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Peat bog restoration: Effect of phosphorus on plant re-establishment

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ABSTRACT

Vegetation responses to phosphorus (P) fertilization were assessed on post-vacuum extracted peatlands under ecological restoration. The study aimed to evaluate the importance of P fertilization in promoting plant re-establishment and to delineate fertilization practices. A total of 11 P treatments were tested across three different peatlands under restoration. After three growing seasons, it was found that bryophytes (excluding sphagna) were the main strata benefiting from P fertilization. Mosses like *Polytrichum strictum* showed positive responses to P addition, provided that the rewetting was optimal and that these bryophytes were present in the donor site. The optimal dose of phosphate rock (PR) to encourage plant re-establishment appears to be in the range of 15–25 g PR m^{-2}. Fertilization timing should be investigated further as applications would probably have more impact during periods of high nutrient uptake by target plants in establishment phase than before or after other restoration steps. Furthermore, splitting the fertilization in two applications slightly improves the re-establishment of *P. strictum*. Fertilization in peatland restoration remains a site-specific decision, considering intrinsic site properties and the effectiveness of restoration measures.

1. Introduction

Peatland restoration aims to reinitiate self-regulatory mechanisms that will lead back to functional peat accumulating ecosystems. As this is a long process, short-term objectives are needed to evaluate the success of peatland restoration in the first years. These objectives are: (1) the re-establishment of a typical peatland flora, including *Sphagnum* mosses, a key species for the accumulation of peat, and (2) the restoration of the hydrological conditions suitable for *Sphagnum* growth, by blocking ditches and improving microclimatic conditions (Sliva and Pfadenhauer, 1999; Rochefort, 2000; Grootjans and van Diggelin, 2002; Lamers et al., 2002; Rochefort et al., 2003; Vasander et al., 2003; Blankenburg and Tonnis, 2004). In North America, one approach to peatland restoration is based on direct *Sphagnum* reintroduction on a thick residual peat layer, usually left behind after peat extraction (Rochefort, 2000). This approach involves collecting the top 5–10 cm of bog vegetation (Campeau and Rochefort, 1996) from a natural peatland (ideally from sectors that will be used for further peat extraction) and spreading it on bare peat surfaces. The reintroduced plant material is typically composed of a mix of sphagna, other bryophytes, vascular plants and seed bank (Rochefort and Campeau, 2002).

In order to promote and speed up vegetation re-establishment, a slight P fertilization has been suggested in

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peatland restoration (Sliva and Pfadenhauer, 1999; Quinty and Rochefort, 2003). Phosphorus has been shown to accelerate the recolonization process of post-extracted peatlands by true mosses and vascular plants (O'Toole and Synnott, 1971; Salonen and Laaksonen, 1994; Ferland and Rochefort, 1997). Quick plant establishment is believed to play an important role in reducing peat instability caused by wind erosion and frost heaving, which are among the biggest barriers to peatland restoration success (Quinty and Rochefort, 2000; Campbell et al., 2002; Groeneveld and Rochefort, 2005). Besides their role in stabilizing peat, rapidly established plants can also act as nursing plants, creating suitable microclimatic conditions for *Sphagnum* re-establishment (Grosvernier et al., 1995; Ferland and Rochefort, 1997; Boudreau and Rochefort, 1999; Tuittila et al., 2000). For example, *P. strictum* has been identified as an important nursing plant for *Sphagnum* re-establishment (Groeneveld et al., 2007) and its spore germination is improved with P addition in laboratory (I. Jarry and L. Rochefort, Université Laval, unpublished data). Phosphorus fertilization could thus be a key factor contributing to the restoration success.

Lacking roots or rhizoids and sensitive to surface instability, sphagna are not good pioneer plants, although they are essential to rebuild a functional peatland ecosystem. Phosphorus was observed to have some direct positive influence on *Sphagnum* spore germination, propagule development and growth in both laboratory (Boatman and Lark, 1971; Baker and Boatman, 1990; Li and Glime, 1990; Li and Vitt, 1994; Sundberg, 2000) and field experiments (Aerts et al., 1992; Money, 1995; Rochefort et al., 1995; Limpens et al., 2003, 2004). Conversely, P can also have detrimental effects on the growth or productivity of some *Sphagnum* species (Clymo, 1987; Li et al., 1993; Thormann and Bayley, 1997). Although confirming the positive influence of P on *Sphagnum* re-establishment, P fertilization tests conducted on post-extracted peatlands in Eastern Canada (Ferland and Rochefort, 1997; L. Rochefort, Université Laval, unpublished data), could not disentangle the direct benefit of the fertilization from the indirect benefit by increased companion species cover.

Organic soils usually have large amounts of P and nitrogen (N) tied up in organic forms, but most of it is unavailable to plants and can limit their growth (Mitsch and Gosselink, 2000). Available P occurs in very low concentrations in pristine peatlands, often in limiting amounts for plant growth (Tamm, 1954; Small, 1972; Damman, 1978; Vitt et al., 1995; Bridgham et al., 1996; Verhoeven et al., 1996; Bedford et al., 1999), and it occurs in even lower concentrations in post-extracted peatlands (Wind-Mulder and Vitt, 2000; Andersen et al., 2006). Potassium (K) is also found in smaller amounts in post-extracted than in pristine peatlands (Wind-Mulder and Vitt, 2000; Andersen et al., 2006). However, K fertilization is not believed to be necessary because of the high K concentration leached from the decaying straw used in restoration (Boudreau, 1999; Quinty and Rochefort, 2003). Moreover, in a fertilization peatland restoration experiment in Germany (Sliva and Pfadenhauer, 1999), K fertilization was not found to have enhanced plant re-establishment. Nitrogen (N), often limiting in pristine peatlands (Bridgham et al., 1996), is enriched in post-extracted sites in its available forms (Wind-Mulder and Vitt, 2000) due to drainage, peat subsidence and peat oxidation (Piispanen and Lähdesmäki, 1983; Wells and Williams, 1996; Wind-Mulder et al., 1996; Andersen et al., 2006); thus neither N addition is considered necessary.

Phosphorus fertilization appears to be an important step to consider in peatland restoration, but many aspects of the fertilization procedure remain unknown. This study investigates the optimal amount of P fertilizer needed for rapid plant re-establishment in various conditions and explores ways of efficient applications. In this regard, specific objectives are: (1) to assess the minimum but sufficient amount of phosphate rock to apply on post-extracted peat fields; (2) to evaluate if fertilization can be applied either before or after plant material reintroduction in order to improve efficiency of restoration techniques; (3) to estimate if two fertilizer applications in a same season can speed up peatland plant re-establishment compared to a single application; (4) to compare the effects of two different forms of P fertilizer, granular phosphate rock and granular triple superphosphate, on plant re-establishment.

2. Materials and methods

2.1. Study areas

In spring 2001, three experimental sites on post-vacuum harvested peat fields were selected in South-Eastern Canada (Table 1).

Saint-Charles-de-Bellechasse, hereafter named Eastern Québec site (I), is located at the southern limit of the Low Boreal Wetland Region of Canada (National Wetland Working Group, 1988). The peatland extends to about 600 ha, 350 of which are currently peat-vacuum harvested. The selected experimental peat field is 220-m long by 30-m wide and delimited by drainage ditches. One side of the peat field is adjacent to vacuum harvested areas while the other side is bordered by an abandoned peat field, restored in 1999, and further on by other abandoned fields densely colonized by birches.

The Sainte-Marguerite-Marie peatland, hereafter named Central Québec site (II), is located in the Low Boreal Wetland Region of Canada (National Wetland Working Group, 1988). The peatland extends to 4315 ha, 200 of which are today vacuum-harvested, while 300 ha are under restoration. The experiment was here conducted on a 730-m long and 15-m wide peat field inside the area under restoration.

Maisonnette, hereafter named New Brunswick site (III), is located in the Atlantic Boreal Wetland Region of Canada (National Wetland Working Group, 1988). The peatland covers 541 ha, 304 of which are currently vacuum-harvested, while 12 of the 14 abandoned hectares are under restoration processes. The experiment was conducted on a 180-m long and 27.5-m wide post-harvested peat field inside the restoration area.

Characteristics of the three experimental sites are presented in Table 1 for regional climate, physico-chemical properties of the peat substrate and in Table 2 for the water table position. Climate normal were compiled from the nearest meteorological stations (Environment Canada, 2004). The depth of the remaining peat layer was measured with a milled iron rod on different locations within each experimental area. The degree of decomposition using the von Post ordinal humification scale (Parent and Caron, 1993) and the

Table 1 – Localization, climate and physico-chemical characteristics of the peat at the three experimental sites

	(I) Eastern Québec	(II) Central Québec	(III) New Brunswick
Geographic coordinates			
Latitude	46°45′N	48°47′N	47°49′N
Longitude	71°00′W	72°10′W	65°02′W
Climate normals[a]			
Mean annual temperature (°C)	3.4	2.3	4.5
January temperature (°C)	−13.1	−16.4	−11.1
July temperature (°C)	18.3	18.2	19.3
Total annual precipitation (mm)	1118	887	1059
Precipitation as rain (mm)	820	591	744
Peat physical characteristics			
Peat depth (minimum–maximum) (cm)	99 (21–197)	114 (104–125)	50 (36–60)
Decomposition (von Post scale)	H3–H4	H4–H5	H3–H4
Peat bulk density (minimum–maximum) ($g\,cm^{-3}$)	0.11 (0.10–0.13)	0.18 (0.17–0.19)	0.09 (0.08–0.11)
Peat chemical characteristics[b]			
pH (with $CaCl_2$)	2.80	3.06	2.64
Corrected conductivity ($\mu S\,cm^{-1}$)	67	68	108
N-NH_4^+ (ppm)	236	1245	39
N-NO_3^- (ppm)	12	7	18
P (ppm)	257	652	224
K (ppm)	324	168	1134
Na (ppm)	96	104	732
Ca (ppm)	1620	891	430
Mg (ppm)	384	63	1173
Fe (ppm)	492	475	2227
Mn (ppm)	88	12	46

All peat characteristics were evaluated on the upper 5 cm of surface peat, except for the peat depth.

[a] Environment Canada (2004).

[b] All analyses were performed at the laboratory in the Centre d'étude de la forêt at Université Laval. The peat pH was measured in a 0.1 M solution of $CaCl_2$. Electric conductivity was measured on samples saturated with distillate water (ratio 1:10) and then corrected according to Sjörs (1950). Total elements were determined using standard methods (ICP spectroscopy for P, K, Na, Ca, Mg, Fe and Mn, FIA Quickchem methods for N–NH_4^+ and N–NO_3^-).

dry bulk density (Boelter, 1969) were assessed from surface peat samples (0–5 cm; $n = 4$ in each site). Peat chemical analyses were done on one or two composite samples of surface peat in each site using standard methods. Finally, water table levels were measured in one to four wells installed at each experimental site, on a weekly or bi-weekly basis over the 2001 and 2002 summer periods (June–August).

2.2. *Restoration techniques*

The experiments were conducted on post-vacuum harvested areas where extraction operations ceased in 2000, and then underwent different restoration processes (Quinty and Rochefort, 2003).

In the Eastern Québec site, the donor site was a natural peatland designated for industrial development. In May 2001, the upper 10-cm layer of the bog vegetation was cut using a rototiller, collected by hand and forks, transported to the experimental site and spread within 2 weeks (reintroduction ratio 1:10). The reintroduced plants were covered with about 4000 $kg\,ha^{-1}$ of straw applied by hand. A 1-m buffer zone was also covered by straw around the experimental plots in order to avoid margin effects.

In the Central Québec site, the snow in the donor site was compacted during the previous winter to freeze a deep peat layer in order to allow work with heavy machinery in early spring. In April 2001, the top 10 cm of bog layer was then scraped off using bulldozers. Because of the snowy 2001 win-

Table 2 – Water table depth below surface during the first 2 years of the study (2001 and 2002) at the three experimental sites

	(I) Eastern Québec		(II) Central Québec		(III) New Brunswick	
	2001	2002	2001	2002	2001	2002
Summer average (June–August)	−13	−16	−22	−28	−42	nd
Summer minimum (June–August)	0	−1	−1	−7	−15	nd
Summer maximum (June–August)	−30	−35	−48	−61	<−51	nd

nd = not measured.

ter, the donor area was still covered by snow in April and a snow-blower was used to clean the bog surface in order to facilitate the collecting operations. Unexpectedly, the snow-blower likely cut and eliminated many of the underneath *Sphagnum* capitula standing at the top of hummocks (Quinty, Planirest Evironnement Inc., personal communication). The plant material was then mechanically spread (reintroduction ratio 1:13) in June 2001 with a manure spreader. About 3125 kg ha^{-1} of straw was then mechanically applied.

In the New Brunswick site, the experimental design was established within a large-scale restoration site of 14 ha. The donor site was a pristine bog, located 40 km SE, in an area designated for future extraction. The living vegetation was cut by rototiller and collected with a loader in late September 2000. The plant material was then spread mechanically (reintroduction ratio 1:13) by a manure spreader, a couple of weeks after collection. Due to a supply problem, the straw was applied 7 months later, in May 2001, at a rate of 3000 kg ha^{-1}.

In order to rewet the sites, the drainage ditches were blocked with dams of well-decomposed peat at the outflows of the experimental areas. Dams were also built at intervals along the peat fields in Eastern and Central Québec sites, but not in the New Brunswick site. Rewetting was thus more efficient in the two Québec sites.

A description of the donor site vegetation was completed during summer 2001, in areas adjacent to the collecting sites and with similar vegetation (Appendix A). Percentage covers of each species were visually estimated inside 25 cm × 25 cm quadrats, systematically distributed along transects. Plant covers were estimated to the closest 1% under 10% cover and to the nearest 5% for higher covers, with frequent calibration between observers.

2.3. *Treatments and experimental designs*

In Eastern Québec, a complete randomized block design of four blocks and 10 fertilizing treatments was put in place. Each fertilizing treatment was tested on 5 m × 5 m plots. The fertilizing treatments were: four different doses of granular phosphate rock (PR; 5, 10, 15 and 25 g m^{-2}) applied once before plant material reintroduction (within the previous week); the same four doses applied once after the plant material reintroduction (within the following week); one treatment of 15 g PR m^{-2}, split in two applications (7.5 g m^{-2} a week after plant material was reintroduced and 7.5 g m^{-2} 3 months later); the last treatment consisted of a control. The buffer zone between plots varied from 1.5 to 2 m. The fertilizer was applied manually.

In Central Québec, a complete randomized block design of four blocks and five fertilizing treatments was put in place. The experimental plots were marked as perpendicular strips of 15 m × 5 m along the restored peat field, separated by a 5-m buffer zone. The fertilizing treatments tested were: four different doses of granular PR (5, 10, 15 and 25 g m^{-2}) applied once, 1 month after the restoration procedures; the fifth treatment consisted of a control.

In New Brunswick, a complete randomized block design of four blocks and six fertilizing treatments was set up. The fertilizing treatments were applied with a manual spreader at the beginning of June 2001, after the other restoration procedures, on 26 m × 5 m experimental plots separated by buffer zones of at least 2 m. Treatments were: the same four doses of PR (5, 10, 15 and 25 g m^{-2}); 5 g m^{-2} of granular triple superphosphate (TSP) and a control. TSP has a bioavailable P concentration about three times higher than phosphate rock. Therefore, the effect of 5 g TSP m^{-2} is comparable to 15 g PR m^{-2}.

The doses tested in these experiments were chosen after preliminary trials had shown that 25 g m^{-2}, among inputs from 25 to 100 g m^{-2} of bone meal or PR, were enough to promote true mosses and vascular plant re-establishment (L. Rochefort, Université Laval, unpublished data). However, no previous experiment investigated the effect of lower fertilizer amounts than 25 g m^{-2}. There was also a need to compare different types of P fertilizers and time of application. In peatland restoration projects, granular PR is recommended although peatland managers sometimes used TSP because of its higher accessibility at local distributors. Moreover, fertilization is commonly done after plant material reintroduction and straw mulch application (Quinty and Rochefort, 2003). However, mechanical application can become problematic on very wet and soft surfaces. Fertilization prior to any other restoration step has been considered as a way to minimize disturbance after plant reintroduction.

Granular PR composition is 0–13–0 (P_2O_5 total 25%, P_2O_5 available 13%) and TSP is 0–46–0 (P_2O_5 total 48.2%, P_2O_5 available 46.2%). The highest PR dose tested, 25 g m^{-2} of PR, is thus equivalent to 3.25 g m^{-2} of available P_2O_5 or 1.4 g P m^{-2}. For TSP, 5 g m^{-2} corresponds to 2.3 g m^{-2} of P_2O_5 or 1 g P m^{-2}.

2.4. *Vegetation re-establishment*

Plant re-establishment was surveyed over three field seasons but only the third year results are presented here (see Sottocornola et al., 2002, for 1 year data). The same approach in estimating plants cover as described above for the donor sites was used. However, in this case, species were grouped by categories, based on abundance and vertical structure: bryophytes were grouped as *Sphagnum* spp., *P. strictum*, *Dicranella cerviculata*; all other bryophyte taxa were included in the “other bryophytes” category; vascular plants were grouped as ericaceous shrubs, herbaceous plants and trees. In Eastern Québec, 20 quadrats were surveyed along four, 1-m distant transects for each plot. In Central Québec, 30 quadrats were surveyed along three, 1.5-m distant transects per plot. In New Brunswick, 32 quadrats were evaluated, placed along two, 2-m distant transects, inside each plot. A list of the most frequent species found on the restored sites appears in Appendix A.

2.5. *Statistical analysis*

The vegetation establishment data was analyzed separately for each taxon or plant group, using ANOVAs in a completely randomized block design. Note that ericaceous shrubs were excluded from the analysis because of extremely low values. A series of planned comparison (polynomial and simple a priori contrasts) were done, each testing a hypothesis about the effect of P doses, type and timing of P fertilizer application. A priori contrasts (planned comparisons) are a powerful tool to compare particular set of means that are relevant to our hypotheses (Day and Quinn, 1989).

Strata Transformation		Total plant cover		*Sphagnum* spp. (log (*x* + 1))		*Polytrichum strictum*		*Dicranella cerviculata*		Other bryophytes (log (*x* + 1))		Herbs (log (*x* + 1))		Trees (log (*x* + 1))	
Source	d.f.	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
(I) Eastern Québec															
Blocks	3														
Fertilization	9	0.79	0.63	0.63	0.76	2.58	**0.03**	1.30	0.28	1.17	0.35	0.96	0.49	1.88	0.10
Error	26														
Total	38														
Contrasts															
Linear effect (after)	1	0.48	0.49	0.33	0.57	2.79	0.11	2.41	0.13	2.15	0.15	0.32	0.57	8.50	**0.007**
Quadratic effect (after)	1	3.04	0.09	0.75	0.39	0.14	0.71	0.35	0.56	0.69	0.41	0.14	0.71	1.81	0.19
Cubic effect (after)	1	0.02	0.90	0.47	0.50	0.03	0.87	0.93	0.34	2.78	0.11	0.47	0.50	0.42	0.52
Linear effect (before)	1	0.20	0.66	0.19	0.67	0.33	0.57	3.20	0.08	0.31	0.58	1.85	0.18	1.62	0.21
Quadratic effect (before)	1	0.70	0.41	0.51	0.48	0.12	0.73	1.57	0.22	1.62	0.21	0.16	0.69	7.39	**0.01**
Cubic effect (before)	1	1.65	0.21	0.82	0.37	4.85	**0.04**	0.00	0.98	0.14	0.71	0.18	0.67	0.03	0.85
Control vs. fertilization	1	2.06	0.16	0.07	0.79	2.24	0.14	2.70	0.11	0.23	0.64	0.22	0.65	9.45	**0.005**
Before vs. after	1	0.13	0.72	0.05	0.83	0.39	0.54	0.09	0.76	1.21	0.28	3.16	0.09	1.45	0.24
1 vs. 2 application	1	0.03	0.87	0.13	0.72	7.66	**0.01**	2.53	0.12	0.01	0.92	0.01	0.94	0.04	0.85
(II) Central Québec															
Blocks	3														
Fertilization	4	3.63	**0.04**	4.20	**0.02**	13.65	**0.0002**	1.62	0.23	12.84	**0.0003**	3.74	**0.03**	1.46	0.28
Error	12														
Total	19														
Contrasts															
Linear effect	1	12.01	**0.005**	15.55	**0.002**	47.22	**<0.0001**	0.33	0.58	40.45	**<0.0001**	14.61	**0.002**	1.64	0.22
Quadratic effect	1	0.22	0.65	0.11	0.75	5.89	**0.03**	0.00	0.97	9.83	**0.009**	0.04	0.85	1.89	0.19
Cubic effect	1	0.24	0.63	1.13	0.31	0.07	0.80	4.91	**0.05**	1.07	0.32	0.25	0.63	0.00	0.96
Control vs. fertilization	1	4.27	0.06	7.58	**0.02**	31.37	**0.0001**	0.53	0.48	41.58	**<0.0001**	4.30	0.06	0.09	0.76
(III) New Brunswick															
Blocks	3														
Fertilization	5	5.25	**0.005**	0.10	0.99	0.87	0.52	1.31	0.31	1.40	0.28	0.90	0.51	1.54	0.24
Error	15														
Total	23														
Contrasts															
Linear effect	1	20.66	**0.0004**	0.16	0.70	0.40	0.54	0.42	0.53	0.76	0.40	2.34	0.15	5.09	**0.04**
Quadratic effect	1	0.07	0.80	0.08	0.77	0.38	0.54	0.37	0.55	0.04	0.84	0.00	0.99	2.17	0.16
Cubic effect	1	2.76	0.12	0.22	0.64	3.47	0.08	5.70	**0.03**	3.80	0.07	1.28	0.27	0.28	0.60
Control vs. fertilization	1	4.72	**0.05**	0.01	0.93	0.68	0.42	0.78	0.39	0.32	0.58	0.08	0.78	5.97	**0.03**
P rock vs. super P	1	7.94	**0.01**	0.00	0.99	0.68	0.42	0.63	0.44	4.77	**0.04**	1.75	0.21	0.34	0.57

Table 3 – ANOVAs for the establishment of each plant species or plant group after three growing seasons, in the three experimental sites

The contrasts are a-priori contrasts. Significant *P*-values are in bold.

All statistical analyses were carried out using the GLM procedure of SAS (SAS Statistical System software, v. 6.12, SAS Institute Inc., Cary, NC, U.S.A.). Some variables were $\log_{10}$ transformed prior to analysis to reduce heterogeneity of variances (see Table 3 for details). The level of significance for testing treatments and for the contrasts was set at $P = 0.05$.

3. Results

3.1. Site characteristics

The three experimental sites were located in different regions and covered a wide range of climatic conditions from continental to sub-maritime (Table 1). They also differed in their peat physico-chemical characteristics (Table 1). The remaining peat layer was uniformly thicker in Central Québec than in other sites, with 114 cm peat left on average. The peat was also more decomposed in this site, with von Post value indicating more mesic peat compared to the Eastern Québec and the New Brunswick sites where peat was more fibric. This was reflected in the bulk density that was also higher in the Central Québec site, since peat becomes denser as it decomposes. On the other hand, the New Brunswick site had a thinner residual peat layer but the peat was fibric with a low bulk density (Table 1). This is typical of sub-maritime bogs that are characterized by fibric peat on almost all the peat profile.

The peat chemical analyses revealed that the experimental sites were quite similar (Table 1) and that they were chemically comparable to pristine bogs studied across Canada (Wind-Mulder et al., 1996; Andersen et al., 2006). The pH was very acidic while the electric conductivity was between bog and poor fen conditions in all three experimental sites. As expected for post-harvested peatlands where surface layers have been removed (Wind-Mulder et al., 1996), K^+ concentrations were generally lower while N (as NH_4 or NO_3) was higher than in pristine bogs.

The sites also differed hydrologically (Table 2). The rewetting was very successful in Eastern Québec site, where the lowest water table was −30 cm and −35 cm during the 2001 and 2002 summers, respectively (Table 2). The Central Québec site also benefited of wet conditions, with average water table levels above −30 cm during the 2001 and 2002 summers. The water table dropped to −60 cm in 2002, a dry year compared to long-term precipitation averages for the region (Environment Canada, 2005), but only for a short period at the end of August. In New Brunswick, the water table was far below −40 cm for most of the first growing season. Deficient rewetting was observed in this site the following two summers too (personal observations) due to an insufficient number of dams, and this phenomenon was exacerbated by low precipitations during the study period (Environment Canada, 2005).

3.2. Fertilization response at the Eastern Québec site

After three growing seasons, plants covered 55% of the experimental plots, all treatments confounded. A large part of it was bryophytes (43%), mostly sphagna (39%). Herbaceous plants and trees reached a mean cover of 9% and 8%, respectively, while Ericaceae and other vascular plants occurred poorly after three growing seasons.

Although no clear evidence was found from the effect of fertilizing treatments on total plant cover, the tree stratum, dominated by *Betula populifolia* (Appendix A), showed the highest re-establishment with the highest PR inputs (15–25 g m^{-2}) either applied before or after the reintroduction of plant material (Table 3, Fig. 1). *P. strictum* also showed a cubic effect with fertilization but in polynomial contrasts, cubic effect is considered as a residual effect and cannot be interpreted as a meaningful biological effect.

Only *P. strictum* benefited from the repeated applications of 7.5 g PR m^{-2} compared to the single application of 15 g m^{-2} (Table 3, Fig. 1). Although sparse, the cover of this species doubled with two applications of PR, from 2% to 4%. Finally, the time of fertilization – whether applied before or after plant material spreading – did not affect the plant establishment success (Table 3; Fig. 1).

Other taxa or plant groups were not influenced by fertilization. The cover of herbaceous plants was quite high in this site but was also highly variable. This stratum was dominated by *Scirpus atrocinctus* (Appendix A), which was abundant in the neighbouring disturbed areas (restored and abandoned peat fields). Likewise, no clear trends were observed for increasing fertilizer doses for the *Sphagnum* mosses.

3.3. Fertilization response at the Central Québec site

In the Central Québec site, about 46% of the restored area was revegetated (all treatments confounded) after three growing seasons, mostly by bryophytes as in the Eastern Québec site. Sphagna reached a percent cover of 5%, while *P. strictum* and *D. cerviculata* covered up to 28% and 3%, respectively. Other bryophytes, mainly *Pohlia nutans*, *Aulacomnium palustre* and *Marchantia polymorpha* (Appendix A), reached 4%. Vascular plants revegetated weakly, not reaching 2% in cover after three growing seasons.

The response of plants to fertilization was highly significant in this site. Higher PR inputs resulted in a higher re-establishment of the bryophyte layer, consequently increasing the total vegetation cover (Table 3; Fig. 1). *P. strictum* showed a clear positive linear response to P application, showing a better revegetation success with higher fertilizer concentrations. Together with the linear effect, a quadratic effect was also significant, meaning that *Polytrichum* re-establishment reached a plateau between 15 and 25 g m^{-2}. A similar curve was observed for the other bryophytes, the only exception being *D. cerviculata* that exhibited a more irregular establishment pattern in response to the different P doses. In this site, fertilization had a slight negative impact on *Sphagnum* mosses, which presented a higher establishment in unfertilized plots. However, one unfertilized experimental unit was randomly located adjacent to a dam where *Sphagnum* benefited from favourable wet conditions (highlighted by the high standard error for the control treatment in Fig. 1). Finally, after three growing seasons, fertilization also induced a slightly higher herbaceous cover (Table 3; Fig. 1), dominated by *Eriophorum vaginatum* (Appendix A).

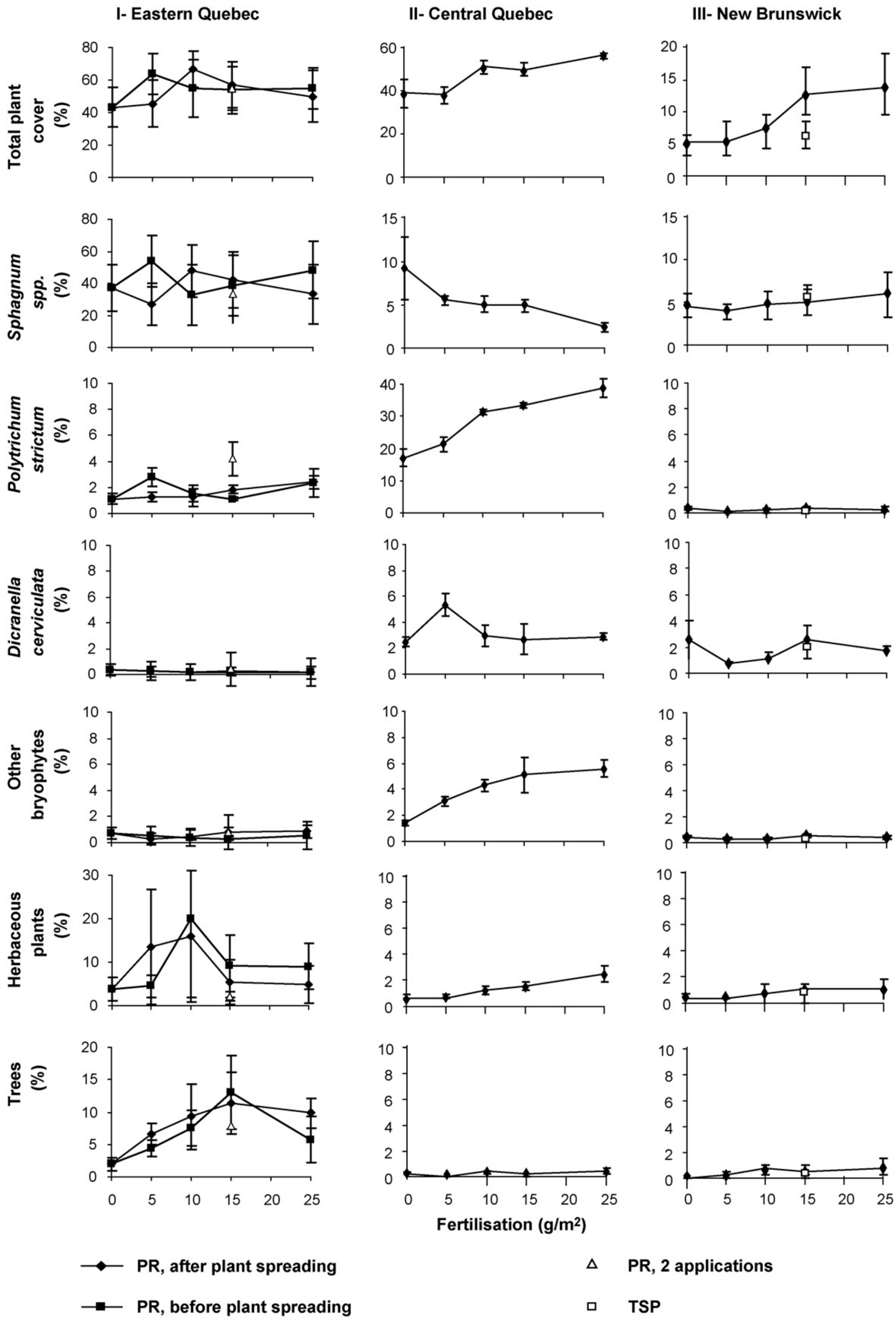

Fig. 1 – Effect of P fertilization on plant establishment in the three experimental sites, after three growing seasons. Fertilization treatments consisted in doses of 0, 5, 10, 15 and 25 $g\,m^{-2}$ of phosphate rock (PR), applied either after or before plant material reintroduction, as well as 15 $g\,m^{-2}$ of PR added in two applications and 5 $g\,m^{-2}$ of triple superphosphate (TSP; dose equivalent to 15 $g\,m^{-2}$ of PR). Beware of the different scales to represent vegetation covers.

3.4. Fertilization response at the New Brunswick site

In New Brunswick, only 8% of the restored area (all treatments confounded) was revegetated after three growing seasons, mostly by bryophytes. *Sphagnum* species had a percentage cover of 5%, *D. cerviculata* of 2%, *P. strictum* and other bryophytes of less than 1%. Vascular plants did not achieve 1% cover (Appendix A). It must be noted that plant establishment generally decreased between the second and third year after plant reintroduction (data not shown).

The total plant re-establishment in New Brunswick showed a significant linear response to the fertilization treatments (Table 3). The plant cover increased with doses, from 5% when not fertilized to almost 15% with 25 g PR m^{-2} (Fig. 1). However, the response of each species or stratum was less clear. Some responses emerged only for the tree layer, mainly *Betula papyrifera* and *B. cordifolia*, with a tendency to higher establishment with the highest PR input. Nevertheless, *Betula* covers remained very low.

The use of TSP was less efficient in promoting plant re-establishment then PR. Only 6% of total plant cover was estimated in plots fertilized with TSP, compared to 12% when fertilized with PR (Table 3; Fig. 1). However, again, the response of each species or stratum was unclear.

4. Discussion

In two out of the three sites, the optimal phosphate rock (PR) fertilizer input leading to the greatest peatland plant re-establishment was the highest dose tested (25 g PR m^{-2}). However, wide variations in re-establishment were observed across sites and types of plant, which could be explained by the effectiveness of restoration measures and intrinsic site properties.

The Eastern Québec site was well recolonized and *Sphagnum* mosses benefited greatly from the wet hydrological conditions and from the manual restoration techniques. Compared to mechanical operations, manual collection and spreading of plant material minimize the impact on *Sphagnum* propagules and favour a more uniform distribution, which enhances *Sphagnum* re-establishment success (Boudreau and Rochefort, 1999; Campeau et al., 2004). On the other hand, bryophytes like *P. strictum* and *P. nutans* did not establish successfully, even though rewetting was good. This may be explained by the species composition of the donor site (Rochefort and Lode, 2006), as these species were not found in abundance in the Eastern Québec donor site. Finally, the bloom of vascular plants in this site likely depended on the proximity of revegetated disturbed areas, which acted as effective seed source (Campbell and Rochefort, 2003; Campbell et al., 2003).

The Central Québec site was also characterized by wet hydrological conditions favourable for peatland plants re-establishment. But despite good rewetting and good establishment of nursing plants such as *P. strictum* and *P. nutans*, *Sphagnum* establishment was rather poor. We think that the damage at the *Sphagnum* capitula caused by the mechanical snow removal during plant collection explains this low success.

Finally, the deficient rewetting encountered in the New Brunswick site resulted in a decrease of plant cover during the third growing season compared to the previous years (data not shown). Consequently, water stress was a more limiting factor for plant re-establishment than other factors such as nutrient addition. It is also possible in this case that part of the propagules were dried or blown away while not protected by straw mulch, applied only 7 months after plant material was spread.

Whatever the variations between sites and their causes are, fertilization will only be useful if the other, more influential steps of restoration are well implemented. All plant strata or categories had their own pattern of response to P fertilization, as described below by plant category.

- *Bryophytes other than sphagna*—P fertilization speeded up recolonization by bryophytes when rewetting was optimal for moss re-establishment and when bryophytes were present in the donor site. The main species taking advantage of P addition were *P. strictum*, which doubled its cover with the medium and highest dose (15–25 g PR m^{-2}), as well as other bryophytes like *P. nutans* and *A. palustre*. In a greenhouse experiment studying moss establishment on bare peat, Li and Vitt (1994) observed various responses to P addition (from 0.5 to 1.2 g P m^2) depending on the species: no effect was observed for *A. palustre* and *P. strictum*, but a positive effect was noted for *Drepanocladus aduncus* with P input of 0.2–0.6 g P m^{-2}. In our study, *P. strictum*, *P. nutans* and *A. palustre* benefited from doses equivalent to 0.9–1.4 g m^{-2} of available P (or 1.6–2.7 g m^{-2} of total P).
- *Sphagnum mosses*—*Sphagnum* species showed no reaction to P fertilization, excepted for a negative effect at the Central Québec experimental site. This could be explained by a particularly high *Sphagnum* establishment in one control experimental unit. On the other hand, the low *Sphagnum* establishment success with fertilizer could potentially come from the relatively high Ca^{2+} content of PR (Clymo, 1973)—although no adverse effect has been observed in other restored sites. In any case, the direct or indirect benefits of PR treatments on *Sphagnum* establishment reported in other field experiments (Ferland and Rochefort, 1997; L. Rochefort, Université Laval, unpublished data) have not been observed in our study. We believe that the great abundance of *P. strictum* promoted by fertilization in the first 2–3 years of restoration would be beneficial in the long-term, given that some *Sphagnum* individuals are dispersed here and there within the moss carpet. *Polytrichum* carpet provides a favourable microclimate for *Sphagnum* moss (Groeneveld et al., 2007).
- *Herbaceous plants*—The effect of P addition was observed for *E. vaginatum* that was slowly colonizing the Central Québec site, with a slightly higher cover in fertilized treatments. Sedges like *E. vaginatum* have been shown to benefit quickly from P fertilization in some experiments, with higher rates of input (Tamm, 1954; Vasander, 1982; Ferland and Rochefort, 1997).
- *Trees*—In the Eastern Québec site, *Betula* establishment was widespread and stimulated by fertilization. A recent study

has shown that *Betula* invasion can be important in relatively dry restored sites and significantly increase dryness because of water loss caused by evapotranspiration (Fay, 2006). The invasion phenomenon would be temporary, the trees withering after some years or some decades, but could be enough to interfere with the restoration process. Yet in our experiment, the high water level and bryophyte covers (43% after three growing season) suggest that trees did not impede the restoration process.

4.1. Fertilization application

Optimal doses for restoration—In light of the present results, the optimal dose of PR to help plant re-establishment appears to be in the range of 15–25 g PR m^{-2}. This amount greatly enhances the recolonization by bryophytes, especially *P. strictum*, when present in the donor site. These amounts of 15 and 25 g m^{-2} of PR (0–13–0) are equivalent to 2.0 and 3.2 g P_2O_5 m^{-2} (or 0.9 and 1.4 g P m^{-2}). A longer time frame is likely needed to verify the effect on the vascular strata and to evaluate the risk of invasion by undesirable species such as *Betula* spp.

Application time and number of applications—The timing of fertilization, that is whether P should be applied before or after the plant material spread, leads to similar responses in plant revegetation. This result suggests that it is possible to apply fertilization prior to any other restoration step, which would make the order of the restoration procedures more flexible in large-scale operations (Quinty and Rochefort, 2003). On the other hand, the time lag between fertilization and the other restoration steps, as tested in this study for both before and after applications (1–2 weeks), might have been insufficient to see any differences in plant uptake and thereby plant re-establishment. The time of application during the growing season can be a more important factor to consider, as suggested by the treatment which included two PR applications. Two applications of PR slightly promote *P. strictum* re-establishment compared to a single application, for the same amount of fertilizer. Although not measured, it is possible that this species had a higher potential to uptake nutrients at the second application, some weeks after plant reintroduction, so once it has formed rhizoids from reintroduced fragments. A second hypothesis is that since P addition promotes spore germination and development (Boatman and Lark, 1971; I. Jarry and L. Rochefort, Université Laval, unpublished data), fertilization later in the season could allow the germination of spores that have been disseminated during June and July from surrounding areas (Miles and Longton, 1990). In this regard, it is interesting to note that fertilization was applied 1 month after reintroduction in Central Québec (in July), a site where P had a great effect on *Polytrichum* re-establishment.

Type of fertilizers—The comparison between two P fertilizers showed PR to be more efficient in promoting plant re-establishment than TSP, for the same amount of P, although this difference was not observed clearly at the species or stratum level. Further testing would be needed to clarify the effectiveness of these two types of fertilizers in a more favourable environment for peatland plants growth, as the experimental site used to test this had an overall low plant re-establishment caused by a deficient rewetting. Nevertheless, PR is recommended because of its efficiency under acidic conditions and its long-term dissolution with soils characterized by high cation exchange capacity (Zapata and Roy, 2004). PR is also known as a more efficient slow-release fertilizer: Nieminen and Jarva (2000) found that most of a superphosphate fertilizer spread on a drained pine bog was dissolved after 2 years whereas, in the same period, only half of a PR fertilizer was released. The latter is therefore expected to benefit vegetation for a longer time, while minimizing the risk of leaching to nearby drainage ditches. Environmental impacts of the fertilizers were not assessed in this study. However, we believe that the leaching of the fertilizer is lower than in peatlands that are drained and fertilized for forestry; restored bogs are indeed closed systems since all ditches are blocked to allow rewetting.

4.2. Implication for restoration

The experiment confirms the importance of a slight P fertilization to encourage plant re-establishment in restored peatlands. Bryophytes, particularly *P. strictum*, seem to benefit more from P addition than vascular plants, which responded weakly to the fertilization in the time frame studied and with the tested doses. Furthermore, bryophytes can quickly stabilize peat surface, reduce frost heaving damage and act as nurse plants for *Sphagnum* mosses (Quinty and Rochefort, 2000; Groeneveld and Rochefort, 2005; Groeneveld et al., 2007).

Fertilization timing should be investigated further, and the period of application during the growing season is probably more important for plant re-establishment than whether fertilization is applied before or after plant material is spread.

Fertilization in peatland restoration remains a site-specific decision, dependent on the intrinsic properties of the site, potential invasion by non-peatland plants (for example *Betula* sp.) and the restoration method used. Indeed, fertilization should be used in optimal conditions, as it cannot compensate for the selection of a donor site excluding target species like *P. strictum* or for deficient rewetting.

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Appendix A. List of most frequent species[a] and mean percent covers (standard deviation) estimated in the three experimental sites (Exp.) all treatments confounded, after three growing seasons, and in their respective donor sites. In the experimental sites, covers of bryophytes were estimated for dominant species or gender only, although all species were identified. See text for methods. Legend: + = < 1%; x = species identified but cover estimated at a higher taxon

	(I) Eastern Québec		(II) Central Québec		(III) New Brunswick	
	Exp., $n = 800$	Donor, $n = 45$	Exp., $n = 600$	Donor, $n = 45$	Exp., $n = 720$	Donor, $n = 35$
(A) Bryophytes, hepatics and lichens	43 (35)	99 (6)	39 (20)	98 (7)	7 (9)	97 (7)
Aulacomnium palustre	0	0	x	+	x	0
Dicranella cerviculata	+	0	3 (7)	0	2 (4)	0
Mylia anomala	x	1 (1)	0	0	x	1 (1)
Pohlia nutans	x	0	x	1 (0.4)	x	+
Polytrichum strictum	2 (2)	0	28 (19)	1 (1)	+	+
Sphagna	40 (36)	98 (6)	6 (8)	98 (7)	5 (7)	95 (8)
Sphagnum angustifolium	0	1 (2)	0	6 (11)	0	0
Sphagnum flavicomans	0	0	0	0	x	10 (20)
Sphagnum fuscum	x	14 (29)	x	71 (27)	x	28 (17)
Sphagnum magellanicum	x	10 (23)	x	2 (4)	x	3 (10)
Sphagnum rubellum	x	73 (35)	x	20 (24)	x	54 (25)
Lichens	+	0	+	0	+	1 (2)
(B) Vascular plants						
Betula ssp.	8 (10)	0	+	0	+	0
Carex trisperma	+	1 (2)	0	0	0	0
Chamaedaphne calyculata	+	9 (7)	+	3 (5)	+	3 (3)
Drosera rotundifolia	+	1 (0.4)	0	0	+	1 (0.4)
Empetrum nigrum	0	0	0	0	+	3 (4)
Eriophorum vaginatum	+	1 (2)	1 (2)	1 (4)	+	+
Gaylussacia baccata	0	0	0	0	0	4 (4)
Kalmia angustifolia	+	6 (10)	+	3 (5)	+	2 (3)
Kalmia polifolia	+	2 (2)	+	+	+	+
Larix laricina	0	1 (3)	0	0	0	0
Ledum groenlandicum	+	+	+	21 (16)	+	+
Rubus chamaemorus	0	0	0	0	0	3 (3)
Sarracenia purpurea	+	1 (1)	0	0	0	+
Scirpus caespitosus	0	0	0	0	0	1 (2)
Scirpus atrocinctus	8 (18)	0	+	0	0	0
Vaccinium myrtilloides	0	2 (5)	0	0	+	2 (4)
Vaccinium oxycoccos	+	1 (1)	+	1 (0.4)	+	1 (0.4)

[a] For the hepatics: Ley and Crowe (1999); for *Sphagnum*: Anderson (1990); for true mosses: Anderson et al. (1990); for vascular plants: Gleason and Cronquist (1991).

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