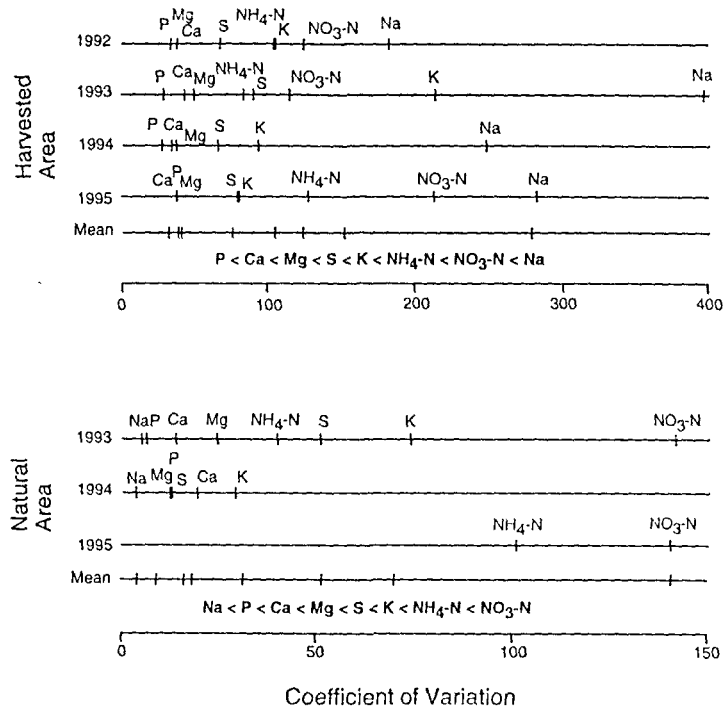


Figure 4 Coefficients of variation for peat chemistry components for natural and harvested areas. Annual and total mean annual values outlined

values for total phosphorus,  $\text{NH}_4^+\text{-N}$ , and  $\text{NO}_3^-\text{-N}$  than from the ditches (Figure 1, striped and solid black bars). Values for  $\text{SO}_4^{2-}$  and  $\text{Cl}^-$  overlapped for the well and ditch sources, and the annual means for both harvested groups were higher than those values of the undisturbed site.

The sequence of increasing variability for mean coefficients of variation for the well and ditch water sources differed from the natural area and from each other (Figure 2). Variability increased in the well samples in the following order.  $\text{K}^+ < \text{Mg}^{2+} < \text{Cl}^- < \text{Ca}^{2+} < \text{Na}^+ < \text{TP} < \text{SO}_4^{2-} < \text{NH}_4^+\text{-N} < \text{NO}_3^-\text{-N}$ , while ditch samples had this order:  $\text{Cl}^- < \text{K}^+ < \text{Na}^+ < \text{NO}_3^-\text{-N} < \text{Mg}^{2+} < \text{TP} < \text{Ca}^{2+} < \text{NH}_4^+\text{-N} < \text{SO}_4^{2-}$ . Within each sequence, the coefficient numbers tended to be close in value, with the top two or three components being higher in variation.

Testing of differences between years within the sampling sources showed only a few significant differences within the various water chemistry components (Table 1). The pH of the ditch samples in 1994 was significantly lower than the 1991 values, and corrected conductivity was higher in 1992 and 1994 compared to 1991 values, but otherwise the years were not significantly different. The well samples had differences between years for  $\text{NH}_4^+\text{-N}$  and  $\text{Cl}^-$ . In 1993, the  $\text{NH}_4^+\text{-N}$  values were significantly higher than the sub-

sequent years, and in 1994,  $\text{Cl}^-$  values were significantly higher than the other sampled years.

With the yearly data grouped together, sampling source comparisons showed significant differences in all the water chemistry attributes except  $\text{SO}_4^{2-}$  (Table 1). The properties pH,  $\text{Na}^+$ , and  $\text{K}^+$  had all three sampling sources significantly different from each other. The wells and ditches were both significantly higher than the natural site for corrected conductivity and the cations  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{NO}_3^-\text{-N}$ . For total P, the well category was significantly higher than both the ditch and the natural area sources. For  $\text{NH}_4^+\text{-N}$  and  $\text{Cl}^-$ , the well source was only significantly higher than the natural area category.

#### Harvested Area Peat Chemistry

Some trends in the water chemistry of the harvested site were also seen in the peat chemistry. With the exception of P and K, peat chemistry values for the harvested site were usually higher than the natural area values (Figure 3). In the harvested site, mean annual peat pH varied from 4.1 to 4.6, and peat conductivity ranged from 37 to 131  $\mu\text{S}/\text{cm}$  (Figure 3, solid bars). Mean annual phosphorus concentrations ranged from 335 to 405 mg/kg. Available  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  ranged from 104 to 138 mg/kg and 17 to 83 mg/kg

Table 1 Significant differences between groupings of the water chemistry components. NA = Natural area, pipe and hollows, D = harvested area wells. Alpha values set at 0.05.

Chemical-Element	Significant Differences Between Years Within a Sampling Source			Years with Significant Differences Between Sampling Sources			Significant Differences Between Sampling Sources When Years Are Grouped Together		
	91	92	93	95	94	df	Chi-Squared Value	df	Chi-Squared Value
pH	Ditches								
Corrected Conductivity ( $\mu\text{S}$ at 20°C)	91 92 93 95 94								
$\text{NH}_4^+$ ( $\mu\text{eq/L}$ )				1993			D W NA		
$\text{K}^+$ ( $\mu\text{eq/L}$ )				1994			D W NA		
				1995			D W NA		
$\text{Ca}^{2+}$ ( $\mu\text{g/L}$ )				1993			W D NA		
$\text{Mg}^{2+}$ ( $\mu\text{g/L}$ )				1993			D W NA		
Total P ( $\mu\text{g/L}$ )				1995			W D NA		
$\text{NH}_4^+-\text{N}$ ( $\mu\text{eq/L}$ )	93 95 94						W D NA		
$\text{NO}_3^- - \text{N}$ ( $\mu\text{eq/L}$ )	93 95 94						W D NA		
$\text{SO}_4^{2-}$ ( $\mu\text{eq/L}$ )	94 95 93						W D NA		
$\text{Cl}^-$ ( $\mu\text{eq}$ )	94 95 93						W D NA		



Table 2. Significant differences between groupings of the peat chemistry components. Significance values are \* for  $p \leq 0.05$ . Alpha values set at 0.05

Chemical-Element	Significant Differences		df	Chi-Squared Value	Years with Significant Differences Between Sampling Sources
	Between Years	Within the Harvested Site			
pH		94 95 91 92	3	15.5	1994*
Corrected conductivity ( $\mu\text{S}$ at $20^\circ\text{C}$ )		95 92 94 91	3	14.6	1994* 1995*
Na (mg/kg)		92 94 95 93	3	15.1	
K (mg/kg)		94 92 95 93	3	24.5	
Ca (mg/kg)					1994*
Mg (mg/kg)		94 95 92 93		11.3	1994*
P (mg/kg)					1994*
Available $\text{NH}_4^+\text{-N}$ (mg/kg)		93 92 95	2	20.5	1993*
S (mg/kg)					1994*
Water content (% by volume)		95 94 92 93	3	48.4	1995*
Bulk density ( $\text{g}/\text{cm}^3$ )		92 95 93 94	3	25.4	1993* 1994* 1995*

for the annual means, respectively. The order of increasing variability, as measured by coefficients of variation, was similar to the natural area peat chemistry, with the exception that Na was not the chemical component with the lowest coefficient of variation, but rather the highest (Figure 4).

Testing of differences between years within the harvested area showed a number of significant differences within the peat chemistry components (Table 2). In 1991, corrected conductivity was significantly lower than in the following years. In 1992, pH was significantly lower, in 1993, Na and water content in the peat were both significantly lower; and in 1995, available  $\text{NO}_3\text{-N}$  was significantly lower than in the other years. No consistent trends were discerned in these results, except that there were more observed yearly differences in the peat chemistry results than in the water chemistry results.

Some significant differences between the natural area and harvested area within years were noted in the peat chemistry data (Table 2). In 1993, significant dif-

ferences in available  $\text{NO}_3\text{-N}$  and bulk density were found. In 1994, significant differences were observed in pH, corrected conductivity, Mg, P, S, and bulk density. In 1995, corrected conductivity, water content, and bulk density had significant differences between the natural and harvested sites. The only two chemical components that did not show some significant differences between the harvested and natural sites within years were Na and available  $\text{NH}_4\text{-N}$ .

## DISCUSSION AND CONCLUSIONS

### Water Chemistry

Removal of the upper peat layers by harvesting has affected the water chemistry of this post-harvested site. Although the low number of sample values for the natural area may have reduced the power of some of the statistical tests, the data obtained from the natural area are similar to other bogs in continental western Canada reported in the literature (Zoltai and Johnson

Table 3. Sequence of mean coefficients of variability for water and peat chemistry

Water chemistry	
Natural area	$\text{Ca}^{2+} < \text{Mg}^{2+} < \text{Na}^+ < \text{NO}_3\text{-N} < \text{Cl}^- < \text{SO}_4^{2-} < \text{K}^+ < \text{NH}_4^+\text{-N} < \text{TP}$
Harvested area wells	$\text{K}^+ < \text{Mg}^{2+} < \text{Cl}^- < \text{Ca}^{2+} < \text{Na}^+ < \text{TP} < \text{SO}_4^{2-} < \text{NH}_4^+\text{-N} < \text{NO}_3\text{-N}$
Harvested area ditches	$\text{Cl}^- < \text{K}^+ < \text{Na}^+ < \text{NO}_3\text{-N} < \text{Mg}^{2+} < \text{TP} < \text{Ca}^{2+} < \text{NH}_4^+\text{-N} < \text{SO}_4^{2-}$
Peat chemistry	
Natural area	$\text{Na} < \text{P} < \text{Ca} < \text{Mg} < \text{S} < \text{K} < \text{NH}_4\text{-N} < \text{NO}_3\text{-N}$
Harvested area	$\text{P} < \text{Ca} < \text{Mg} < \text{S} < \text{K} < \text{NH}_4\text{-N} < \text{NO}_3\text{-N} < \text{Na}$

1987, Nicholson 1993, Vitt et al. 1995). The low chemical concentrations found in the natural area are in contrast to the higher concentrations in the post-harvested site, which show the effects of exposure to more minerotrophic peat in the harvested area. All the chemical components from the harvested area well samples were significantly greater than those from the natural area. The water chemistry of the harvested area is no longer typical of a bog but now is similar to a poor or moderate-rich fen (cf. Vitt and Chee 1990).

Water samples from both the ditches and the wells in the middle of harvested bays had similarly high chemical concentrations. However, chemical concentrations were higher in the wells than in the ditches, and this was possibly due to differences in vegetation growth around the two water sources. In addition, dilution of ditch water by rainfall was also a likely factor reducing chemical concentrations in ditch waters. Vegetation grew on the ditch banks throughout the study, while vegetation cover around the wells was low, although it did increase over the years. The good vegetation growth in the ditches may have resulted in a higher level of aqueous nutrients being consumed. Two chemical components, pH and  $K^+$ , were significantly greater in the ditches compared to the well samples. Possibly, the exposure of deeper peat in the ditches resulted in higher concentrations for these two components. Thus, chemical conditions in the ditches and on the harvested bays are different.

Nutrient concentrations of total P,  $NH_4^+$ -N, and  $NO_3^-$ -N were significantly higher in the harvested site than in the natural area and were higher than values recorded from other undisturbed peatlands (Wind-Mulder et al. 1996). Total P concentrations were significantly higher in the wells than in the ditches or natural area, possibly due to the lower vegetation cover on the harvested bays. Several reasons could explain why the aqueous  $NH_4^+$ -N and  $NO_3^-$ -N values were higher in the post-harvested site than in the natural area. The harvested area had higher pH values that may allow more nitrifying bacteria to grow (Dickinson 1983). Some portions of the harvested site were quite dry, which may have favored more biological activity of aerobic microbes (Lahde 1969) and higher numbers of nitrifying bacteria (Waksman and Stevens 1928, Zimlenko and Misnik 1970, Duncan and Rosswall 1974). These micro-organisms mineralize more organic nitrogen (Heikkinen 1990). Overall low vegetation growth on the harvested site may have permitted higher nitrogen concentrations to remain available due to lack of nitrogen consumption.

While nutrient concentrations were always higher in the harvested site than the natural peatland, concentrations of  $NH_4^+$ -N did not increase significantly in the wells in 1994 and 1995 (Table 1). As mentioned above, veg-

etation cover was low on the harvested bays, yet vegetation cover did increase over the years, especially in the wetter areas. Randomly placed permanent control plots showed a mean annual vegetation cover increase of 0 to 10% in the dry areas and an increase of 0 to 50% in the wetter areas from 1993 to 1995. The low vegetation cover in the dry areas may have allowed the  $NO_3^-$ -N concentrations to remain high, while the greater increase in vegetation in the wetter areas may have caused the significant reduction of  $NH_4^+$ -N concentrations in 1994 and 1995 in the wells.

Very few differences were noted between years within the three water sample sources (harvested area wells, harvested area ditches, and natural area) with the Kruskal-Wallis one-way analysis of variance and Tukey Type Multiple Comparisons tests. Besides the decrease in  $NH_4^+$ -N concentrations in the well samples as previously discussed, the only other two chemical components with differences between years were pH and Cl<sup>-</sup>. Water pH was significantly higher in the ditches in 1991 compared to 1994, and the 1994 Cl<sup>-</sup> concentrations were significantly higher in wells compared to 1993 and 1995 concentrations. The reasons for these particular yearly differences are unclear. With these exceptions, no other significant differences were found between years for the chemical components of the three water sources.

Calculated coefficients of variation for the three water sources showed some, mainly minor, differences among years for the chemistry ranking. As the size of *n* varies among sampling sources, the relative order of ranking is more comparable than the actual coefficient of variation value. With all three sources, the nutrients  $NO_3^-$ -N,  $NH_4^+$ -N,  $SO_4^{2-}$ , and total phosphorus, tended to have higher ranks for the coefficient of variation than the cations. More studies of chemical variation in other harvested and natural peatlands would be helpful to provide comparisons and address additional questions. For example, do all natural, undisturbed peatlands have low variability in the water chemistry components? Are there changes in chemical variability in harvested sites, perhaps starting at one level with the completion of harvesting, increasing as rewetting begins with the resulting mixture of wet and dry areas, then decreasing to become more comparable to undisturbed peatlands as restoration of the entire site occurs? Also, why do nutrients vary more than cations?

#### Peat Chemistry

Peat chemistry of the natural area was similar to other undisturbed bogs reported in the literature (Zoltoi and Johnson 1987, Nicholson 1993). The chemical concentrations in the natural area were generally lower than in the harvested area, and no significant differ-

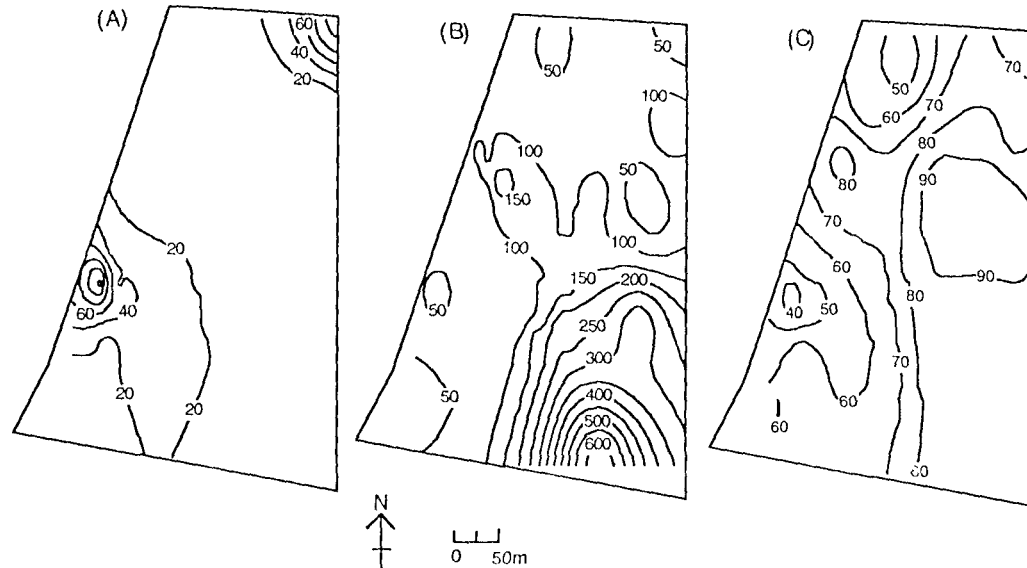


Figure 5 (A) Available nitrate-nitrogen, (B) available ammonia-nitrogen across the harvested site (in mg/kg, to 5 cm depth) (C) Soil moisture (% by volume) across the site July 1995 values

ences between years were found in the natural area. The peat chemistry was more variable between years in the harvested area, with almost all the studied chemical components having some significant differences between years. Although not all years showed significant differences between the harvested and natural areas, all but three elements had significant differences during the study period.

Many of the chemical elements were higher in the harvested site than in the natural area due to the removal of the ombrotrophic bog peat and the exposure of the more minerotrophic fen peat. Conductivity, pH, Ca, Mg, available  $\text{NO}_3\text{-N}$ , S, and bulk density all had significantly higher values in the harvested area than in the natural site. Peat pH and conductivity have been shown to increase with increasing depth in peat cores (Mornsjö 1968), as has sulfur (Zoltai and Johnson 1987). Peat pH, conductivity, Ca, Mg, S, and bulk density have also been documented to be greater in fens than in bogs (Zoltai and Johnson 1987, Nicholson 1993).

In contrast, concentrations of P and K in the peat were lower in the harvested site compared to the natural site. Higher concentrations of P and K in the natural area were due to the biological activity of *Sphagnum* concentrating these elements in the surface layers (Mornsjö 1968, Lahde 1969, Damman 1978, Hemond 1980). Harvesting of these surface peat horizons has removed these higher surface concentrations at the post-harvested site.

In the peat, another two nutrients affected by har-

vesting were KCl-extractable (available)  $\text{NO}_3\text{-N}$  and  $\text{NH}_4\text{-N}$ . The harvested site had significantly higher concentrations of available  $\text{NO}_3\text{-N}$  compared to the natural area. Available  $\text{NH}_4\text{-N}$  concentrations tended to be higher in the harvested area but not significantly higher than the neighboring natural area. As previously suggested in Wind-Mulder et al. (1996), these higher concentrations 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.

Changes in nitrogen concentrations have occurred over the study period. Concentrations of available  $\text{NO}_3\text{-N}$  significantly decreased in the harvested field in 1995 compared to 1992 and 1993 concentrations, while concentrations of available  $\text{NH}_4\text{-N}$  remained unchanged during this period. The distribution of nitrogen also changed across the site, as shown by 1992 and 1995 concentration maps. In 1992, wetter areas of the harvested site in the south had higher  $\text{NH}_4\text{-N}$  concentrations and lower  $\text{NO}_3\text{-N}$  concentrations, while drier areas in the north end of the field had higher  $\text{NO}_3\text{-N}$  concentrations and lower  $\text{NH}_4\text{-N}$  concentrations (Wind-Mulder et al. 1996). Between 1992 and 1995, soil moisture increased. High moisture values were not solely found in the lower southern half of the field but rather in the central and southeastern portions of the site (Figure 5). In these wet areas, available nitrate-nitrogen concentrations were low, while available ammonia-nitrogen concentrations were high. High water levels can restrict the process of nitrification, by

reducing oxygen concentrations available for microbial activity (Williams and Crawford 1983). Perhaps the proportion of ammonifying and nitrifying microbial populations have changed with the changing moisture condition. Zimenko and Mtsnik (1970) noted that field sites with lower water levels had higher concentrations of nitrate and nitrifying bacteria and lower concentrations of ammonia and ammonifying bacteria. In addition, denitrification in wetter sites would likely reduce nitrate-nitrogen as, in the absence of oxygen, nitrate becomes the terminal electron acceptor of choice by the microbial population (cf. Phillips 1990). Although microbial activity may help to explain the nitrogen distribution observed on the site, microbes and microbial processes were not studied here.

The 1992 maps show a clearer relationship of nitrogen concentrations and soil moisture, probably due to the lower vegetation cover in 1992 (data not shown). Although the vegetation cover remained low overall on the harvested site during the study period, randomly placed permanent control plots showed a mean annual vegetation cover increase of 0 to 50% in the wetter areas from 1993 to 1995. Thus, the wetter, vegetated areas had lower  $\text{NH}_4\text{-N}$  values than expected, although overall numbers were not significantly different from previous years.

The changes of decreasing nitrate-nitrogen concentrations in the peat are contrary to the changes found in the well samples. While available  $\text{NO}_3\text{-N}$  concentrations in the peat significantly decreased in latter part of the study and available  $\text{NH}_4\text{-N}$  concentrations remained unchanged in the harvest area peat, the well samples had a significant decrease in  $\text{NH}_4\text{-N}$  in the latter two years of the study, while  $\text{NO}_3\text{-N}$  concentrations had no significant changes. Increasing water levels on the site may have reduced nitrification rates, while increasing vegetation cover in the wetter areas may have consumed some of the excess available  $\text{NH}_4\text{-N}$  in the peat and decreased concentrations of  $\text{NH}_4\text{-N}$  in the water.

The peat chemistry of harvested sites is more variable compared to natural sites (Wind-Mulder et al. 1996). Here, we show that the peat chemistry of this harvested site was also quite variable between years. The restoring site is a dynamic, rapidly changing system, with increasing water levels and vegetation cover affecting peat chemistry. The changes in the harvested site formed complex changing patterns in peat chemistry, with only clearly identified trends in concentrations of available  $\text{NO}_3\text{-N}$  and available  $\text{NH}_4\text{-N}$ . In contrast to the peat chemistry yearly variation, few significant differences were noted between years in the water chemistry analyses. The changing water levels across the field (Wind-Mulder 1998) affected the peat chemistry more significantly than the water chemistry.

Although many significant differences between years were shown with the Kruskal-Wallis one-way analysis of variance and Tukey Type Multiple Comparisons tests, the coefficients of variation showed the relative variability of peat chemistry components was similar among years. In addition, both the harvested and natural areas had the same mean ranking order, with the exception that the harvested site had Na as the element with the highest relative variability, and the natural peatland had Na as the least variable element. In both sites, the nutrients available  $\text{NO}_3\text{-N}$  and available  $\text{NH}_4\text{-N}$  had high ranks of variation.

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