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Drivers of success in 53 cutover bogs restored by a moss layer transfer technique

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ABSTRACT

The moss layer transfer technique has been used since the 1990s to restore bogs in North America after peat extraction. This article assesses the influence of drainage-related, peat physicochemical, meteorological, management and landscape factors on the vegetation of extracted peatlands that have been restored in this manner. It draws upon data from a unique long-term monitoring programme covering 53 restoration projects spanning 600 km across eastern Canada. The time since restoration ranged from 3 to 15 years, and the rehabilitated peatlands had on average three permanent plots where vegetation was recorded every two years. Overall, the study included 246 permanent plots and 946 observations (plots*year of survey). Redundancy and cluster analyses showed that successful restoration, defined by the dominance of a *Sphagnum* carpet (54% of all plots at the most recent observation), was mainly associated with effective blocking of the former secondary drainage network within the restored sector, while plots dominated by bare peat (24% of all plots) occurred more often if a hot summer followed restoration works and where higher proportions of the surrounding land were subject to peat extraction. Management decisions, such as the season when restoration work was carried out, also substantially influenced restoration outcomes. For example, restoring in spring increased the likelihood of initiating an alternative successional trajectory characterised by dominance of the pioneer moss *Polytrichum strictum* (22% of all plots). However, a tendency towards *Sphagnum* colonisation and the development of *Sphagnum* carpets was observed over time in practically all plots. These results will inform future restoration efforts using the moss layer transfer as a peatland restoration method.

1. Introduction

In North America, peatland restoration has so far focused on cutover bogs where peat has been vacuum extracted (Rochefort et al., 2003). Cutover peatlands are rarely re-colonised spontaneously by plants (Poulin et al., 2005; Triisberg et al., 2011) or, if they are re-colonised, they tend to become dominated by a single species and can remain in that state for several decades (Poschlod et al., 2007). This is the result of harsh environmental filters such as altered hydrology (Price et al., 2003; Price and Whitehead, 2004), wind erosion, frost heaving (Campbell et al., 2002; Groeneveld and Rochefort, 2002) and unsuitable physical properties of the residual peat (Price and Whitehead, 2001). Consequently, since the first North American trials in the early 1990s, efforts to restore peatlands from peat harvesting have included active re-introductions of vegetation and various management options (Rochefort et al., 1995; Rochefort and Lode, 2006).

For bog ecosystems in the northern hemisphere, the main objective is usually to re-establish a plant community dominated by *Sphagnum* (Rochefort, 2000), a typical bog bryophyte that is able to initiate self-regulatory mechanisms that tend to reinstate the process of peat accumulation (van Breemen, 1995). The first attempts to re-introduce *Sphagnum* on abandoned cutover peatlands consisted of transplanting nuclei of *Sphagnum* shoots or fragments into wet hollows and water-filled ditches, in the futile hope that they would expand naturally over the rest of the abandoned peat fields (Rochefort and Lode, 2006). Another focus of early experimental work was to match *Sphagnum* species to the physicochemical conditions of the bare residual peat (Wind-Mulder et al., 1996), but this approach also failed because regeneration niches were later shown to differ from habitat niches and to be more important for *Sphagnum* establishment (Rochefort and Lode,

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Abbreviation: RDA, Redundancy Analysis.

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2006). Trials that improved the microclimatic environment proved to be the turning point for successful establishment of introduced moss diaspores on residual peat surfaces (Rochefort and Bastien, 1998). Graf et al. (2012) summarise the sequence of restoration actions that was subsequently designed to alleviate the severe environmental constraints found on bare peat, and which ultimately led to development of the moss layer transfer technique. This relatively simple yet robust restoration method consists of: (1) re-shaping field topography and blocking drainage ditches to establish suitable hydrological conditions; (2) spreading plant diaspores including fragmented *Sphagnum* previously collected from a donor site; (3) spreading a straw mulch to protect the plant fragments from desiccation; and (4) in some cases fertilising with phosphorus to favour colonisation by 'nurse plants' for the developing *Sphagnum* shoots (Rochefort et al., 2003). More than ten years of monitoring cutover peatlands across eastern Canada where the moss transfer technique has been applied have shown that the method has frequently been successful in re-creating moss carpets typical of natural bogs within a decade (Boudreau and Rochefort, 2008; Poulin et al., 2012). On this basis, its application has recently been extended into several other Canadian provinces and American states. However, monitoring has also shown that it leads to unwanted successional trajectories in around 40% of cases (González et al., 2013a, in press).

Why *Sphagnum* species do not colonise all restored sites remains an open question. Of all the factors that could potentially affect how readily *Sphagnum* colonises vacuum-harvested peat fields, the hydrological conditions on the restored site are amongst the most important (Price et al., 2003; Holden et al., 2004). The establishment of *Sphagnum* requires special hydrological conditions, namely high water table (generally <40 cm below the peat surface), soil moisture > 50% and soil water pressure > −100 mb (Price and Whitehead, 2001). However, simply raising the water table and re-wetting the peat may not be sufficient to ensure successful restoration (Aapala et al., 2008). For example, the introduced material may be flushed away by floods occurring before the plants become established (Rochefort and Lode, 2006). Various techniques can be applied to improve the distribution of water within an area that is to be restored, including blocking of former drainage systems, re-profiling of peat fields, building of berms and excavation of shallow basins (Bugnon et al., 1997; Price, 1997; Price et al., 2002, 2003; Quinty and Rochefort, 2003; Campeau et al., 2004; Landry and Rochefort, 2011), but their relative effectiveness across different restored bogs has rarely been evaluated (Armstrong et al., 2009). Furthermore, water drainage may interact with other environmental factors that could also be key drivers of restoration success. This is the case for degree of decomposition of the residual peat, which determines physical properties such as porosity and hydraulic conductivity that ultimately control the rate of water movement through the peat layer (Schlotzhauer and Price, 1999). Also, frost heaving is a physical process that frequently impedes the recolonisation of bare peat by plants (Groeneveld and Rochefort, 2002); and residual peat depth has been identified as an important driver for the trajectory of plant succession in spontaneously regenerating cutover peatlands in Estonia (Triisberg et al., 2013). The peat chemistry of the residual peat is variable among post-harvested sites and may also play a role as driver of success (Andersen et al., 2011).

Among other factors that may help to explain outcomes, the meteorological conditions during the first growing season after restoration are of particular concern, as *Sphagnum* fragments cannot survive under conditions of extremely low humidity (Sagot and Rochefort, 1996; Campeau et al., 2004). Attempts to re-introduce *Sphagnum* by the moss layer transfer technique in dry years lead to incomplete development of the moss carpet, and the delay in moss establishment persists for years even if the weather conditions subsequently improve (Chirino et al., 2006). Success may also be affected by management and technical aspects of practice, such as commercially driven constraints on the availability of manpower or machinery for restoration work; for example, if they result in a prolonged interval between spreading of the transferred moss layer and application of the protective mulch. Moreover, it has been questioned whether phosphorus fertilisation is necessary for restoration under all conditions or should be limited to sites that are prone to frost heaving (Groeneveld and Rochefort, 2002; Sottocornola et al., 2007). Finally, as for other ecosystems, plant assemblages on bogs are affected by human activities in the surrounding landscapes (Pellerin and Lavoie, 2000, 2003; Lachance and Lavoie, 2004). Land uses may influence succession in vegetation that is re-establishing on previously extracted bogs (González et al., 2013b, 2014), and thus affect restoration outcomes.

Our study is one of the first attempts to evaluate success in bog restoration at regional scale, and draws upon data from a unique long-term monitoring programme covering 53 restored sites across eastern Canada. The primary objective of this work is to assess the relative importance of a range of factors in controlling the success of bog restoration by the moss layer transfer technique. In particular, we examine the effects of drainage, peat physicochemical, meteorological, management and landscape factors on the vegetation of restored sites. It is of paramount importance to know how such factors have affected the success of past restoration projects in order to inform the adaptation of management strategies for future restoration actions (Herrick et al., 2006; Walker et al., 2007; Shafroth et al., 2008; Bernhardt and Palmer, 2011). A secondary objective is to describe the trajectories of different restoration outcomes, and thus enable practitioners to recognise them easily in the field and to assess restoration success within a short period of time.

2. Materials and methods

2.1. Study sites

We monitored bog sites where peat had been vacuum extracted for horticultural use, which had subsequently been restored using the moss layer transfer technique (PERG, 2013) by the peat industry in collaboration with the Université Laval (Quebec) Peatland Ecology Research Group. The 53 sites included in this study are all located within an area of 166,400 km^2 spanning the provinces of New Brunswick and Quebec in eastern Canada, where 12 peatland complexes have been monitored for periods of 3–15 years post-restoration (Fig. 1). Most of these peatlands originally developed over lowland sand, silt and marine clay deposits. Classified as Atlantic boreal peatlands and Maritime Atlantic boreal peatlands, they are primarily rain-fed ombrotrophic bogs (National Wetlands Working Group, 1988) and span three major Canadian climatic regions, namely: the Atlantic region, the Great Lakes Lowland/St. Lawrence region and the Inland of Northeastern Forest region (Environment Canada, 2012, Table 1).

For the peat extraction process, bogs are divided into sectors of a few hectares delimited by large (primary) drainage ditches. Sectors are close to production when the quality of the exposed peat falls below the required commercial standard, but the chemistry of the residual peat surfaces at all sites included in this study was still within the range that characterises ombrotrophic conditions. Individual abandoned sectors are spatially and temporally homogeneous, and are restored as units. Hereafter we shall use the term *sector* to denote a single site restored in a given year.

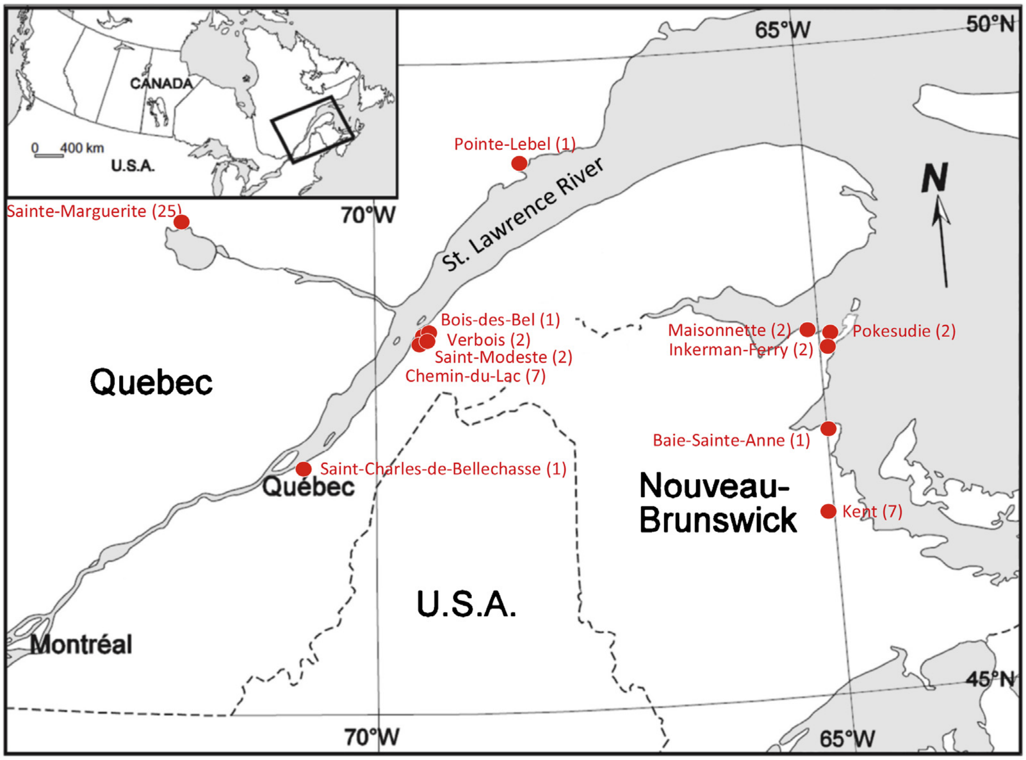

Fig. 1. Locations of the 12 peatlands and 53 restoration sectors (number of sectors within each peatland in parentheses) in the provinces of New Brunswick and Quebec (eastern Canada) that are included in this study.

Different monitored sectors may be located 2–5 km apart within the same peatland complex, or in different peatland complexes.

The post-restoration monitoring programme covered 53 sectors, and documented the changes of plant communities in 246 permanent 5 m × 5 m plots (Table 1). The number of permanent plots per sector varied with sector size, the topographical heterogeneity created during the first phase of restoration works, and local constraints.

2.2. *Vegetation survey*

Vegetation was first surveyed at each permanent plot during the autumn of the third growing season after restoration and, normally, biannually thereafter. The third year was chosen as the starting point of the monitoring programme because it is difficult to identify some species (especially developing mosses) at earlier stages, and to ensure that only well established plants rather than loose propagule fragments were recorded. For vascular plant cover, four 1 m × 1 m quadrats were placed systematically within each permanent plot. All vascular plants (trees, ericaceous and other shrubs, herbs) within each quadrat were identified to species level, and the ground covered by their vertical projections, as well as bare peat and litter cover, were estimated visually. Cover of all bryophyte and lichen species was recorded in 20 smaller (25 cm × 25 cm) quadrats that were also systematically distributed within the permanent plots.

2.3. *Potential drivers of restoration success*

The variables that could have roles in determining the success of restoration were classified into five groups, namely: (1) drainage, (2) peat physicochemistry, (3) meteorology, (4) management and (5) landscape (see Appendices). We did not consider time since restoration as a potential driver for two reasons. First, exploratory analyses showed that differences between the sectors outweighed elapsed time in determining the assemblages of plant species recorded. Secondly, we expected better outcomes from younger restorations than from older ones because our practical expertise in implementing the moss layer transfer technique increased from year to year, and this would invalidate any ecological interpretation of time as a factor controlling success.

(1) The drainage at each restored sector was assessed using three surrogates (primary blockage, secondary blockage, blockage effectiveness), which were estimated visually on a semi-quantitative basis during the summer of 2012 (Appendix A). The degree of blockage within primary and secondary ditches was estimated on two different four-point scales, and its effectiveness was estimated on a five-point scale.

(i) For blockage of primary ditches (Fig. 2) the scoring system was as follows: 1 – the primary ditch defining the sector was active; 2 – the ditch was active but situated several metres beyond an intervening buffer feature, such as a berm or strip of residual forest that would tend to reduce drainage from the sector; 3 – the ditch was only partially blocked, e.g. by peat dams (usual) or infilling (occasional) along only one side of the restored sector; 4 – the primary ditch was fully blocked.

(ii) For blockage of secondary ditches, all secondary ditches (see Fig. 2) within the sector were blocked, but their condition was: 1 – clean; 2 – less than 50% collapsed; 3 – more than 50% collapsed; or 4–completely infilled or not identifiable.

(iii) The effectiveness of ditch blocking within each sector was estimated from signs of recurrent flooding. These were: the presence of bare peat and accumulated water in depressions, the surface crusting that is noticeable once water has receded, and the presence of plants typical of wetter micro-habitats (mainly *Sphagnum* and *Carex* spp.). The spatial distribution of these signs within the

Table 1
Attributes of the 53 restored sectors on 12 bogs in eastern Canada that were included in this study.

Sector code	Bog	Restoration year	Size (ha)	Age of the restored sector at latest vegetation survey	Latitude and longitude	Number of permanent plots	Restoration outcome at time of the most recent vegetation survey (% of plots)[a]
Atlantic region (province of New Brunswick)							
1	Baie-Sainte-Anne	2000	12	10	47°01′05″ N 64°52′46″ W	7	B (57) P (29) S (14)
2	Inkerman Ferry	1997	3	9	47°42′12″ N 64°49′02″ W	28	B (71) S (29)
3	Inkerman Ferry	2008	7	3	47°42′21″ N 64°49′07″ W	5	B (60) S (40)
4	Kent	2001	5	10	46°18′32″ N 65°08′11″ W	5	S (100)
5	Kent	2007	8	4	46°18′42″ N 65°08′36″ W	4	B (50) S (50)
6	Kent	2008	7	3	46°18′40″ N 65°08′09″ W	4	B (75) S (25)
7	Kent	2008	4	3	46°18′28″ N 65°08′04″ W	3	B (66) S (33)
8	Kent	2008	2	3	46°19′03″ N 65°08′16″ W	2	B (100)
9	Kent	2008	3	3	46°18′55″ N 65°08′22″ W	1	B (100)
10	Kent	2008	7	3	46°18′51″ N 65°08′16″ W	4	S (100)
11	Maisonnette	2000	11	10	47°49′43″ N 65°02′02″ W	26	S (62) B (35) P (4)
12	Maisonnette	2006	9	5	47°49′37″ N 65°01′50″ W	6	S (66) P (33)
13	Pokesudie	2006	14	5	47°48′47″ N 64°46′20″ W	5	S (60) B (40)
14	Pokesudie	2008	9	3	47°48′42″ N 64°46′02″ W	4	S (100)
Lowland of Great Lakes/St. Lawrence region (province of Quebec)							
15	Bois des Bel	2000	12	9	47°58′03″ N 69°25′44″ W	32	S (100)
16	Chemin du Lac	1995	4	15	47°46′06″ N 69°31′37″ W	6	S (100)
17	Chemin du Lac	1997	3	11	47°45′47″ N 69°31′34″ W	6	S (83) P (17)
18	Chemin du Lac	1999	1	10	47°45′42″ N 69°31′36″ W	2	S (100)
19	Chemin du Lac	2000	2	10	47°45′39″ N 69°31′35″ W	4	S (100)
20	Chemin du Lac	2001	3	10	47°45′37″ N 69°31′30″ W	3	S (100)
21	Chemin du Lac	2002	5	7	47°45′51″ N 69°31′31″ W	4	S (75) B (25)
22	Chemin du Lac	2003	11	7	47°45′41″ N 69°31′09″ W	4	S (75) B (25)
23	Pointe-Lebel	2004	4	7	49°07′03″ N 68°11′25″ W	8	P (100)
24	Saint-Charles-de-Bellechasse	1999	1	10	46°44′53″ N 70°59′46″ W	4	S (60) B (40)
25	Saint-Modeste	1997	1	9	47°50′01″ N 69°27′51″ W	4	B (50) P (50)
26	Saint-Modeste	1997	1	9	47°50′02″ N 69°27′50″ W	2	S (100)
27	Verbois	2005	9	5	47°50′24″ N 69°26′41″ W	6	S (66) P (33)
28	Verbois	2006	7	5	47°50′16″ N 69°26′22″ W	4	P (75) S (25)
Inland of Northeastern Forest region (province of Quebec)							
29	Sainte-Marguerite (Section A)	1994	6	15	48°49′15″ N 72°10′15″ W	3	P (100)
30	Sainte-Marguerite (Section A)	1995	6	15	48°49′13″ N 72°10′13″ W	3	P (100)
31	Sainte-Marguerite (Section B)	1995	6	15	48°49′07″ N 72°10′30″ W	3	S (33) B (33) P (33)
32	Sainte-Marguerite (Section B)	1996	6	15	48°49′05″ N 72°10′29″ W	3	P (66) B (33)
33	Sainte-Marguerite (Section H)	1997	2	15	48°48′40″ N 72°10′17″ W	3	S (66) P (33)
34	Sainte-Marguerite (Section H)	1998	2	9	48°48′36″ N 72°10′27″ W	2	B (100)

Table 1 (*Continued*)

35	Sainte-Marguerite (Section AA)	1999	2	10	48°49′37″ N 72°10′41″ W	2	P (100)
36	Sainte-Marguerite (Section H)	1999	1	10	48°48′36″ N 72°10′21″ W	1	P (100)
37	Sainte-Marguerite (Section AA)	2000	4	10	48°49′36″ N 72°10′39″ W	2	P (100)
38	Sainte-Marguerite (Section E)	2000	15	10	48°48′29″ N 72°10′57″ W	1	S (100)
39	Sainte-Marguerite (Section K)	2000	10	10	48°48′23″ N 72°10′48″ W	2	S (100)
40	Sainte-Marguerite (Section L)	2000	11	4	48°48′15″ N 72°11′04″ W	1	B (100)
41	Sainte-Marguerite (Section AA)	2001	10	10	48°49′29″ N 72°10′47″ W	3	P (100)
42	Sainte-Marguerite (Section E)	2001	10	10	48°48′45″ N 72°11′13″ W	1	S (100)
43	Sainte-Marguerite (Section G)	2001	10	10	48°49′06″ N 72°10′52″ W	2	S (100)
44	Sainte-Marguerite (Section K)	2001	17	10	48°48′11″ N 72°10′38″ W	1	S (100)
45	Sainte-Marguerite (Section L)	2001	17	10	48°48′07″ N 72°10′54″ W	1	S (100)
46	Sainte-Marguerite (Section AA)	2002	10	10	48°49′28″ N 72°10′46″ W	3	P (100)
47	Sainte-Marguerite (Section H)	2002	12	7	48°48′33″ N 72°10′12″ W	2	P (100)
48	Sainte-Marguerite (Section J)	2002	27	7	48°48′21″ N 72°10′27″ W	3	P (100)
49	Sainte-Marguerite (Section AA)	2003	21	7	48°49′24″ N 72°10′37″ W	2	P (100)
50	Sainte-Marguerite (Section DD)	2003	30	7	48°48′45″ N 72°10′51″ W	3	P (100)
51	Sainte-Marguerite (Section F)	2003	15	7	48°48′36″ N 72°11′31″ W	2	S (100)
52	Sainte-Marguerite (Section L)	2003	1	7	48°48′04″ N 72°10′52″ W	2	S (100)
53	Sainte-Marguerite (Section AA)	2004	21	7	48°49′22″ N 72°10′22″ W	2	P (100)
						Total = 246	

Regions corresponding to major Canadian climatic regions: Atlantic region: mean annual temperature = 4.5 °C, total annual precipitation = 1059 mm, precipitation as snow = 318 mm. Lowland of Great Lakes/St. Lawrence region: mean annual temperature = 3.2 °C, total annual precipitation = 963 mm, precipitation as snow = 270 mm. Inland of Northeastern Forest region: mean annual temperature = 2.3 °C, total annual precipitation = 887 mm, precipitation as snow = 296 mm (Environment Canada, 2012).

[a] S – *Sphagnum-dominated*, B – bare peat-dominated, P – *Polytrichum*-dominated restoration.

sector was assessed as a composite indicator of the extent of recurrent flooding, and classed as: 1 – absent (no signs of recurrent flooding); 2 – very heterogeneous; 3 – heterogeneous; 4 – homogeneous; or 5 – very homogeneous.

(2) Physicochemical properties of peat (Appendix A) were determined on composite samples made up from peat collected near all of the permanent plots within each restored sector. A sub-sample was saturated with distilled water (ratio 1:10) for measurement of electrical conductivity (EC), which was then corrected according to Sjörs (1952). Peat pH was measured on the same 1:10 solution. Degree of decomposition on the von Post scale (Von Post and Granlund, 1926) was assessed manually in the field. The thickness of the residual peat layer (peat depth) was measured by probing with a threaded steel rod at three random locations nearby each permanent plot and was averaged per sector.

(3) Weather data for each restored peatland were obtained from the closest meteorological station (Environment Canada, 2012; Appendix B). We used mean monthly temperature (°C) and total monthly precipitation (mm) data to calculate mean temperature and cumulative precipitation for the spring (May–June), summer (July–August) and autumn (September–October) of the first growing season after restoration works. The first growing season was chosen because Chirino et al. (2006) showed that the weather in subsequent years has a minor effect on *Sphagnum* establishment and development. In cases where restoration was carried out in spring or summer rather than in autumn (Appendix C), weather data for the growing season of the same year were used. Additional meteorological variables calculated were the "rain days": numbers of days with precipitation during the growing season (May–October) and in summer (July–August) only. For the summer period, we also calculated the "effective rain days": the number of days with effective rain, i.e., days with precipitation ≥2 mm; and, as a proxy for summer drought, the maximum number of consecutive days with no effective rain (i.e., <2 mm). Two millimetres is the amount of rain that is estimated to be absorbed by the mulch before any water penetrates to the plant diaspores beneath (Price et al., 1998).

(4) Management was represented by the following five variables: season of restoration works, delay in restoration, sector size, donor site ratio, and delay in P fertilisation (Appendix C).

(i) Season of restoration works was a qualitative variable with three possible values (spring, summer, autumn). It was not intended to represent a phenological or climatic variable, but rather to reflect the different levels of site disturbance that may have arisen from working on it with heavy machinery at different times of year; for example, when the ground (bare peat) was more likely to be wet and thus especially prone to mechanical disturbance (e.g. rutting by caterpillar tracks or tires).

(ii) Delay in restoration was the number of years that had elapsed between the sector was closed to production and restored.

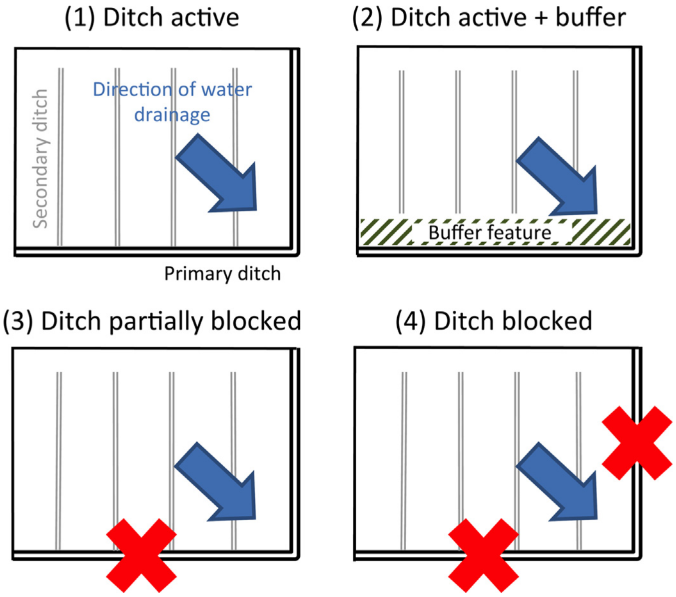

Fig. 2. Degree of blockage within primary ditches. Buffer features are berms or strips of residual forest that existed between the restored sector and primary drainage network to reduce drainage.

(iii) Sector size was the area of the restored sector in ha.

(iv) The donor site ratio (donor area: restored area) was the ratio of the area of donor site from which diaspores were collected to the area over which they were spread.

(v) Delay in phosphorus fertilisation was a semi-qualitative variable reflecting the time that had elapsed since restoration when (and if) this treatment was applied, scored as: 0 – no delay, 1 – one-year delay, 2 – two-year delay, 3 – three-year delay, 4 – four-year delay, 5 – no fertiliser application. Phosphorus fertiliser is most commonly applied where serious frost heaving is observed, to promote colonisation by the moss *Polytrichum strictum*, which can help to stabilise the peat substrate (Sottocornola et al., 2007).

Other management variables that could potentially influence restoration outcomes were recorded, but were not included in the analyses because there were either too many missing data or severe deviations from normality in their distributions. These variables included the time delays between collecting plant material from the donor site and spreading it on the restored sector, and between spreading the plant material and applying the protective mulch.

(5) Landscape was characterised in terms of land uses on areas adjacent to the restored sites, which were identified using aerial photographs obtained from the satellite view of Google Maps and verified in the field during the summer of 2012. Using GIS (ArcMap 10) a rectangle was drawn around each sector in turn, such that its sides ran north-south and east-west and the distance between each side and the closest point on the edge of the sector was 500 m. Then, calculations were made of the relative areas (%) of the rectangle that belonged to each of the following five land use categories: natural (mainly forest, water bodies and peatlands); current peat extraction; previously extracted and restored peatland; previously extracted and abandoned peatland; and anthropic land uses other than peat extraction (mainly agriculture) (Appendix C). The area occupied by the sector itself was excluded from these calculations.

2.4. Data processing and statistical analyses

Cover values for all vascular plant species, non-vascular plant species and bare peat were averaged for each permanent plot to generate a vegetation matrix with one row per plot for each survey year, and one column per species (dimensions: 946 × 88).

A Redundancy Analysis (RDA) was run on the Hellinger transformed vegetation matrix to assess the role of each of the five driver groups (drainage, peat physicochemistry, meteorology, management, landscape) in determining vegetation composition on the restored bogs.

As multi-collinearity between driver variables was expected, we used forward selection of variables before implementing the RDA (Blanchet et al., 2008). We also removed variables that were highly correlated (Spearman coefficient > 0.7). Even if there is some degree of correlation between variables belonging to different driver groups, practitioners need to consider each group independently when taking decisions. Therefore, we were especially interested in the capacity of each of the five groups, considered alone, to explain restoration success. For this reason, we restricted the control of multi-collinearity to variables within the same group by running five independent forward selections, one for each of the five groups of drivers, and the Spearman tests only for variables within the same group. This enabled us to avoid removing variables with high predictive power that were redundant amongst the five driver groups. Even though this approach reduced the parsimony of our models, it was preferable because it allowed us to provide practitioners with a better assessment of the importance of each group as a driver of success. The significance of the RDA was assessed using a permutation test with 9999 randomised runs (Legendre and Legendre, 2012).

To facilitate the interpretation of the RDA results, the Hellinger transformed vegetation matrix was also subjected to a k-means partitioning. This analysis allowed us to classify the observations (plots × year of survey) into k groups that were interpreted in terms of their restoration success (i.e., recovery of a *Sphagnum* carpet, González et al., 2013a). Following Milligan's (1996) recommendation, the Calinski-Harabasz criterion was used to determine the most appropriate number of clusters. The restoration trajectories for the plots were assessed by exploring the temporal changes of the observations into the canonical space, and changes in group membership over time.

All analyses were carried out using R software (version 2.15.2). More precisely, RDA and *k*-means partitioning employed the functions rda and cascadeKM of the vegan package (Oksanen et al., 2011); and the forward selection procedure used forward.sel in the packfor package (Dray et al., 2009).

3. Results

3.1. Possible outcomes of restoration in extracted peatlands

An RDA model incorporating the chosen drainage, peat physicochemical, meteorological, management and landscape variables explained 30.3% of the variability of the Hellinger's transformed vegetation matrix (adjusted $r^2 = 0.303$, $F = 20.566$, $P < 0.001$). The first gradient of the RDA separated the observations (i.e., plot in a given year) where moss carpets (mainly *Sphagnum rubellum*, *S. fuscum and Polytrichum strictum*) had successfully established from those dominated by bare peat and, to a lesser degree, *Betula* trees and the bryophyte *Dicranella cerviculata* (RDA1 of 'species scores' graph, Fig. 3). The second gradient separated the observations dominated by typical bog species such as the tussock-forming cottongrass *Eriophorum vaginatum*, *Sphagnum rubellum* and *S. magellanicum* from those dominated by the pioneer moss *Polytrichum strictum* (RDA2 of 'species scores' graph, Fig. 3). According to the first two axes of the RDA, the k-means partitioning divided the 946 observations satisfactorily into

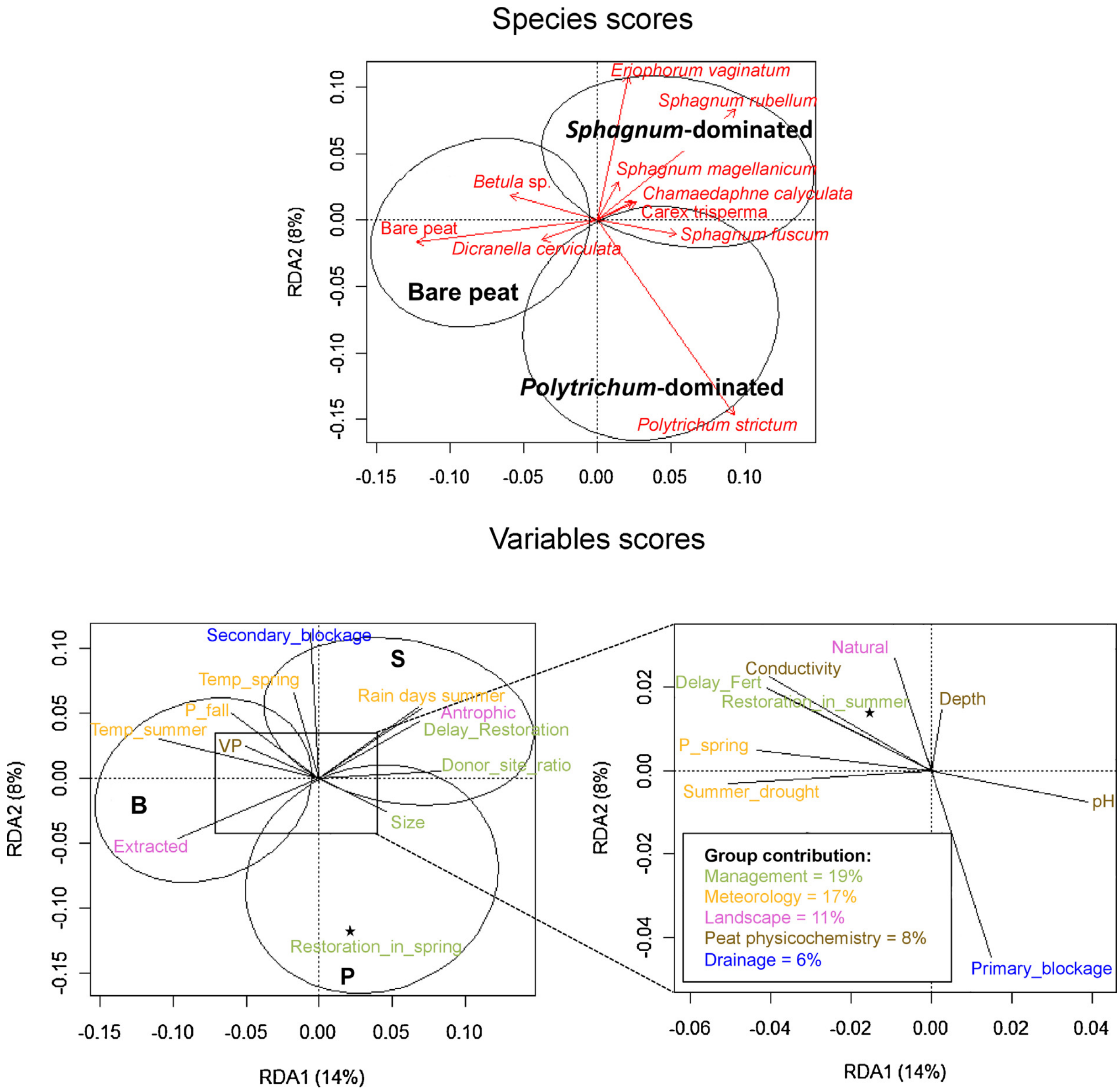

Fig. 3. RDA triplot (scaling = 1) for the 246 plots distributed across 53 restored bogs in eastern Canada. Species and variables scores were scaled by dividing by 20 and 7, respectively. A total of 87 species plus bare peat were identified, but only the 10 with the highest scores are represented. The groups obtained by *k*-means partitioning are represented by ellipses that include 90% of the plots belonging to each category. The contribution of each group of variables was the adjusted r^2 of respective RDAs implemented for each group of variables and, therefore, includes independent and shared explained variance. To improve the visual clarity of the variables scores graph, variables with more and less importance in the model were divided into the lower left and lower right subplots of the figure, respectively. Stars represent the centroid of the sites that have the description "spring" or "summer"for season of restoration works.

three groups. These groups, defined in terms of species composition, reflected the following three classes of restoration status: *Sphagnum-dominated* (402 observations), *Bare peat-dominated* (359 observations); and *Polytrichum-dominated* (185 observations).

3.2. Factors controlling restoration outcomes

All five driver groups were significant in explaining plant community composition on the restored sites and were ranked, in decreasing order of importance, as follows: management > meteorology > landscape > peat physicochemistry > drainage ("Group contribution" in 'variables scores' graph, Fig. 3). *Bare peat-dominated* status was more common when the first summer following restoration was relatively warm, and where peat extraction occupied higher proportions of the surrounding land (left-hand side of RDA1 axis in 'variables scores' graph, Fig. 3). Higher donor site ratios (i.e., larger quantities of plant material introduced to the restored sector), within the range 1:5 to 1:15, were more commonly associated with better vegetation establishment (right-hand side of RDA1 axis in 'variables scores' graph, Fig. 3). Among plots that had been colonised by typical bog vegetation, *Sphagnum-dominated* observations were distinguished from *Polytrichum-dominated* observations mainly by the former having more effective blockage of secondary ditches and by the latter being restored in spring (extremes of RDA2 axis in 'variables scores' graph, Fig. 3). Higher precipitation in autumn and summer (the latter expressed as number of rain days) and higher temperatures in spring seemed to favour the *Sphagnum-dominated* over the *Polytrichum-dominated* restoration outcome.

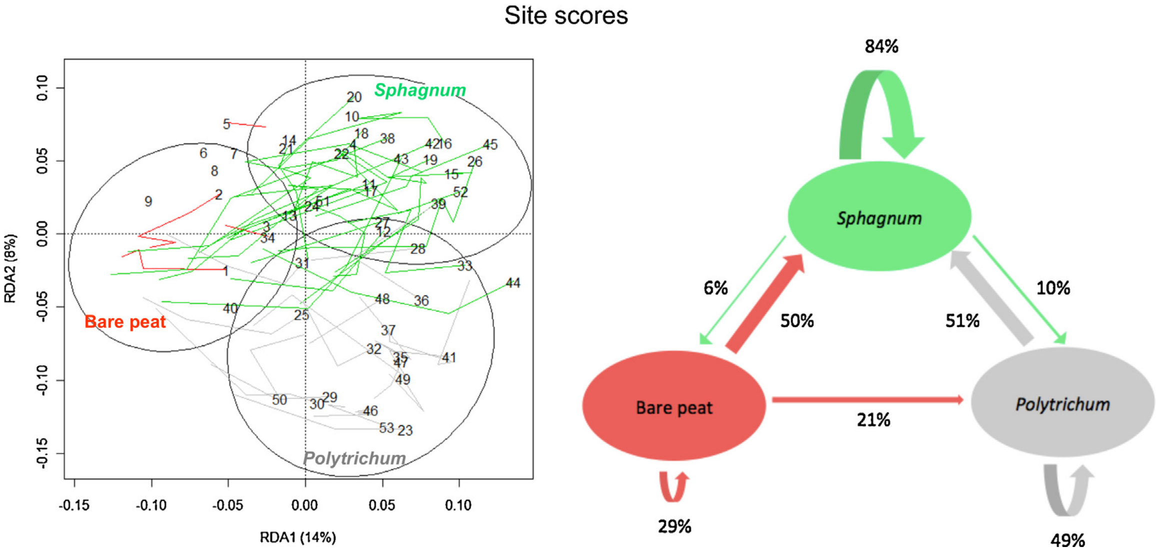

Fig. 4. RDA site scores (scaling = 1) for the 246 plots distributed across 53 restored bogs in eastern Canada. Left – trajectories of restored sectors over time. To improve the visual clarity of the diagrams, only the centroid (site score mean) for each restored sector was drawn; each line indicates the temporal trajectory of a sector, with colours representing the success category of the most recent observation and the sector code indicating its final position in the canonical space. The groups obtained by *k*-means partitioning are represented by ellipses that include 90% of the plots belonging to each category. Right – percentage of permanent plots changing success category membership from the first to the most recent observation. Arrows were drawn proportional to the percentages; note that success reversal (green arrows) was rarely observed.

3.3. Temporal changes of vegetation in restored peatlands

Even though the differences between sectors outweighed time since restoration in determining species composition, the vegetation in the plots exhibited some changes between successive observations. In fact, the number of years after restoration explained 4.7% of the variability of the Hellinger transformed vegetation matrix (RDA not shown, $F = 46.148$, $P < 0.001$). Plots generally moved rightwards along the first RDA gradient (RDA1 of 'site scores' graph, left of Fig. 4), that is, from *Bare peat-dominated* into either of the other two categories. Indeed, of the 146 plots that were classified as *Bare peat-dominated* in the third year after restoration, 50% later changed to *Sphagnum-dominated* and 21% to *Polytrichum-dominated*, so that only 43 were still classified as *Bare peat-dominated* in the final year of survey (right of Fig. 4). Conversely, only two of the 75 plots that were *Sphagnum-dominated* or *Polytrichum-dominated* at the first observation had evolved to *Bare peat-dominated* by the end of the monitoring period. Sectors evolved less dramatically along RDA2. Half of the 43 plots initially defined as *Polytrichum-dominated* had changed to *Sphagnum-dominated* by the final year of survey, and 84% of the 32 plots initially classified as *Sphagnum-dominated* retained this status at the end of the observation period (RDA2 of 'site scores' graph in Fig. 4). Nevertheless, sectors exhibited a tendency to move upwards along RDA2. As a result, the number of *Sphagnum-dominated* plots in the last year of survey was 134, which is almost three times the number of either *Bare peat-dominated* (54) or *Polytrichum-dominated* (58) plots at that stage (Table 1). The changes of vascular and non-vascular plant cover in the 246 plots, categorised according to the most recent observations, is summarised in Fig. 5. In *Sphagnum-dominated* plots, *Sphagnum* species covered almost 50% of the peat surface 9–10 years after restoration and this, in conjunction with the vigorous development of herb (23%) and shrub (22%) cover, reduced bare peat to only 13%. In *Polytrichum-dominated* plots, bryophytes other than *Sphagnum* dominated the moss carpet and occupied more than half of the peat surface. However, because vascular plants developed poorly in this group, almost one third of the peat surface was still devoid of vegetation 9–10 years after completion of the restoration work. In *Bare peat-dominated* plots, more than 10% cover was rarely attained by any plant stratum, and bare peat cover remained high (~60%) and stable across the years.

4. Discussion

4.1. Multifactorial control of restoration success

Success in restoration of bogs after horticultural peat extraction (i.e., recovery of a *Sphagnum* carpet, González et al., 2013a, in press) is controlled by a combination of factors. Considering these in groups, the most important role is assigned to management of the restoration procedure (Group contribution of 19% in 'variables scores' graph, Fig. 3). This highlights the skill of the practitioner as an essential ingredient of a successful restoration project (Boudreau and Rochefort, 2008). For example, simple decisions such as the quantity of plant material to spread on the restoration site (donor site ratio) and the season in which restoration work is carried out, which we interpret as a proxy for ground wetness, can substantially influence the eventual outcome. We observed here that small deviations from this the optimum donor site ratio of 1:10 (Rochefort et al., 2003) down to 1:12 or 1:15 can negatively affect the degree of success achieved. Restoring in spring may favour the development of *P. strictum* moss carpets because this species, unlike *Sphagnum*, grows well in the singular microtopography that is created by heavy machinery operating on the wet peat surfaces that are encountered most consistently during the snowmelt period in spring. Tire tracks (in the order of 20 cm or more deep) drain enough water to impede *Sphagnum* establishment (Price et al., 1998) by causing slight drying of the peat surface, especially at the uppermost edges of ruts, which makes it most suitable for colonisation by *P. strictum* (Rochefort, field observations). Our results showed that the delayed application of phosphorus also contributed to averting restoration failure whilst favouring *P. strictum* development ("Delay_Fertilization" pointing upwards to the left in the 'variables scores' graph, Fig. 3), but the correlation of this factor with the main gradients of plant community composition was weaker than expected. Moreover, it may be unsound to invoke a causal relationship with vegetation development because

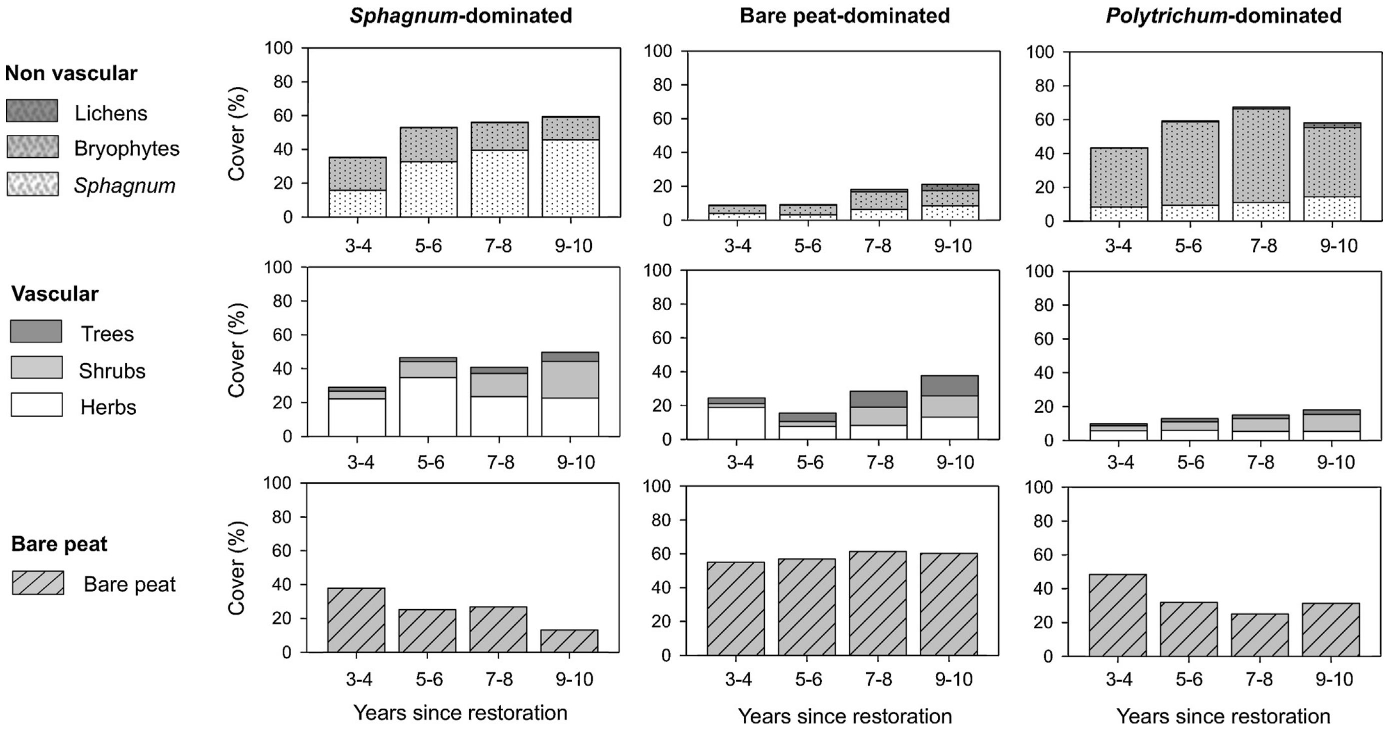

Fig. 5. Temporal changes of vascular and non-vascular plant cover, and % bare peat, on *Sphagnum-dominated* (134 plots), bare peat-dominated (54 plots) and *Polytrichum*-dominated (58 plots) restored peatlands. For this analysis, plots were assigned to the categories indicated by *k*-means partitioning at the most recent vegetation survey. Data collected more than 10 years after restoration are not shown because there were few samples (only 27 plots on 6 peatlands) (Table 1). 'Bryophytes' indicates bryophytes belonging to genera other than *Sphagnum*.

phosphorus was frequently applied a posteriori in locations where restoration had resulted in bare peat prevalence.

As expected, meteorological factors during the first growing season after restoration also notably influenced the outcome of restoration (Group contribution of 17% in 'variables scores' graph, Fig. 3). As noted by Chirino et al. (2006), warm weather during the year when propagules were introduced did not favour recolonisation by plants. Higher spring and, especially, summer temperatures ("Temp_spring" and "Temp_summer" in Fig. 3), which were positively correlated with summer droughts (Spearman correlation coefficient = 0.39, $P < 0.001$), were most closely associated with *Bare peat-dominated* restoration status; presumably due to reduced air humidity, which must be maintained at high levels for successful establishment of newly introduced moss fragments (Rochefort and Lode, 2006). Higher autumn precipitation totals and more frequent summer rainfall were both associated with better performance of *Sphagnum* relative to *P. strictum* ('variables scores' graph, Fig. 3). This is consistent with the results of Chirino et al. (2006), who highlighted the importance of both the quantity of precipitation and its homogeneous distribution through time for developing *Sphagnum* moss carpets.

Drainage as a group of factors contributed less (6%) to the model than we initially expected. However, drainage included the factor that correlated most strongly with the second main gradient of vegetation variability, in that more complete blockage of secondary ditches greatly favoured *Sphagnum* over *P. strictum* ('variables scores' graph, Fig. 3) and, thus, successful restoration. Although further detailed studies are needed to clarify the effects of ditch blocking on the surface water balances of restored sectors, our direct assessments of secondary ditch blockage correlated rather well with our 'blockage effectiveness' observations, which reflected the spatial homogeneity of signs of flooding (Spearman correlation coefficient = 0.71, $P < 0.001$). In general, well-blocked secondary ditches promoted more homogeneous re-wetting, and this in turn resulted in the development of more extensive *Sphagnum* carpets. Surprisingly, however, better blockage of the primary ditches did not especially favour the establishment of moss carpets ('variables scores' graph, Fig. 3) and was not associated with effective re-wetting of the sectors (Spearman correlation coefficient = −0.32, $P < 0.001$). A plausible explanation for this apparent paradox may arise from the fact that a requirement for drainage to support ongoing peat extraction on adjacent and upstream peat fields often continues after a specific sector has been abandoned and restored. Although the drainage network is usually re-designed to accommodate the restoration, it must frequently still be routed past the restored sector (upper and left sides of the sector, Fig. 2). Our finding that one of the most important variables in explaining bare peat prevalence in restoration is the proportion of land subject to peat extraction in the surroundings of restored sectors (left-hand side of RDA1 axis in 'variables scores' graph, Fig. 3) is consistent with the hypothesis of active drains in adjacent peat extractions counteracting primary blockage in restored sectors. For future studies we recommend that hydrological processes in restored bogs should be monitored more systematically, for example using submersible pressure transducers that can register water level on a continuous basis, as we believe that hydrology is likely to play a much more important role in controlling vegetation establishment than we were able to demonstrate in this study.

In addition to the possible contribution of drainage serving sectors to the failure of restoration projects, ongoing peat extraction nearby could be interacting negatively with the establishment of bryophytes in ways that were not investigated in this study. For example, through deposition of windblown dry peat (Faubert and Rochefort, 2002), reduced supply of plant propagules (Poulin et al., 1999), etc. For these reasons, and also because our analysis links longer delays between abandonment of peat extraction units and restoration with more successful establishment of *Sphagnum* (right-hand side of RDA1 in 'variables scores' graph, Fig. 3), we recommend that practitioners should, in future, consider delaying the implementation of single-sector restoration projects until it becomes practical to restore a larger multi-sector area that can be managed as a discrete hydrological unit. Support for this suggestion is provided by Girard et al. (2002), who observed that large abandoned sectors re-vegetated more readily because better re-wetting was achieved than on small sectors surrounded by active peat fields. Accordingly, they concluded that it is preferable to cease peat extraction activities simultaneously across large areas. Although the correlation was weak, we also noted that larger sectors were more strongly associated with *Sphagnum-dominated* restoration than were smaller ones ("Size" in 'variables scores' graph, Fig. 3).

4.2. Lessons learned from the long-term monitoring of vegetation in restored bogs

Succession in restored peatlands is slow (Haapalehto et al., 2011). However, we observed substantial changes in plant communities over the relatively short recovery period considered in this study (~10 years; Figs. 4 and 5). The main temporal trend recorded was a decline in the extent of bare peat as vegetation developed. This caused 71% of the plots that were initially classified as *Bare peat-dominated* to change to *Sphagnum-dominated* and *Polytrichum-dominated* over subsequent years (Fig. 4). In fact, we believe that most of the *Bare peat-dominated* observations during the early years following restoration (~60% of plots after 3 years, ~40% of plots after 5 years) were classified in this way simply because insufficient time had elapsed for the vegetation to develop. According to this hypothesis, in many cases our *Bare peat-dominated* category would be only a temporary state within the framework of a longer successional trajectory. Indeed, detailed monitoring of vegetation recovery in a whole-ecosystem experiment (Bois-des-Bel peatland; Rochefort et al., 2013) showed that, although *Polytrichum* was the dominant moss 2–4 years after restoration, it was superseded in this role by *Sphagnum* when 6–8 post-restoration years had elapsed. The next problem is that some plots will move to a different restoration status more slowly than others, and this raises the question of when is the best time to evaluate success. The work of Rochefort et al. (2013) indicated that evaluation should be delayed until a decade or more post-restoration and, at that stage, success in achieving goals should be measured against regional reference ecosystems (Poulin et al., 2012; Rochefort et al., 2013). Considering structural attributes, however, Pouliot et al. (2011) found that a minimum period of 10–30 years is required for the recovery of typical hollow-hummock microtopography on restored cutover bogs. On the other hand, practitioners need to evaluate success shortly (≤5 years in eastern Canada) after project implementation, either for environmental certification or to meet legislative obligations. As restoration is, essentially, the acceleration of natural succession (Walker et al., 2007), we think that it is legitimate to regard "early" *Bare peat-dominated* cases as truly failed restoration experiments, even if they represent a temporary state of affairs. On this basis, failure would be defined as the absence of the desired vegetation after an agreed minimum period has elapsed post-restoration. In this study, similarities in the vegetation matrix between years increased with time; in other words, the rate of vegetation change declined dramatically between successive observations (data not shown, but see Fig. 5). Similarly, at the Bois-des-Bel peatland, Rochefort et al. (2013) observed that the cover of different species and plant strata did not stabilise until approximately six years post-restoration. Therefore, we suggest that success in bog restoration should not be definitively evaluated until at least five years after project implementation. This recommendation does not exclude the possibility that success might be predicted earlier on the basis of retrospective analyses of the vegetation records assigned to each success category. For example, using data collected from 34 bog sectors, González et al. (2013a, in press) have identified indicator species and key environmental and management factors that could have been used to anticipate the success of restoration in the third year after project implementation. This approach would allow practitioners to evaluate success and identify needs for adaptive management at a relatively early stage.

Important conclusions to inform future restoration strategies may also be drawn from the observed temporal changes of restored sites along the second gradient of vegetation variability (RDA2). Plots that were initially classified as *Polytrichum-dominated* were more resistant to changes towards another category than were *Bare peat-dominated* examples, but half of them had changed to *Sphagnum-dominated* status by the time of the last vegetation survey (Fig. 4). A *Polytrichum-dominated* to *Sphagnum-dominated* transition fits well with the role of *P. strictum* as a nurse species for *Sphagnum* establishment that is already described in the literature (Groeneveld and Rochefort, 2002; Groeneveld et al., 2007). Recent work suggests that this nursing function can operate only below some time-varying thresholds of *P. strictum* cover, for example, ~30% in the third year post-restoration (34 restored sites across eastern Canada including Bois-des-Bel, González et al., 2013a). In any case, once these thresholds are exceeded, we regard the *Polytrichum-dominated* condition as an alternative stable state (*sensu* Beisner et al., 2003). If the goal of applying the moss layer transfer technique is always to achieve *Sphagnum* abundance similar to that in regional reference ecosystems, *Polytrichum-dominated* status might be classified as a second category of 'Failed' outcome, indicating a requirement for additional human intervention to accelerate the development of the desired *Sphagnum* carpet. On the other hand, it might be viewed as a successful outcome if the goal is to stabilise the bare peat surface in order to prevent erosion and sedimentation of water bodies, or as the first step in establishing an alternative use of the peatland such as cranberry production or plantation forestry.

Even though a variety of failures occurred, the moss layer transfer technique led to successful ecological restoration in most cases, specifically in 54% of the plots at the times of the most recent vegetation surveys (51% of the sectors had the majority of their plots classified as successful, Table 1). Moreover, the assessment of successional trajectories showed a tendency for this percentage to increase over the years and that, once established, a trajectory of *Sphagnum* colonisation and development was rarely diverted (see Fig. 4). These are promising results towards endorsing the moss layer transfer technique as a method for enhancing the recovery of *Sphagnum-dominated* ecosystems whose long-term peat accumulation function will eventually resume. With careful management of the variables controlling restoration success identified in this study, the prospect of developing a capability to systematically achieve ecological restoration of extracted peat bogs looks increasingly realistic.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2014.03.051.

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Appendix A. Hydrological and peat physicochemical characteristics of the restored sectors. See Materials and Methods for explanation of variables. Missing data in some sectors were replaced with the median value of all sectors to perform RDA analyses. EC - Peat electrical conductivity, VP – von Post peat decomposition (H) index. N.D.=no data

			Hydrology			Peat physicochemistry			
Sector code	Bog	Restoration year	Primary blockage	Secondary blockage	Blockage effectiveness	EC (µS cm^{-1})	pH	VP	Depth (cm)
Atlantic region									
1	Baie-Sainte-Anne	2000	3	4	3	199	3.2	3	72
2	Inkerman Ferry	1997	2	4	4	69	3.5	5	250
3	Inkerman Ferry	2008	1	4	1	98	4.2	5	250
4	Kent	2001	3	3	5	177	3.2	4	74
5	Kent	2007	3	4	5	145	3.1	3	128
6	Kent	2008	3	2	2	32	3.8	5	91
7	Kent	2008	1	4	2	13	3.8	5	149
8	Kent	2008	1	1	1	0	3.2	5	89
9	Kent	2008	1	1	1	0	3.4	5	50
10	Kent	2008	4	4	1	0	3.3	4	33
11	Maisonnette	2000	4	3	3	279	3.1	5	53
12	Maisonnette	2006	3	4	4	184	2.8	4	27
13	Pokesudie	2006	3	4	5	201	3.4	2	140
14	Pokesudie	2008	2	4	4	80	4.2	4	224
Lowland of Great Lakes / St. Lawrence region									
15	Bois des Bel	2000	3	4	4	91	3.5	4	203
16	Chemin du Lac	1995	2	4	4	55	4.6	7	63
17	Chemin du Lac	1997	2	4	4	56	3.7	5	63
18	Chemin du Lac	1999	1	4	4	69	4.0	4	87
19	Chemin du Lac	2000	1	4	4	151	3.2	4	105
20	Chemin du Lac	2001	1	4	4	160	3.4	4	70
21	Chemin du Lac	2002	2	4	3	0	3.5	6	75
22	Chemin du Lac	2003	3	4	3	59	4.2	5	111
23	Pointe-Lebel	2004	2	3	1	49	3.7	5	50
24	Saint-Charles-de-Bellechasse	1999	1	2	1	63	3.8	4	65
25	Saint-Modeste	1997	4	4	2	67	4.0	5	94
26	Saint-Modeste	1997	4	4	2	67	4.0	5	99
27	Verbois	2005	4	4	4	0	3.8	5	91
28	Verbois	2006	4	4	5	80	3.8	4	61
Inland of Northeastern Forest region									
29	Sainte-Marguerite (Section A)	1994	4	1	1	83	3.9	3	205
30	Sainte-Marguerite (Section A)	1995	4	1	1	83	3.9	3	179
31	Sainte-Marguerite (Section B)	1995	3	1	1	89	3.9	4	156
32	Sainte-Marguerite (Section B)	1996	3	1	1	89	3.9	4	165
33	Sainte-Marguerite (Section H)	1997	4	2	2	0	4.7	3	188
34	Sainte-Marguerite (Section H)	1998	4	2	2	0	3.4	4	193
35	Sainte-Marguerite (Section AA)	1999	4	1	1	83	4.2	4	123
36	Sainte-Marguerite (Section H)	1999	4	2	2	78	4.5	3	202
37	Sainte-Marguerite (Section AA)	2000	4	1	1	108	3.8	4	116
38	Sainte-Marguerite (Section E)	2000	3	4	5	0	3.4	3	138
39	Sainte-Marguerite (Section K)	2000	4	2	4	83	3.7	2	150
40	Sainte-Marguerite (Section L)	2000	1	2	4	83	3.7	2	150
41	Sainte-Marguerite (Section AA)	2001	4	1	1	27	3.9	4	104
42	Sainte-Marguerite (Section E)	2001	4	3	3	0	3.5	3	N.D.

43	Sainte-Marguerite (Section G)	2001	3	N.D.	N.D.	0	3.1	2	150
44	Sainte-Marguerite (Section K)	2001	1	3	3	83	3.7	2	150
45	Sainte-Marguerite (Section L)	2001	1	2	3	83	3.7	2	150
46	Sainte-Marguerite (Section AA)	2002	4	1	1	0	3.6	4	116
47	Sainte-Marguerite (Section H)	2002	1	3	4	0	3.3	3	187
48	Sainte-Marguerite (Section J)	2002	3	2	3	90	4.7	2	150
49	Sainte-Marguerite (Section AA)	2003	4	1	1	0	3.4	4	112
50	Sainte-Marguerite (Section DD)	2003	1	1	1	0	3.2	3	152
51	Sainte-Marguerite (Section F)	2003	4	2	3	0	3.1	3	110
52	Sainte-Marguerite (Section L)	2003	1	3	3	83	3.7	3	241
53	Sainte-Marguerite (Section AA)	2004	4	1	1	0	3.6	4	139

Appendix B. Meteorological variables for the first growing season after restoration; i.e., for the same year as restoration works if implemented in spring or summer, and for the following year if the sector was restored in autumn. See Materials and Methods for explanation of variables. Missing data in some sectors were replaced with the median value of all sectors to perform RDA analyses. N.D.=no data

					Temperature (ºC)			Precipitation						
Sector code	Bog	Restoration year	Station	Distance from sector (km)	Spring (May–Jun)	Summer (Jly–Aug)	Autumn (Sep–Oct)	Spring (mm)	Summer (mm)	Autumn (mm)	Rain days (year)	Rain days (summer)	Effective rain days (summer)	Longest effective drought (days)
Atlantic region														
1	Baie-Sainte-Anne	2000	Kouchibouguac	44	14.7	20.1	12.7	240	137	136	72	23	11	23
2	Inkerman Ferry	1997	Bas Caraquet	22	12.6	18.7	10.8	217	183	212	99	30	14	14
3	Inkerman Ferry	2008	Bas Caraquet	22	11.4	18.0	9.8	226	135	254	88	31	13	16
4	Kent	2001	Moncton	74	12.1	18.4	10.4	173	162	243	85	23	14	12
5	Kent	2007	Moncton	74	12.6	19.3	10.6	191	181	204	101	33	18	14
6	Kent	2008	Moncton	74	13.3	18.7	9.4	206	326	310	96	33	20	13
7	Kent	2008	Moncton	74	13.3	18.7	9.4	206	326	310	96	33	20	13
8	Kent	2008	Moncton	74	13.3	18.7	9.4	206	326	310	96	33	20	13
9	Kent	2008	Moncton	74	13.3	18.7	9.4	206	326	310	96	33	20	13
10	Kent	2008	Moncton	74	13.3	18.7	9.4	206	326	310	96	33	20	13
11	Maisonnette	2000	Bas Caraquet	32	13.8	19.7	12.8	145	114	191	60	21	16	17
12	Maisonnette	2006	Bas Caraquet	32	11.3	18.0	11.3	119	201	190	66	27	19	9
13	Pokesudie	2006	Bas Caraquet	9	11.3	18.0	11.3	119	201	190	66	27	19	9
14	Pokesudie	2008	Bas Caraquet	9	11.4	18.0	9.8	226	135	254	88	31	13	16
Lowland of Great Lakes / St. Lawrence region														
15	Bois des Bel	2000	Rivière du Loup	30	13.2	17.1	10.4	N.D.	195	N.D.	N.D.	33	15	13
16	Chemin du Lac	1995	Rivière du Loup	13	12.1	16.1	7.8	88	296	163	81	28	20	14
17	Chemin du Lac	1997	Rivière du Loup	13	11.3	16.7	8.8	115	148	151	88	27	14	18
18	Chemin du Lac	1999	Rivière du Loup	13	11.1	16.6	8.1	95	181	98	72	28	21	9
19	Chemin du Lac	2000	Rivière du Loup	13	13.2	17.1	10.4	N.D.	195	N.D.	N.D.	33	15	13
20	Chemin du Lac	2001	Rivière du Loup	13	10.9	17.6	8.6	109	95	N.D.	N.D.	29	15	25
21	Chemin du Lac	2002	Rivière du Loup	13	11.9	16.5	10.0	96	204	N.D.	N.D.	35	20	7

22	Chemin du Lac	2003	Rivière du Loup	13	10.5	16.8	9.4	662	669	260	127	46	39	7
23	Pointe-Lebel	2004	Baie Comeau	23	8.9	16.3	8.8	162	212	110	76	28	21	10
24	Saint-Charles-de-Bellechasse	1999	Honfleur	28	12.6	17.5	8.5	280	176	125	78	28	22	10
25	Saint-Modeste	1997	Rivière du Loup	11	11.3	16.7	8.8	115	148	151	88	27	14	18
26	Saint-Modeste	1997	Rivière du Loup	11	11.3	16.7	8.8	115	148	151	88	27	14	18
27	Verbois	2005	Rivière du Loup	12	13.1	16.8	8.7	183	118	256	105	35	16	12
28	Verbois	2006	Rivière du Loup	12	12.1	16.7	10.4	141	284	224	85	37	15	12
Inland of Northeastern Forest region														
29	Sainte-Marguerite (Section A)	1994	Normandin	52	11.8	14.4	8.5	186	109	93	93	15	10	N.D.
30	Sainte-Marguerite (Section A)	1995	Normandin	52	11.8	17.4	8.0	189	77	126	74	20	10	14
31	Sainte-Marguerite (Section B)	1995	Normandin	52	11.8	17.4	8.0	189	77	126	74	20	10	14
32	Sainte-Marguerite (Section B)	1996	Normandin	52	11.5	16.5	8.0	136	250	224	92	38	23	8
33	Sainte-Marguerite (Section H)	1997	Normandin	52	10.6	16.1	7.6	142	173	139	86	30	16	14
34	Sainte-Marguerite (Section H)	1998	Normandin	52	13.9	16.4	8.3	N.D.	105	107	N.D.	23	15	13
35	Sainte-Marguerite (Section AA)	1999	Normandin	52	14.4	16.3	8.8	121	272	180	75	31	25	14
36	Sainte-Marguerite (Section H)	1999	Normandin	52	10.6	16.0	7.1	135	135	97	73	27	19	10
37	Sainte-Marguerite (Section AA)	2000	Normandin	52	10.6	16.0	7.1	135	135	97	73	27	19	10
38	Sainte-Marguerite (Section E)	2000	Normandin	52	13.7	16.7	9.0	106	210	185	84	28	23	17
39	Sainte-Marguerite (Section K)	2000	Normandin	52	13.7	16.7	9.0	106	210	185	84	28	23	17
40	Sainte-Marguerite (Section L)	2000	Normandin	52	13.7	16.7	9.0	106	210	185	84	28	23	17
41	Sainte-Marguerite (Section AA)	2001	Normandin	52	13.7	16.7	9.0	106	210	185	84	28	23	17
42	Sainte-Marguerite (Section E)	2001	Normandin	52	13.7	16.7	9.0	106	210	185	84	28	23	17
43	Sainte-Marguerite (Section G)	2001	Normandin	52	13.7	16.7	9.0	106	210	185	84	28	23	17
44	Sainte-Marguerite (Section K)	2001	Normandin	52	10.2	17.2	7.1	155	140	109	78	27	20	13
45	Sainte-Marguerite (Section L)	2001	Normandin	52	10.2	17.2	7.1	155	140	109	78	27	20	13
46	Sainte-Marguerite (Section AA)	2002	Normandin	52	10.2	17.2	7.1	155	140	109	78	27	20	13
47	Sainte-Marguerite (Section H)	2002	Normandin	52	12.6	16.7	8.3	68	159	210	69	26	17	19
48	Sainte-Marguerite (Section J)	2002	Normandin	52	12.6	16.7	8.3	68	159	210	69	26	17	19
49	Sainte-Marguerite (Section AA)	2003	Normandin	52	12.6	16.7	8.3	68	159	210	69	26	17	19
50	Sainte-Marguerite (Section DD)	2003	Normandin	52	9.3	16.2	8.3	197	142	128	78	31	26	9
51	Sainte-Marguerite (Section F)	2003	Normandin	52	12.6	16.7	8.3	68	159	210	69	26	17	19
52	Sainte-Marguerite (Section L)	2003	Normandin	52	12.6	16.7	8.3	68	159	210	69	26	17	19
53	Sainte-Marguerite (Section AA)	2004	Normandin	52	9.3	16.2	8.3	197	142	128	78	31	26	9

Appendix C. Data relating to the management of restoration works and human use of the land adjacent to the restored sectors. See Materials and Methods for explanation of variables. Missing data in some sectors were replaced with the median value of all sectors to perform RDA analyses. N.D.=no data

			Management					Landscape				
Sector code	Bog	Restoration year	Season of restoration works	Delay in restoration (years)	Sector size (ha)	Ratio Donor:Restored	Delay in P fertilisation (years)	Natural (%)	Extracted (%)	Restored (%)	Abandoned (%)	Anthropic (%)
Atlantic region												
1	Baie-Sainte-Anne	2000	Autumn	1	12	1 : 12	5	43	37	0	0	20
2	Inkerman Ferry	1997	Autumn	11	3	1 : 15	1	50	26	6	0	18
3	Inkerman Ferry	2008	Autumn	N.D.	7	1 : 10	5	41	49	3	0	7
4	Kent	2001	Autumn	3	5	1 : 15	0	44	25	18	13	0
5	Kent	2007	Summer	9	8	1 : 12	5	52	15	13	20	0
6	Kent	2008	Summer	6	7	N.D.	5	29	40	18	13	0
7	Kent	2008	Summer	13	4	N.D.	5	55	22	12	11	0
8	Kent	2008	Summer	21	2	N.D.	5	42	36	10	7	6

9	Kent	2008	Summer	21	3	N.D.	5	39	32	16	13	0
10	Kent	2008	Summer	1	7	N.D.	5	28	44	20	8	0
11	Maisonnette	2000	Autumn	0	11	1 : 10	2	64	30	2	3	2
12	Maisonnette	2006	Autumn	3	9	1 : 5	0	60	28	7	2	2
13	Pokesudie	2006	Autumn	6	14	1 : 15	0	63	0	5	32	0
14	Pokesudie	2008	Autumn	7	9	1 : 12	0	80	0	13	7	0
Lowland of Great Lakes / St. Lawrence region												
15	Bois des Bel	2000	Autumn	19	12	1 : 10	0	54	0	0	3	44
16	Chemin du Lac	1995	Autumn	5	4	1 : 10	4	42	27	8	20	3
17	Chemin du Lac	1997	Autumn	5	3	1 : 10	2	29	27	24	7	13
18	Chemin du Lac	1999	Autumn	7	1	1 : 5	5	31	19	25	4	20
19	Chemin du Lac	2000	Autumn	8	2	1 : 10	5	29	19	28	4	20
20	Chemin du Lac	2001	Autumn	9	3	1 : 10	5	34	16	27	3	20
21	Chemin du Lac	2002	Autumn	3	5	1 : 10	5	34	30	24	11	1
22	Chemin du Lac	2003	Autumn	4	11	1 : 10	5	36	23	21	0	21
23	Pointe-Lebel	2004	Spring	6	4	1 : 10	0	63	34	0	1	2
24	Saint-Charles-de-Bellechasse	1999	Autumn	23	1	1 : 10	0	60	30	0	4	6
25	Saint-Modeste	1997	Autumn	10	1	1 : 10	5	44	15	2	39	0
26	Saint-Modeste	1997	Autumn	10	1	1 : 10	0	44	15	2	39	0
27	Verbois	2005	Autumn	7	9	1 : 10	5	21	11	5	56	7
28	Verbois	2006	Autumn	7	7	1 : 10	5	33	1	7	45	14
Inland of Northeastern Forest region												
29	Sainte-Marguerite (Section A)	1994	Spring	N.D.	6	1 : 15	5	6	42	51	0	0
30	Sainte-Marguerite (Section A)	1995	Spring	N.D.	6	1 : 12	5	6	42	51	0	0
31	Sainte-Marguerite (Section B)	1995	Spring	N.D.	6	1 : 12	5	12	25	62	0	0
32	Sainte-Marguerite (Section B)	1996	Spring	N.D.	6	1 : 10	5	11	26	63	0	0
33	Sainte-Marguerite (Section H)	1997	Spring	0	2	1 : 10	5	31	12	57	0	0
34	Sainte-Marguerite (Section H)	1998	Spring	1	2	1 : 10	5	24	12	64	0	0
35	Sainte-Marguerite (Section AA)	1999	Spring	0	2	1 : 5	0	49	15	23	0	13
36	Sainte-Marguerite (Section H)	1999	Autumn	3	1	1 : 10	5	33	9	59	0	0
37	Sainte-Marguerite (Section AA)	2000	Spring	0	4	1 : 5	0	48	15	24	0	12
38	Sainte-Marguerite (Section E)	2000	Autumn	N.D.	15	1 : 12	0	20	14	66	0	0
39	Sainte-Marguerite (Section K)	2000	Spring	N.D.	10	1 : 12	0	12	19	68	0	0
40	Sainte-Marguerite (Section L)	2000	Autumn	N.D.	11	1 : 12	1	17	28	55	0	0
41	Sainte-Marguerite (Section AA)	2001	Spring	N.D.	10	1 : 12	0	46	17	26	0	11
42	Sainte-Marguerite (Section E)	2001	Spring	N.D.	10	1 : 12	0	43	9	45	0	2
43	Sainte-Marguerite (Section G)	2001	Spring	N.D.	10	1 : 12	0	34	9	54	0	2
44	Sainte-Marguerite (Section K)	2001	Autumn	N.D.	17	1 : 12	0	20	34	46	0	0
45	Sainte-Marguerite (Section L)	2001	Autumn	N.D.	17	1 : 12	0	11	52	37	0	0
46	Sainte-Marguerite (Section AA)	2002	Spring	N.D.	10	1 : 12	0	42	20	29	0	10
47	Sainte-Marguerite (Section H)	2002	Autumn	6	12	1 : 12	1	43	12	45	0	0
48	Sainte-Marguerite (Section J)	2002	Autumn	N.D.	27	1 : 12	5	31	21	48	0	0
49	Sainte-Marguerite (Section AA)	2003	Spring	N.D.	21	1 : 12	0	33	28	32	0	7
50	Sainte-Marguerite (Section DD)	2003	Summer	N.D.	30	1 : 12	0	32	10	58	0	0
51	Sainte-Marguerite (Section F)	2003	Spring	N.D.	15	1 : 12	0	44	4	40	0	12
52	Sainte-Marguerite (Section L)	2003	Spring	N.D.	1	1 : 12	0	11	52	37	0	0
53	Sainte-Marguerite (Section AA)	2004	Spring	N.D.	21	1 : 12	0	19	37	42	0	2