



# Peat, Water and Plant Tissue Chemistry Monitoring: A Seven-Year Case-Study in a Restored Peatland

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Received: 20 February 2009 / Accepted: 22 September 2009 / Published online: 9 December 2009  
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**Abstract** Following ecosystem-scale restoration of a post-harvested bog in Eastern Canada, a long term monitoring program was set up. Peat, water and plant chemistry data were collected during 7 years in a restored peatland, an adjoining post-harvested non-restored peatland, and in a neighboring natural peatland to determine the potential of chemistry data for evaluating of restoration success over time. We used a multivariate Principal Response Curves (PRC) approach to study the temporal evolution of peat, water, and plant tissue chemistry. Nitrogen, iron, and sodium were the most responsive elements to restoration in the peat. Water chemistry was still different between natural and restored sections 7 years after restoration, but the difference was not constant over the growing season. The analyses of plant tissue chemistry provided useful information related to fundamental processes (nutrient retention/leaching, plant nutrition). Among other, it highlighted P deficiencies in the non-restored section, and nutrient replenishment in the restored plant tissues. P levels appear to be a good indicator of restoration success and should be used routinely in monitoring studies. Since the

three plants species tested in this study displayed different responses to restoration, we also recommend targeting key species or functional groups for monitoring.

**Keywords** Ombrotrophic peatland · Peatland chemistry · Principal Response Curves · Restoration monitoring

## Introduction

In the developing field of ecological restoration, the central question of temporal succession of restored ecosystems following intervention arises inevitably. Monitoring the changes occurring in restored sites is therefore a key aspect of restoration, since it allows ecologists to know whether their interventions are successful or not (Erhenfeld 2001; Ormerod 2003). Although the definition of success itself varies according to the targeted goals set in the initial stages of restoration projects, long term sustainability should always remain a major concern.

In North America, a technique specifically adapted to the challenging conditions found on abandoned vacuum-harvested peatlands has been developed, and has been used for many years (Rochefort et al. 2003). This restoration technique aims, in the short term perspective, to recover vegetation and a hydrological regime within a range similar to what is found in pristine mires of a region (Gorham and Rochefort 2003). If plant establishment is a key point in the success of restoration, so are plant survival, persistence, and ecosystem sustainability. Restored peatlands are expected to reach a primary production rate within the natural range, to accumulate decaying organic matter, to sequester carbon, to sustain a functional nutrient cycling, and to resist to invading species (Wheeler and Shaw 1995; Rochefort 2001; Gorham and Rochefort 2003).

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Water and peat chemistry monitoring are likely to show the way these processes are changing in peatlands. For instance, the presence of nutrients in runoff and surface water reflects the intensity of nutrient leaching (Prévoist et al. 1999; Renou et al. 2000). Many studies reported seasonal fluctuations in water chemistry that are generally thought to be closely associated with the water balance of a given site (e.g.: Gerdol 1991; Proctor 1994; Proctor 2006). As peat harvesting and restoration cause profound changes in hydrology (Price et al. 2003), it can also affect the seasonal trends in water chemistry, and the consequences upon nutrient replenishment or plant recovery are largely unknown. Even though the monitoring of chemistry might be very informative, it can represent a large investment of time and money. Hence, it is important to know how valuable such a monitoring is. Many aspects of soil, water and plant chemistry are expected to co-vary spatially and temporally (Vitt and Chee 1990; Vitt et al. 1995) and monitoring could eventually be limited to some key variables. The time frame within which changes in chemistry can be detected in a restored peatland is also an important aspect of monitoring that has yet to be evaluated.

More precisely the focus of this study was to compare the temporal evolution of chemistry in peat, water and plant tissues, between the natural, the post-harvested non-restored and the restored portions of a large peatland during the first 7 years following restoration. In addition, we identified a limited set of chemical variables that could be used as a monitoring tool for the evaluation of restoration success. This last objective should help to adjust monitoring programs by reducing costs without losing information.

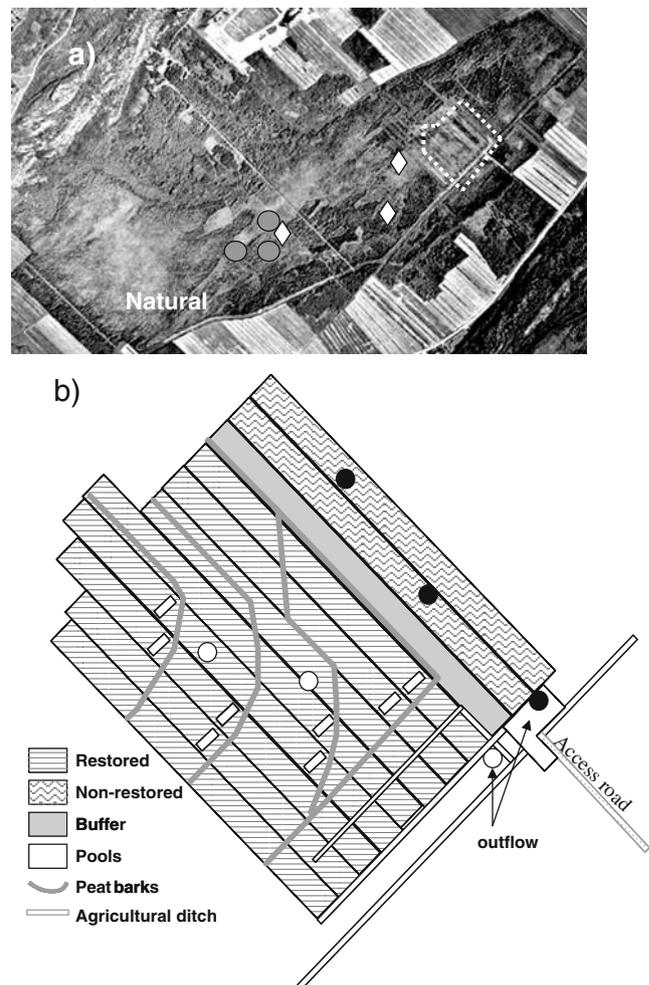
## Materials and Methods

### Study Area

The study took place in the Bois-des-Bel peatland (47° 58' N, 69° 26' W) in Eastern Québec. Between 1972 and 1980, a portion of 11.5 ha of the 189 ha site had been drained and vacuum-harvested and the site was left untouched thereafter. The upper 65 cm of peat were removed by harvesting, and then further eroded by wind and oxidation (Waddington and McNeil 2002). The residual peat column was close to two meters thick, of which the top 80 cm mainly consisted of *Sphagnum* peat (Lavoie et al. 2001). Twenty years after abandonment, mosses such as *Polytrichum strictum* had barely colonized the site and no *Sphagnum* species was present (Isselin-Nondedeu et al. 2007). In fall 1999, an ecosystem-scale restoration was attempted over an area of 8.4 ha of the cutover site. Eight rectangular pools were created during restoration (Mazerolle et al. 2006). A 3.1 ha area remained non-restored, including 2 ha used for

comparison with the restored zone and 1 ha used as a buffer area (not monitored) between the restored and non-restored zones (Fig. 1).

The restoration technique involves the six steps of the *Sphagnum* moss layer transfer technique (Rocheftort et al. 2003, Quinty and Rocheftort 2003). Briefly, the site was flattened and dead woody debris were removed, plant fragments were collected in a nearby donor site, spread over the site (1:15 ratio), protected using straw mulch



**Fig. 1** a Aerial photograph of the Bois-des-Bel peatland. The natural section is indicated by the white line and the restored and non-restored sections are indicated by the black line. b Schematic representation of the restored and non-restored sections of the peatland. Peat samples were only collected in the restored and the non-restored sections, in different locations randomly selected each year (11 in the restored section and four in the non-restored section). Water samples were collected in three water wells in the natural peatland (●), in the eight restored pools (white rectangles), the two water wells, and the outflow channel of the restored section (○) and the non-restored section (●). Plant tissues were collected in different locations randomly selected each year in the restored (15) and non-restored (5) sections, but they were always taken at the same three locations in the natural section (◇)

(3,000 kg ha<sup>-1</sup>) and lastly the drainage ditches were blocked. The following spring phosphorus fertilization was applied where granular phosphate rock (0-13-0; McInnes Natural Fertilizers) was spread at the rate of 15 g m<sup>-2</sup>.

A natural ombrotrophic peatland surrounds the non-restored and restored areas. It is semi-forested and the vegetation mosaic includes *Picea mariana* and *Larix laricina* as dominant tree species, a *Sphagnum* carpet (*Sphagnum fuscum*, *S. magellanicum*, *S. rubellum*, and *S. capillifolium*), and dense ericaceous shrubs (*Kalmia angustifolia*, *Ledum groenlandicum*, *Chamaedaphne calyculata*, and *Vaccinium angustifolium*) (Lachance and Lavoie 2004).

### Sampling and Analyses

Table 1 provides a detailed description of the sampling design and the chemical analyses performed on the different types of samples, with references.

**Peat** Peat samples were collected in the restored and the non-restored sites only, where sampling points were randomly selected each year. Other studies (Wind-Mulder et al. 1996; Andersen et al. 2006) already demonstrated that surface peat in natural sites was significantly different from either restored or cutover peat, and as peat formation is a slow process, the natural surface peat was not sampled. Peat

in the non-restored and restored section was collected in early October, as a thin layer of approximately 2 cm to 3 cm, directly under living vegetation when vegetation was present. Samples were placed in plastic bags, brought back to the laboratory and homogenized. Sub-samples of approximately 100 g were dried at 40°C and sent for analyses. Exchangeable cations (K, Ca, Na, Mg, Fe, and Mn) were extracted following Amacher et al. (1990) and subsequently analyzed by ICP (Perkin-Elmer P40). In addition, we determined total P, K, Ca, Fe, Mg, and organic matter in the peat ash after loss on ignition, using ICP spectroscopy (Optima 4300 DV from Perkin Elmer).

**Water** Water was collected in polyethylene bottles in the three sections (natural, restored, and non-restored). The bottles were always conditioned with sampled water two times before they were filled with water from water wells, outflow channels, or the created pools (Fig. 1). Bottles were then frozen until they were analysed. We measured pH and Electrical Conductivity (EC) in the laboratory before freezing the samples between 2000 and 2004. After 2004, a portable pH meter allowed measurements of pH and EC directly in the field. All EC measurements were corrected for pH according to Sjörs (1950). Na, K, Ca, Mg, P, Mn, and Fe content was determined with by ICP (Perkin-Elmer P40). Chlorides, sulfates, nitrates, and ammonium were analyzed by FIA, as listed in Table 1.

**Table 1** Sampling design and chemical analyses for peat, water, and plant tissues (*Chamaedaphne calyculata*, *Sphagnum* spp., *Polytrichum strictum*) collected in the Bois-des-Bel experimental research station.

EC = Electrical Conductivity, Exch. = exchangeable, Tot. = total, OM = Organic Matter, FIA = Flow Injection Analysis, ICP = Inductively Coupled Plasma spectroscopy (Optima 4300 DV from Perkin Elmer)

Material Sampling Years Sample type	Peat Once a year (Oct.) 2000–2005 Surface peat	Water			Plant tissues		
		Monthly (May–Oct) 2000–2006			Once a year (Sept.) 2000–2006		
		Wells	Outflow	Pools	<i>C. calyculata</i>	<i>Sphagnum</i> spp	<i>P.strictum</i>
n samples							
Natural	0	3	0	0	3	3	3
Restored	11	2	1	8	17	17	17
Non-restored	4	2	1	0	5 <sup>f</sup>	0	5
Total	15	7	2	8	25	20	25
Analyses (method)	pH, EC P <sub>sol</sub> <sup>a</sup> (FIA), NO <sub>3</sub> , NH <sub>4</sub> <sup>b</sup> , Cl <sup>c</sup> Exch. K, Ca, Na, Mg, Fe, Mn <sup>d</sup> (ICP) Tot. P, K, Ca, Mg, Fe, OM (ICP)	pH, corrected EC <sup>e</sup> Cl, SO <sub>4</sub> , NO <sub>3</sub> , NH <sub>4</sub> (FIA) K, Ca, Na, Mg, Fe, Mn (ICP)			N, P, K, Ca, Na, Mg, Fe, Mn		

<sup>a</sup>Bray and Kurtz 1945

<sup>b</sup>Keeney and Nelson 1982

<sup>c</sup>Selmer-Olsen and Oein 1973

<sup>d</sup>Amacher et al. 1990

<sup>e</sup>Sjörs 1950

<sup>f</sup>When the species was present

**Plant Tissues** Plant tissues were randomly sampled once a year at the end of the growing season but before leaf senescence, in early September. In the natural zone, sampling locations were positioned in areas with different tree densities, going from an open bog area to a treed bog area. In all three treatment sites, when present, three species were sampled: *Chamaedaphne calyculata* (leaves only), *Polytrichum strictum* (green parts), and *Sphagnum* from the *Acutifolia* section (*S. rubellum* or *S. fuscum*). *Sphagnum* was absent in the non-restored site. Approximately 100 g of plant material was collected with metal grips and put in plastic bags. Vegetation tissues were cleaned, dried (40°C), and analyzed by Flow Injection Analysis for N, P, Ca, Mg, Fe, Mn, K, and Na content.

### Statistical Analyses

We used a partial redundancy analysis (RDA) (Ter Braak 1988; Lepš and Šmilauer 2003) followed by Monte Carlo permutations to assess if the chemical composition of the water chemistry of the samples taken in the eight pools of the restored site was significantly different from that of the samples taken in water wells and the outflow channel. Since the difference was significant ( $df=1$ ,  $F=20.03$ ,  $p=0.001$ ), pool and non-pool samples were treated separately. Similarly, we performed a partial RDA for tissue samples, using years and sites as covariables, to test if the three monitored species had a different chemical tissue composition. As it was the case ( $df=2$ ,  $F=55.16$ ,  $p=0.001$ ), the temporal variation in tissue chemistry was assessed for each plant species separately.

To compare the evolution of water, peat and tissue chemistry of the restored, the non-restored, and the natural sections over time, we used Principal Response Curves (PRC) using CANOCO 4.5 (Van den Brink and Ter Braak 1998, 1999). PRC is a particular case of redundancy analysis (RDA) for which the response variables for a given treatment at a given time are expressed as deviations from a reference set *a priori*, instead of absolute values (van den Brink and ter Braak 1998; Lepš and Šmilauer 2003). Therefore, it displays the overall relative difference between a treatment and the reference over time: graphically, it is represented as a response curve. This difference can be statistically tested using Monte Carlo permutation tests ( $n=999$ ).

In our particular case, peat analyses only included the restored and the non-restored sections, therefore we chose to measure the effect of restoration by comparing it to the non-restored section, which was the “reference” in this case. For water and tissues analyses, samples from the natural section were collected so we used these natural samples as the reference to which the restored and non-restored samples were compared. Moreover, for peat and tissue chemistry, the time

unit was a year, whereas for water, we separated the samples into spring, summer, and fall of each monitoring year to account for seasonal variability (Proctor 2006). In addition to the direction and amplitude of the changes over time, the PRCs provide information on the variables driving these changes. In fact, as it is based upon RDA, a canonical coefficient is calculated for each of the response variables. These coefficients are presented along a vertical axis on the right of the response curves on the graphs. Response variables with high positive coefficients follow the overall temporal trend of a curve relatively to the reference, while high negative values indicate that the response variables are opposite to the trend. This can be verified with graphs presenting the temporal evolution of the individual response variables.

## Results

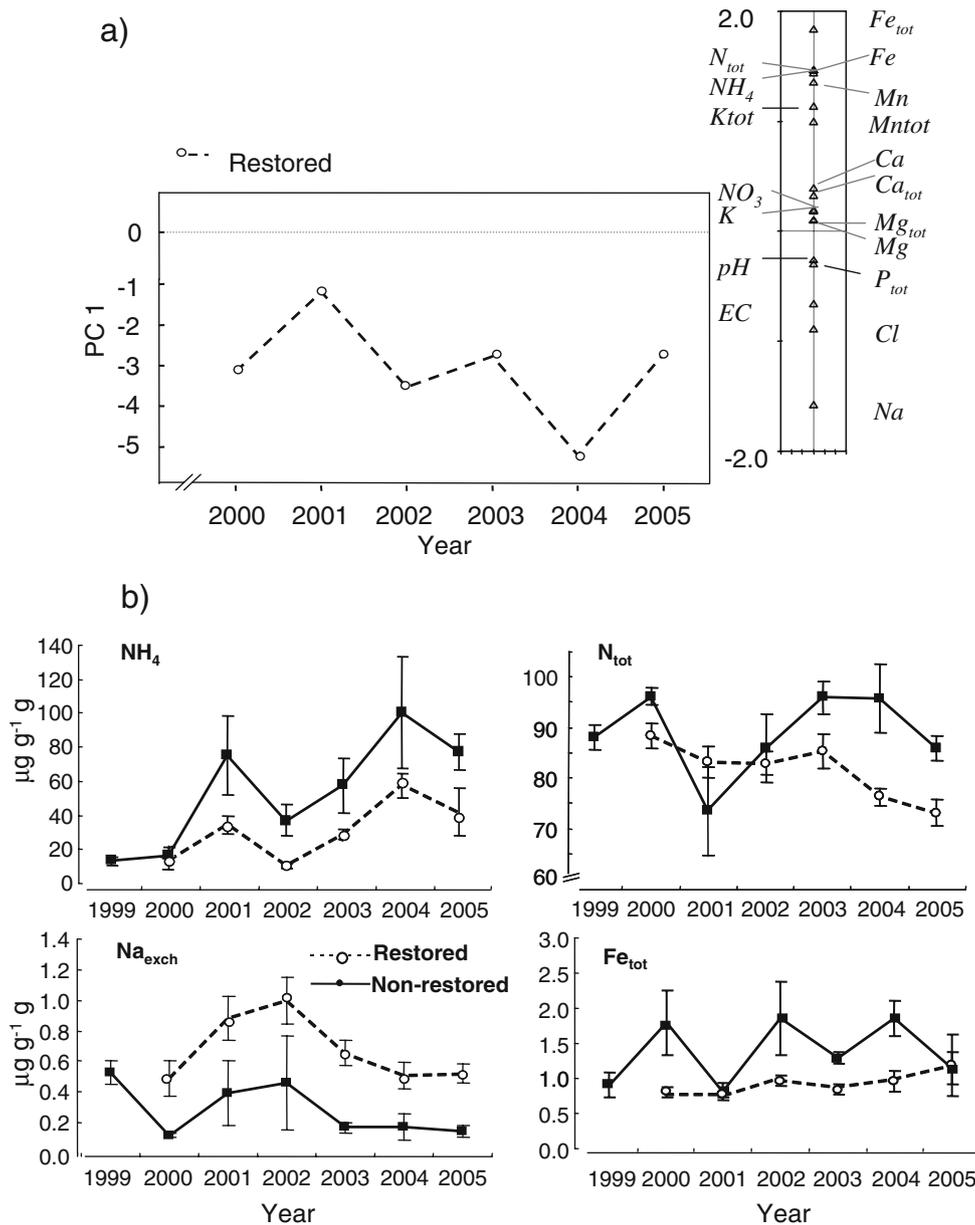
### Peat Chemistry

The difference in the chemical composition of the peat between the restored and the non-restored section changed significantly with time ( $df=10$ ,  $F=7.2$ ,  $p=0.009$ ), although the effect of time represented only 6.4% of the overall variation in the data. Fe (total and soluble) and N ( $\text{NH}_4$  and  $\text{N}_{\text{tot}}$ ) were generally more concentrated in the non-restored peat, but Na was more concentrated in the restored peat (Fig. 2).

### Water Chemistry

The chemical composition of water varied significantly for the different treatments over time ( $df=60$ ,  $F=149.0$ ,  $p=0.001$ ). The difference between the natural samples (reference baseline) and the other samples (the three curves) was greatest in summer, which corresponds to the peaks in the graph (Fig. 3). The effect of time represented 20% of the variability in the water chemistry of the various types of samples. According to the distance between the curves and the reference zero-line, the non-restored samples were the most distinct from the natural ones, whereas the samples collected in the pools of the restored section were the most similar. Along the vertical axis, Ca, EC, Mg, Cl, Na, and pH had high positive values, indicating values in non-restored samples and in restored samples were higher than in natural samples, especially in summer. On the contrary, the values of P,  $\text{SO}_4$ ,  $\text{NH}_4$ , and Mn along the vertical axis were close to zero, indicating that they did not follow the patterns of variation represented by response curves.

The graphical comparison of the separate elements (Fig. 4) coincides with the result of the PRC. In most cases, the natural samples were the least variable and the

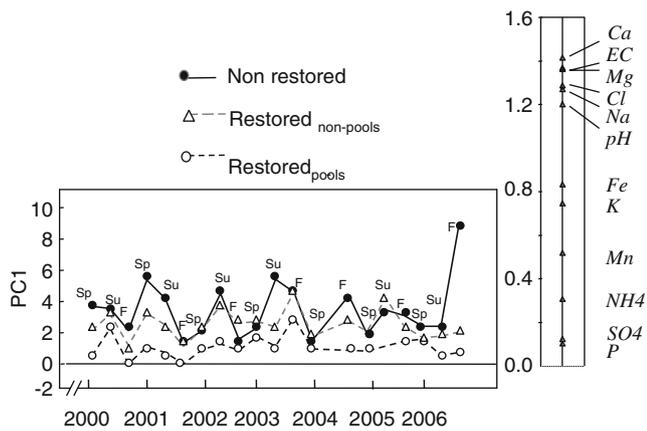


**Fig. 2 a** Principal Response Curves for peat chemistry. On the left side of the figure, the curves represent the overall difference in the chemical composition of peat from the restored section over time (expressed as a canonical coefficient on the first principal component axis, PC1), in comparison with the non-restored peat, represented by the zero line. On the right side of the figure, the vertical axis displays the canonical coefficients for all the elements. For a given element, a high positive value indicates a trend similar to that of the curve, a high

negative value indicates a trend opposite to that of the curve, and a value close to zero suggests a trend unrelated to that of the curve. **b** Concentrations of  $NH_4$ , exchangeable  $Na$ , total  $N$ , and total  $Fe$  (means and standard errors),  $pH$  and electrical conductivity ( $EC$ ) in restored and non-restored peat over time. There are no restored values in 1999 because the sampling was done prior to restoration, therefore only in non-restored peat

non-restored samples were the most variable. In the non-restored and restored samples,  $pH$ ,  $Ca$ ,  $Mg$ ,  $Na$ ,  $Cl$ , and  $Mn$ , exhibited peaks in summer months. This was not the case in the natural samples, where the concentration of elements was more stable throughout the seasons. Within the restored section, the variation for these elements was less pronounced in the samples taken in pools than in the samples

collected in wells and outflow channels. For  $NH_4$  and  $SO_4$ , the typical summer peaks were present on both graphs between 2001 and 2006, but  $SO_4$  concentrations increased with time, while  $NH_4$  concentrations showed the opposite trend. The pattern for  $P$  was slightly different: the concentrations were very high in the first year, especially for non-restored and restored<sub>non-pools</sub> samples. Phosphorus



**Fig. 3** Principal Response Curves for water chemistry. On the left side of the figure, the curves represent the overall difference in the chemical composition of water from the restored section (pools and non-pools samples) and the non-restored section over time (expressed as a canonical coefficient on the first principal component axis, PC1), in comparison with the natural water, represented by the zero line. On the right side of the figure, the vertical axis displays the canonical coefficients for all the elements interpreted as in Fig. 2. Sp=spring, Su=Summer, F=Fall

concentrations then decreased over time and increased again in the last years, but remained highly variable between years. There were no clear seasonal patterns for K.

#### Plant Chemistry and Nutrient Content

Even though the foliar concentrations of the various nutrients were different in the three plants, the principal response curves displayed some similarities (Fig. 5a, b and c). For instance, in the first year following restoration, the restored curves were all very far from the natural samples represented by the zero line, but became closer as time passed. Moreover, for all three plants, the effect of time over the variation in chemical composition of the tissues represented a similar proportion of the variability: 13.6% (df=12,  $F=31.75$ ,  $p=0.001$ ) for *Chamaedaphne calyculata*, 13.4% (df=12,  $F=28.34$ ;  $p=0.001$ ) for *Polytrichum strictum*, and 11.2% (df=12,  $F=25.64$ ,  $p=0.001$ ) for *Sphagnum* spp. Finally, in the three graphs, N:P ratios had a high positive value along the vertical axis while P had a highly negative one. This means that in comparison with the natural reference, N:P ratios were higher in the non-restored section while P concentration was higher in the restored section. The graphs representing N:P ratios of the three species taken in the natural, restored and non-restored sections of the peatland support this result (Fig. 6). They ranged between  $9.5 \pm 2.9$  and  $25.6 \pm 3.3$  for *C. calyculata*,  $8.5 \pm 0.9$  and  $20.5 \pm 2.9$  for *P. strictum*, and  $5.5 \pm 1.2$  and  $25.3 \pm 6.67$  for *Sphagnum* spp.

There were also fundamental differences in the temporal evolution of tissue chemistry among the three plant species. For instance, in the tissues of *C. calyculata* and *Sphagnum*

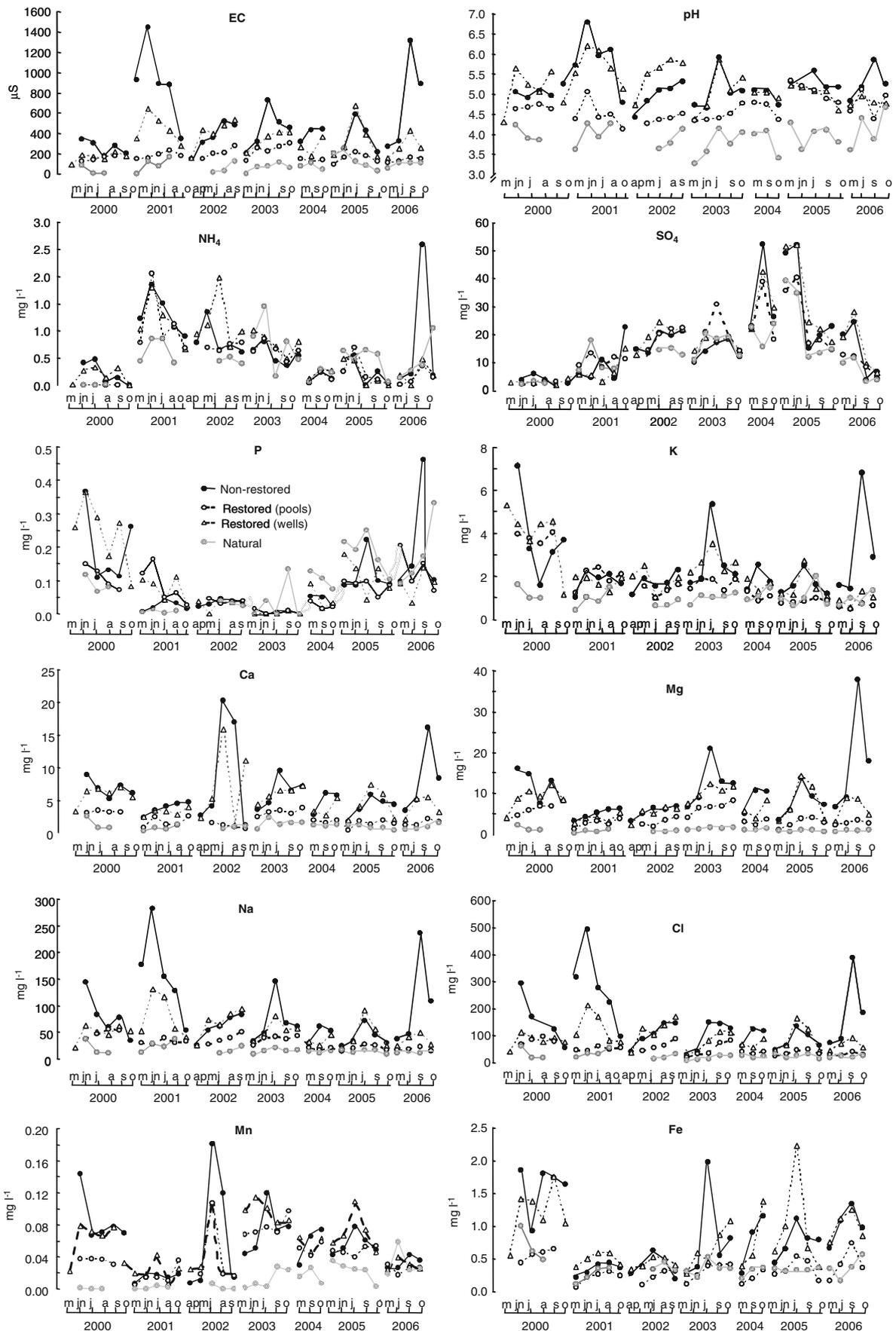
mosses collected in the restored section (Fig. 5a), the chemical composition evolved over time to approach natural values 5 years after restoration, when the curve reached the reference line. In *P. strictum*, the chemical composition of the restored tissues was already close to the natural reference line after only 2 years. In *C. calyculata*, the non-restored curve remained very stable over time and constantly above the natural reference line, whereas in *P. strictum*, it gradually approached the natural reference as time passed. Finally, the elements with high negative values along the vertical axis, thus displaying a temporal variability opposite to the trend in the curves, were not the same for the three plant species, except for P. These elements were Mg and Mn in *C. calyculata*, K in *P. strictum*, and Mg, N, Ca, and Na in *Sphagnum* spp.

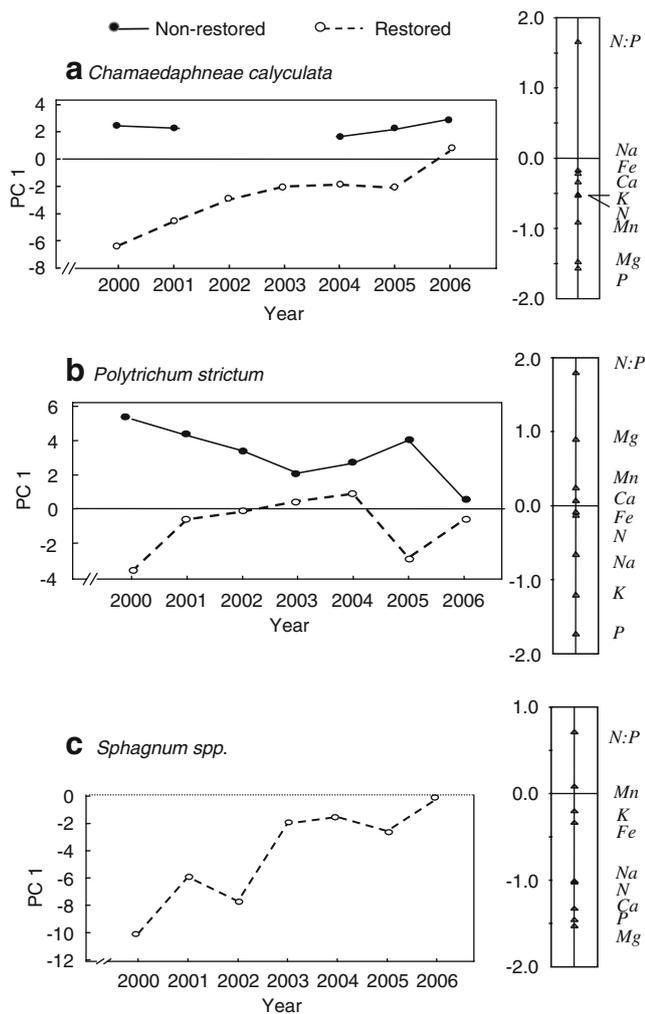
## Discussion

### Changes in Peat Chemistry Over Time

Following harvesting activities, the surface layer of peat consists of highly decomposed peat, where the reduced microbial biological activity (Andersen et al. 2006) limits nutrient replenishment (Wind-Mulder et al. 1996) and where the physico-chemical properties are altered (Van Duren et al. 1997, Price et al. 2003). In the restored section, although an average of  $430 \text{ g m}^{-2}$  of *Sphagnum* biomass had already accumulated after seven years and keeps accumulating (L. Rochefort, unpublished data), the peat soil underneath the vegetation layer had not yet started to form. The relative decrease of  $\text{NH}_4$  observed in peat of the restored section could be explained by biological uptake by microbes and plants, and by the fact that the nitrogen cycle is known to be stopped at the ammonification level in cutover peat (Croft et al. 2001). In non-restored peat the variability in water levels (Table 2) impact oxidation states and mobility of iron, and might be responsible for the irregular pattern displayed in Fig. 2. The higher concentrations of Na in the restored section were probably a consequence of increase interception of the precipitations in comparison with the bare surface of the non-restored section (Schauffler et al. 1996), where Na is more likely to be leached. More changes, particularly in the nutrient content of the peat, are likely to occur when new peat starts to form and accumulate.

**Fig. 4** Water chemistry (means and standard errors) over time for the seven years of monitoring. Months of sampling change from year to year, and they are identified on the horizontal axis as following: April (ap) May (m), June (jn), July (j), August (a), September (s), and October (o). Non-pool restored samples and non-restored samples include data from water wells and outflow channels





**Fig. 5** Principal Response Curves for tissue chemistry for **a** *Chamaedaphneae calyculata*, **b** *Polytrichum strictum*, and **c** *Sphagnum* spp. On the left side of the figures, the curves represent the overall difference in the chemical composition of tissues from the restored section and/or the non-restored section over time (expressed as a canonical coefficient on the first principal component axis, PC1), in comparison with the natural tissues, represented by the zero line. On the right side of the figure, the vertical axis displays the canonical coefficients for all the elements, interpreted as in Fig. 2

### Seasonal Variation in Water Chemistry

The concentrations of elements in water from the natural peatland were within the range of values found in the literature for bogs in North America (Zoltai and Vitt 1995). According to many authors, depths and environmental conditions influence the composition of water in peatlands (Vitt and Chee 1990; Vitt et al. 1995). Thus, the difference between pool and non-pool samples within the restored site was expected.

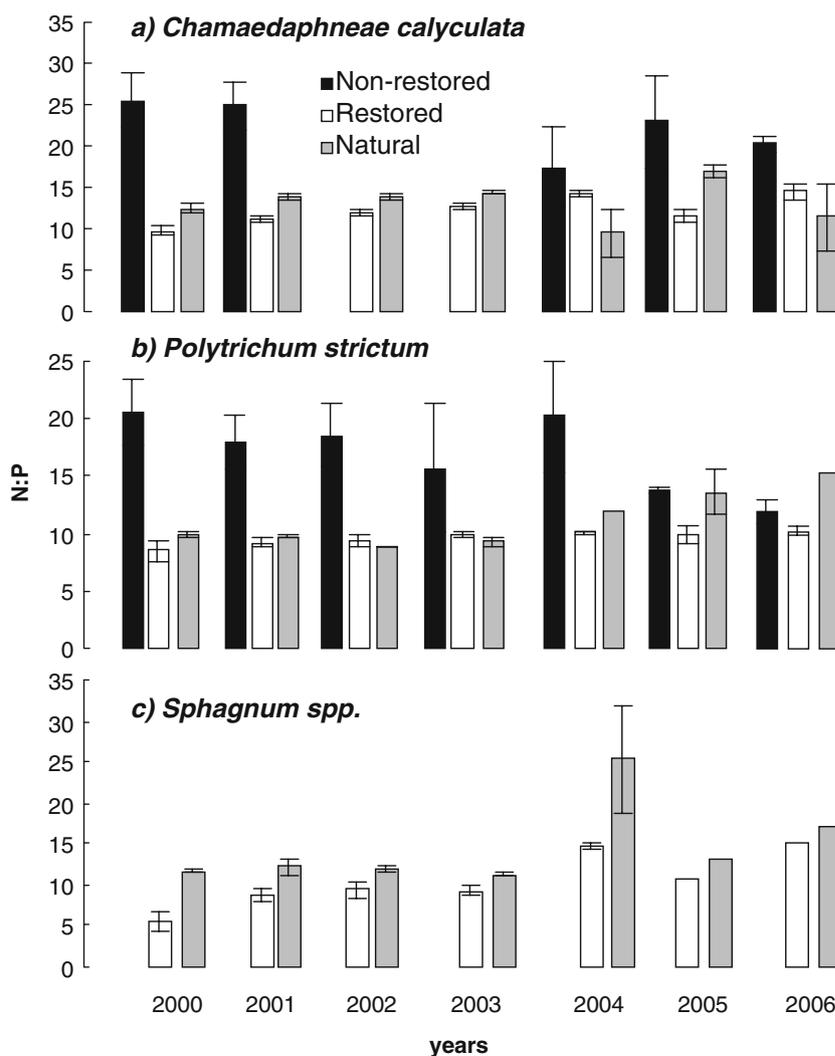
The largest difference in chemistry composition between the natural, the restored and the non-restored samples was found during mid-summer (Fig. 3). Seasonal variation

within a given peatland is typically related to changes in evapotranspiration and oxido-reduction processes associated with the water table position (Proctor 1994). In the non-restored sites higher rates of evaporation (Shantz and Price 2006) and variable hydrology might have contributed to increase variation in water chemistry. Proctor (1994, 2006) observed that more extreme variations in seasonal patterns occurred in disturbed sites, and that the absence of actively growing *Sphagnum* reduced the capacity of the peatland to buffer the rainfall inputs, which concurs with our results.

We expected that following restoration, the amplitude of variation in water chemistry would decrease as the diplothemlic structure would begin to re-establish and the hydrology would stabilize. Shantz and Price (2006) observed reduced evapotranspiration in the Bois-des-Bel peatland following restoration, but the range of variation of the water table remained large (Table 2). This explains why despite good *Sphagnum* cover, the natural and the restored water chemistry were still different after many years post-restoration, especially during dry periods, when water table dropped enough to reach the highly decomposed peat. Indeed, with a large decline in the water table during the hottest months of the growing season, minerals such as Ca, Mg, Na, and Cl, but also in  $\text{NH}_4$  concentrate in the water, which in turn increase pH and EC values (Prévost et al. 1999; Adamson et al. 2001). The highest peaks for these elements occurred in the driest period, 2001 and 2002 (Figs. 4, 7). Fe is also sensitive to redox conditions in the peat, as it is not stable in any ionic form, varying seasonally in accordance with the dissolved organic matter with which it forms complexes (Urban et al. 1990, Proctor 2006). Waddington et al. (2008) reported that DOC pore water concentration and export, although varying seasonally, were higher in cutover and newly restored peatland, and suggested that the DOC export from restored peatlands will remain high until a new surface moss layer develops that can constrain water table fluctuations. Our results support this contention. In the natural section, the water table was stable throughout the years and was always in contact with living *Sphagnum*, which caused the seasonal patterns to be less pronounced. From a functional point of view, it means that it takes more than good *Sphagnum* cover to stabilize water chemistry in restored peatlands; it can be expected to be more stable when the water regime is restored within the newly formed acrotelm.

P content was very high in restored and non-restored samples the year of restoration. It is possible that some of the P applied during fertilization leached into the water. Well humified peat has a low capacity to retain P, and in the first growing season after restoration, plants had not grown enough to be able to uptake all the P applied to the reintroduced plant fragments. Similar P losses in outflow water are also observed in young plantations established on

**Fig. 6** N:P ratios (means and standard errors) in **a** *Chamaedaphneae calyculata*, **b** *Polytrichum strictum*, and **c** *Sphagnum* spp. tissues

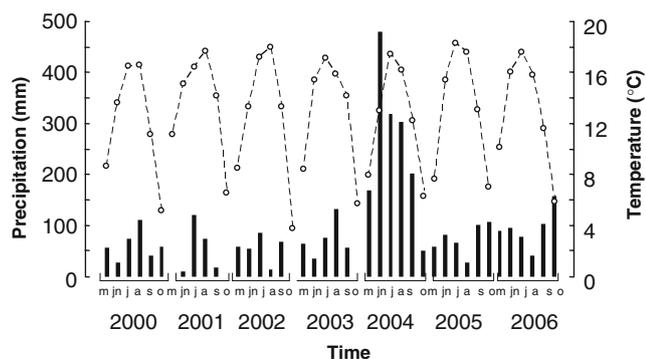


**Table 2** Water table position (mean), maximum value (max), and minimum value (min) for the monitoring years (2000–2006). Hydrological data come from Shantz and Price (2006) and from measures of

water table depths taken in water wells when sampling water for chemistry. Negative values indicate water table levels above soil surface. No data were available for the Natural section before 2004

Year	Non-restored			Restored			Natural		
	WT cm (n)	max	min	WT cm (n)	max	min	WT cm (n)	max	Min
2000 <sup>a</sup>	45.5 (41)	33	67	30.0(41)	13	49	NA		
2001 <sup>a</sup>	40.4 (96)	25	54	30.4 (95)	4	65	NA		
2002 <sup>a</sup>	44.3 (72)	30	60	37.2 (74)	10	70	NA		
2003	55.1 (12)	36	68	37.0 (17)	-15	65	NA		
2004	33.9 (11)	24	42	9.0 (17)	-4	23	33.9 (15)	9	48
2005	32 (3)	28	34	8.0 (3)	4	10	24.5 (3)	18	35
2006	41.7 (12)	30	50	14.0 (48)	5	20	37.5 (12)	30	45
Overall	42 (247)	24	68	22.0 (285)	-17	70	30.0 (30)	9	48

<sup>a</sup> Shantz and Price 2006



**Fig. 7** Monthly averages (water sampling period only) for Precipitations (mm) and Temperature (°C) from the Rivière-du-Loup meteorological station. Precipitation data were not available for May and October 2001 and October 2002. (Data from Environment Canada)

cutaway peatlands (Malcolm and Cuttle 1983; Renou et al. 2000). The concentrations decreased sharply in the second spring post-restoration, to reach values below the natural ones in the third year. Afterwards, as described by Proctor (2006), P definitely showed irregular variation and no obvious seasonal pattern.

Sulphate peaked late in the season rather than in the summer, and even though the peaks were more pronounced in the non-restored section of the peatland, they were synchronous in all four types of sample. This corresponds to delayed acidification of stream flow, a phenomenon described in other wetlands (Bayley et al. 1986), when  $\text{SO}_4$  formed during the driest periods of the season leaches after precipitation resumes water flow in the peatland. The highest peaks corresponded to repeated, major precipitation events that occurred in August and September of 2004 and 2005 (Fig. 7, Environment Canada).

#### Plant Chemistry and Nutrient Status

In general, concentrations of the elements in plant tissues in natural and restored sections were within the expected natural ranges for each species (Wojtun 1994, Bedford et al. 1999), while elements in the non-restored section are found either in lower (nutrients) or higher (cations) concentrations. Plants found in the non-restored section suffered from P limitation. According to Jonasson and Shaver (1999), plant characteristics (nutrient resorption, tissue type, and longevity) mirror the functioning of the system rather than play a major role in regulating overall element cycling. High N:P ratios in plants meant that nutrient cycling was hampered in the non-restored site. In natural peatland ecosystems, P is limited to the superior layers where it is recycled very efficiently by microbes. In contrast, a certain proportion of N stays in the decomposing vegetation even deeper in the profile (Damman 1978). Horticultural

exploitation consequently removes most of the accessible P pool, thus generating P-limitation. P fertilizer applied during restoration clearly counteracts limitation, as visible in the shape of the three restored curves in the PRC graphs. As a consequence of high P content of plants in the years following restoration, tissues from the restored section were far from the natural or the non-restored state. This means that the three study plant species were able to actively uptake part of the fertilizer. The uptake by plants, the low sorption of P in the peat, and the leaching in the water gradually reduced P availability and this was reflected in restored plant tissues where nutrient content also decreased with time. In the case of *C. calyculata*, the similar weight of Mg, Mn, and P along the vertical axis, indicative of a similar temporal evolution, could be related to an increase uptake of Mn and Mg following P fertilization (Shaver and Chapin III 1980).

*Polytrichum strictum* is the species for which chemical composition of the tissues most rapidly became similar to the natural reference. In the first year, N:P ratios already decreased in comparison to the non-restored area, to reach values close to those of the natural section. This reflects the ability of this pioneer species to stabilize the peat surface (Groeneveld and Rochefort 2005) and to benefit rapidly from improved microclimate and nutrient availability induced by fertilization (Sottocornola et al. 2007). Although the general goal is to restore a *Sphagnum* dominated peatland and not a *Polytrichum* carpet, one should note that where conditions are favourable for *Sphagnum*, competitive interaction can cause a decline in *P. strictum* cover (Li and Vitt 1995). In fact, in natural conditions, *P. strictum* is often found interspersed within *Sphagnum* carpets, but is relegated to disturbed and dryer spots; this was visible in the restored site (L. Rochefort, unpublished data).

Even in the non-restored site, *P. strictum* is slowly recolonizing local patches, along with cotton grass, shrubs, and black spruce. As these stabilized spots become denser, nutrient retention may improve. In the PRC curves, the non-restored curve came closer to natural values as time passed. The absence of this trend on the *C. calyculata* non-restored PRC curve, as well as the small difference between the non-restored curve and the reference line, could be related to the fact that like many ericaceous shrubs, *C. calyculata* benefits from ericoid mycorrhizal associations. Although they improve its nutrition (Read 1996), this relationship is probably still lagging behind given the drier nature of the non-restored peat.

For *Sphagnum*, N, Na, and Ca had a high negative value, which means that they were initially more concentrated in restored tissues and then decreased as the restored curve approached the reference line. P fertilization probably enhanced the capacity of *Sphagnum* to assimilate N (Limpen et al. 2004). Additionally, elevated concentrations

of cations in the peat or in the water lead to high concentration in *Sphagnum* tissues, as the plant uptake them directly on the cell walls. As moss grows, it becomes more and more isolated from the influence of the highly decomposed peat, and approaches natural conditions in terms of tissue chemistry.

### Monitoring Recommendations

Our study highlights the benefits of using a reference site in monitoring programs—either natural, non-restored, or both. Without reference sites, it would have been impossible to interpret the concentrations and the amplitude of variations in the restored site. Reference sites allowed us to use PRC analyses, which have known value in synthesizing information and comparing temporal series of multivariate data sets in different ecosystems (Pakeman 2004; Vandvik et al. 2005; Maccherini et al. 2007). Our study also emphasized that water chemistry from restored and non-restored sections had higher amplitudes of variation than natural conditions. Temporally this deviation decreased in open pools more rapidly than in water wells or outflow channels. The strong seasonality indicates that monitoring programs should favour multiple samplings throughout the growing season. We observed that P deficiency was rapidly offset by the fertilization, which also increased N uptake by *Sphagnum*. Further studies should therefore investigate when the best moment to apply fertilizer and minimize losses is. We showed that different plant species had different responses to restoration and fertilization, highlighting the importance of targeting key species or group of species in monitoring programs. Foliar analysis was a valuable approach that provided insight on plant nutrient status and nutritional needs and should be routinely implemented in long-term monitoring programs evaluating the success of restoration in bogs.

**Acknowledgements** We thank Suzanne Campeau, Claire Boismenu, Stéphanie Boudreau and Rémy Pouliot for assistance in the field, Alain Brousseau for laboratory chemical analyses, and anonymous reviewers for helpful comments. This project was funded by NSERC as part of the Industrial Research Chair in Peatland management, and with a NSERC scholarship to RA.

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