Declaring success in *Sphagnum* peatland restoration: Identifying outcomes from readily measurable vegetation descriptors

E. González and L. Rochefort

Peatland Ecology Research Group and Centre d'Études Nordiques, Université Laval, Québec, Canada

SUMMARY

Managers of restoration projects need readily applicable tools that give them an unequivocal declaration of success or failure based on primary goals that may vary according to different jurisdictions. We used restored extracted *Sphagnum* peatlands in Canada to illustrate how different types of plant communities assigned to different restoration outcomes can be identified from readily measurable descriptors. Vegetation was surveyed from 5–10 years after restoration at 2–3 year intervals in a total of 274 permanent plots in 66 restored peatlands located across 4500 km, from Alberta in the drier continental interior to the wetter maritime coastal province of New Brunswick. Plant community data were subjected to a k-means clustering that resulted in three restoration outcome categories. A linear discriminant analysis (LDA) model (the "declaration tool") correctly classified 91 % of the plots in a calibration database that included 75 % of the peatlands, and 93 % of the validation database (25 % of the peatlands), into the restoration outcome categories, using plant strata and number of years since restoration (only) as descriptors. The model includes classification functions that can be used to assign a new plot (not used to construct the model) to its restoration outcome category. We found that ~70 % of the severely degraded peatland is successfully regenerating towards the target plant community.

KEY WORDS: adaptive management, moss layer transfer technique, peat-accumulating, peat extraction

INTRODUCTION

Restoration of ecosystems is as complex as their nature. Outcomes can be multiple, often stochastic; and trajectories of change variable, rather unpredictable and open-ended (Hughes *et al.* 2005). However, to reclaim environmental down payment and fulfil legislation obligations, restoration practitioners need to assess the fate of restored ecosystems with unambiguous determinations of success and failure of their projects (Bernhardt *et al.* 2007, Suding 2011). Success is a nebulous part of the lexicon of restoration (Ruiz-Jaen & Aide 2005); target criteria can vary widely in both ambition and rationale, even among stakeholders within the same project. Ecological outcomes also differ from success related to economics, aesthetics, recreation, or education. Setting evaluation standards requires consensus among scientists, funding agencies and citizen groups. For managers to declare success unequivocally, science-based tools are needed (Bonnett *et al.* 2009). If these tools were based on simple, easily recognisable indicators such as the presence of a particular species or the abundance of a plant group, monitoring would be much easier to implement and the cost would be greatly reduced (Herrick *et al.* 2006). However, reducing the multi-dimensional nature of restored ecosystems to simplified estimators that give an unequivocal declaration of success is not a trivial task and can lead to bias in restoration evaluations if these are not properly integrated. In the context of *Sphagnum* peatland restoration, González *et al.* (2013) showed that, while it is possible to identify plant species that are significant indicators of three main plant categories (respectively dominated by *Sphagnum*, *Polytrichum strictum* which is another bryophyte typical of peatlands, and bare peat), variations in frequency and cover of these indicator species are very small between different plant categories, making it difficult to evaluate related restoration outcomes with certainty. In addition, managers must integrate abundance thresholds from many indicators, a complex task when species representing failure or success co-occur in the same site (Bachand *et al.* 2014). Integrating these factors into comprehensive models could facilitate the implementation of adaptive management strategies.

Multivariate analyses can be used effectively to develop integrative tools for evaluating restoration trajectories (i.e., change in plant community over time in this article) since they make it possible to synthesise environmental information, thereby explaining most system variability on fewer dimensions. González *et al.* (2014) combined indicator species, environmental and management variables through Linear Discriminant Analysis (LDA; Fisher 1936, Rao 1948, Rao 1952) to predict one of three dominating plant categories shortly after restoration of extracted *Sphagnum* peatlands. While their method succeeded in developing an analytical approach for unequivocally predicting restoration trajectory after restoration measures using readily measurable indicators, their model was restricted to an early prediction of restoration outcomes. That is, their tool served to predict the future outcome of restoration after the implementation of restoration works, not strictly to declare "success" at a certain time point over the process of ecosystem recovery. Restoration success can be defined *a priori* as the re-establishment of moss species typical of dominated *Sphagnum* peatlands known to have a good peat accumulation potential (Rochefort 2001). Likewise, Vitt *et al*. (2011) defines the return of degraded peatlands to an equivalent land capability as a return to peatland communities that are capable of sequestering carbon, a key function of peatland ecosystems directly related to peat accumulation. The central question of the present article is when to declare success post-restoration? The development of a simple and integrative predictive tool to describe the outcomes will be the main goal, not the drivers of succession in the various restoration sites.

In this work, we used an LDA model that served to declare success unequivocally by identifying the restoration outcomes in extracted and later restored *Sphagnum* peatlands from readily measurable vegetation descriptors, within a window of 5–10 years since restoration, and at the scale of an entire country encompassing diverse climatic and biogeographical regions (Canada). The restoration outcome categories themselves are discussed within different frameworks of performance.

METHODS

Study sites

The present analysis is based on more than 80 extracted peatlands that have been restored across Canada. Only 66 of them, which had been restored at least 5 years previously, were used for this study. They ranged in size from 1 to 39 ha. Restoration of an entire extracted peatland could take years. Hereafter we use the term "restoration site" to designate a sector of an extracted peatland that was restored within a given year; consequently under slightly different management actions and sometimes under widely different annual weather conditions. Restoration sites might be located 2–5 km apart within the same peatland complex or in different peatlands, and were distributed from the drier interior continental climate of Alberta (mean annual precipitation 400 mm) to the wetter more maritime climate of coastal New Brunswick (mean annual precipitation 1200 mm). More restoration sites were located in the east because of the longer history of peat extraction and restoration activities, with 11 sites in western Canada compared to 55 sites in eastern Canada (35 of the 55 sites were included by González *et al*. (2014) but with actualised recovery evaluations). Together, they stretch for more than 4500 km across the country.

The restoration sites were restored by the moss layer transfer technique, in the following steps: (1) re-shaping field topography to optimise rewetting; (2) spreading plant diaspores, including *Sphagnum* mosses previously collected from a donor site; (3) spreading straw mulch to protect diaspores by improving microclimatic conditions and preventing desiccation of plant fragments; (4) blocking drainage ditches; and (5) in some cases, fertilising with phosphorus to favour colonisation by *Polytrichum strictum* to 'nurse' *Sphagnum* mosses (Quinty & Rochefort 2003, Rochefort *et al.* 2003, Sottocornola *et al.* 2007, Graf & Rochefort 2016).

Post-restoration monitoring programme

Permanent 5 m × 5 m plots were established in each restoration site to document the evolution of the vegetation community after restoration. The number of plots differed (ranging from one to six) between restoration sites as a function of restored peatland size and heterogeneity of the establishing vegetation. A total of 274 permanent plots were monitored in the 66 restoration sites; thus, 50 % (135 of them) were not part of the database of González *et al*. (2014). Even though the plots are being surveyed during the autumn at 5, 7, 10, 15 and 20 years post-restoration, data collected eleven or more years since restoration were not used in this study in order to shorten the time window and thus reduce differences in the successional stage across restoration sites, peatlands and regions. Sites in western Canada, for example, were incorporated into the long-term monitoring programme later than the sites in eastern Canada.

In the permanent plots we first identified visually the total cover of vascular plant strata (trees and shrubs excluding ericaceous species, ericaceous shrubs, and herbs: forbs and graminoid plants), as well as bare peat and litter cover, on a seven-point scale: 0 = absent, 0.5 = present, 1 = 1–10 %, 2 = 11–25 %, 3 = 26–50 %, 4 = 51–75 % and 5 = 76–100 %. Vascular plants were then identified to species level (or assigned to a higher taxonomic level when this was impossible) and the ground covered by their vertical projection visually estimated within four 1 m × 1 m quadrats located systematically within each permanent plot. Cover of all bryophyte species and lichens was recorded in 12 quadrats of 25 cm × 25 cm that were also systematically distributed within each permanent plot. A total of 113 lichens, bryophytes and vascular plant species were recorded; 19 taxa were identified to the genus level or a higher taxon (Table 1).

Data processing and statistical analyses

To account for the fact that some peatland complexes and some regions were incorporated into the monitoring program later than others and to avoid temporal pseudo-replication, we first chose one year of monitoring among the 5–10 yr post-restoration time series at each restoration site by stratified random sampling, so that the years since restoration were equally distributed across all peatland complexes and regions. Plant cover values obtained within the quadrats were averaged for each permanent plot to create a database with one row per plot and one column per species plus ‘bare peat and litter’ (dimensions 274 × 133, range of years since restoration = 5–10).

Our analytical approach included two steps: (1) we classified each plot into different restoration outcome categories using the plant community data (including ‘bare peat and litter’); (2) we then searched for the combination of readily measurable vegetation descriptors - plant strata and time since restoration - that best predicted the restoration outcome categories.

(1) In the first step, to control for the effect of different numbers of years since restoration at the restoration sites chosen for analyses, a redundancy analysis (RDA) was run to remove the effect of years since restoration from the post 5–10 years plant composition matrix (González *et al*. 2014). Therefore, the RDA was run with only one explanatory variable “age”, and this accounted for differences in age between the various restoration sites and plots when assigning plant category. A Hellinger transformation was applied to species cover so that a Euclidean distance based method such as RDA (Legendre & Gallagher 2001) could be used. The significance of the RDA was assessed using a permutation test with 9999 randomised runs (Legendre & Legendre 2012). The residuals of the RDA were classified into k groups by a k-means partitioning technique. K-means partitioning is a non-hierarchical clustering method that finds a single partition of a set of objects such that the objects within each cluster are more similar to one another than to objects in the other clusters (Legendre & Legendre 2012). The number of clusters is determined *a priori* by the user. We chose a number that maximised the Calinski–Harabasz criterion (Milligan 1996). The species composition of each group was explored to assign a restoration outcome plant category to each of the obtained k groups. These restoration outcome categories were interpreted as more or less “successful” on the basis of how much they resembled desirable plant communities with the re-establishment of moss species typical of *Sphagnum* dominated peatlands known to have a good peat accumulation potential.

(2) We then conducted a linear discriminant analysis (LDA) to find the combination of readily measurable vegetation descriptors (plant strata and time since restoration, explained below) that best segregated restoration outcome categories. LDA is a method of linear modelling originally proposed by Fisher (1936) and developed by Rao (1948, 1952) that searches for the best combination of descriptors to discriminate among previously defined groups of observations. In our case, the plots in the restoration sites were treated as observations. The restoration outcomes categories defined after examining vegetation composition in the post 5–10 year vegetation matrix using the k-means partitioning corresponded to the plant groups.

One of the main advantages of LDA is that it makes it possible to allocate new objects to one of the groups by providing classification functions that are computed from the original descriptors (Legendre & Legendre 2012). Classification functions look like multiple regression equations, with a constant and a weight for each original descriptor, and are computed for each group. A classification score for each new object is calculated for each classification function. Then, the object is assigned to the group whose classification function gave the highest score. In our case, the LDA model, and particularly its classification functions, served as a tool to assign one - and only one - restoration outcome category to which a new restored plot from a new restoration site (not included in the 274 plots and 66 restoration sites used to build the model) belongs.

Since a higher number of observations than the number of descriptors plus the number of groups is recommended (Ter Braak 1987), our analysis included only a few readily measurable vegetation descriptors, namely total cover of (1) trees and shrubs excluding ericaceous species, (2) ericaceous shrubs, (3) herbs, (4) *Sphagnum* spp. and (5) *Polytrichum* spp. The first three descriptors were obtained from

Table 1. Median and range of plant strata, and frequency and mean cover when present (error is ± 1 SE) of all taxa identified in the 274 permanent plots on 66 restored peatlands clustered into three restoration outcome categories after k-means partitioning: (a) *Sphagnum*-cottongrass, (b) *Polytrichum*-*Sphagnum*, (c) Low cover-diverse peatland plants. Key species are highlighted in grey. *species not typical of peatland ecosystems. The a, b, and c categories are equivalent to the categories "Successful", "*Polytrichum*-dominated" and "Failed" of González *et al*. (2013, 2014) and to the categories "Successful", "*Polytrichum*-dominated" and "Bare peat-dominated" of González & Rochefort (2014).

	(a) *Sphagnum*-cottongrass (109 plots)		(b) *Polytrichum*-*Sphagnum* (78 plots)		(c) Low cover-diverse peatland plants (87 plots)	
Strata 0 = absent, 0.5 = present, 1 = 1–10 %, 2 = 11–25 %, 3 = 26–50 %, 4 = 51–75 % and 5 = 76–100 %	**Median**	**Range**	**Median**	**Range**	**Median**	**Range**
Bare peat and litter	1	0–5	2	0–3	4	2–5
Trees and shrubs excluding ericaceous species	1	0–3	0.5	0–3	0.5	0–4
Ericaceous shrubs	2	0.5–5	1	0.5–4	1	0–4
Herbs: forbs and graminoid plants	4	1–5	1	0–5	1	0.5–5
Species	**Freq.**	**Cover**	**Freq.**	**Cover**	**Freq.**	**Cover**
Total peatland species	100	106.7 ± 3.0	100	90.3 ± 3.0	100	30.6 ± 2.5
Richness (number of taxa)	16 ± 0		15 ± 1		10 ± 1	
Total non-peatland species	57	5.9 ± 1.0	55	2.9 ± 0.6	60	5.1 ± 0.9
All mosses	100	46.4 ± 2.4	100	68.2 ± 2.8	77	13.0 ± 1.5
Sphagnum	99	36.0 ± 2.2	96	23.4 ± 2.8	52	6.9 ± 1.4
Sub-genus *Acutifolia*	98	26.4 ± 1.9	94	20.9 ± 2.6	46	5.8 ± 1.2
Sphagnum flavicomans	*15*	*2.0 ± 0.5*	*5*	*1.6 ± 0.8*	*5*	*0.8 ± 0.6*
Sphagnum fuscum	*56*	*3.6 ± 0.5*	*69*	*6.7 ± 1.4*	*14*	*2.7 ± 1.2*
Sphagnum rubellum	*98*	*24.0 ± 1.8*	*90*	*16.2 ± 2.2*	*46*	*4.9 ± 1.1*
Sphagnum russowii	*4*	*0.8 ± 0.4*	*3*	*10.9 ± 10.8*	*0*	-

Species	**Freq.**	**Cover**		**Freq.**	**Cover**		**Freq.**	**Cover**
Sub-genus *Cuspidata*	54	3.1 ± 0.7		31	3.7 ± 1.8		9	6.0 ± 4.4
Sphagnum angustifolium	34	2.2 ± 0.6		31	3.7 ± 1.8		8	2.6 ± 1.5
Sphagnum cuspidatum	1	0.0 ± 0.0		0	-		0	-
Sphagnum fallax	28	3.4 ± 0.9		4	0.3 ± 0.2		3	9.9 ± 9.9
Sub-genus *Sphagnum*	97	8.3 ± 1.1		76	2.4 ± 0.7		30	1.2 ± 0.4
Sphagnum magellanicum	97	8.0 ± 1.0		76	2.4 ± 0.7		30	1.2 ± 0.4
Sphagnum papillosum	7	3.6 ± 2.2		0	-		0	-
Bryophytes other than *Sphagnum*	98	11 ± 1.1		100	45.6 ± 2.6		76	8.5 ± 1.1
Aulacomnium palustre	1	17.6 ± 0.0		3	0.3 ± 0.2		9	4.8 ± 3.1
Bryum species*	1	0.2 ± 0.0		1	2.8 ± 0.0		16	3.3 ± 1.0
*Campylium stellatum**	0	-		0	-		2	0.2 ± 0.0
*Ceratodon purpureus**	0	-		0	-		3	1.2 ± 0.6
Dicranella cerviculata	27	0.9 ± 0.2		44	1.7 ± 0.8		37	1.6 ± 0.4
Dicranum undulatum	0	-		1	0.2 ± 0.0		1	0.1 ± 0.0
Dicranum species	39	0.3 ± 0.1		40	1.8 ± 0.7		26	1.0 ± 0.3
Gymnocolea inflata	0	-		0	-		0	-
Hamatocaulis vernicosus	1	0.6 ± 0.0		0	-		1	1.2 ± 0.0
Hypnum lindbergii	0	-		0	-		1	2.1 ± 0.0
Leiomylia anomala	58	2.6 ± 0.5		56	3.1 ± 0.7		24	0.6 ± 0.1
Leptobryum pyriforme	1	1.5 ± 0.0		0	-		0	-
Marchantia polymorpha	1	4.3 ± 0.0		1	0.1 ± 0.0		6	1.7 ± 1.5
Hepatic other than *Leiomylia anomala*	35	1.6 ± 0.5		22	0.3 ± 0.1		13	0.5 ± 0.2
Palustriella falcate	1	0.3 ± 0.0		0	-		0	-
*Plagiomnium medium**	1	0.3 ± 0.0	-	0	-	-	0	-
Pleurozium schreberii	0	-	-	0	-	-	3	0.1 ± 0.0
Pohlia nutans	54	1.4 ± 0.7		74	1.2 ± 0.2		21	1.0 ± 0.4
Polytrichum strictum	85	8.6 ± 0.8		100	41.1 ± 2.6		54	7.3 ± 1.0
Polytrichum commune	5	1.2 ± 1.2		18	1.5 ± 0.8		3	1.3 ± 1.2
Sanionia uncinata	0	-		0	-		1	0.2 ± 0.0
*Thuidium recognitum**	0	-		0	-		1	3.4 ± 0.0
*Tomentypnum nitens**	0	-		0	-		1	2.1 ± 0.0

Species	Freq.	Cover	Freq.	Cover	Freq.	Cover
Lichens	38	0.5 ± 0.1	64	1.8 ± 0.6	39	2.4 ± 0.8
Cladonia species	20	0.6 ± 0.2	32	1.5 ± 0.7	25	0.8 ± 0.2
Lichens	34	0.2 ± 0.0	53	1.3 ± 0.5	32	2.2 ± 0.9
Herbs	100	44.1 ± 2.1	92	11.6 ± 1.5	100	13.5 ± 1.5
Agrostis species*	1	0.5 ± 0.0	6	0.3 ± 0.1	28	0.9 ± 0.5
Anaphalis margaritacea*	1	3.8 ± 0.0	3	0.6 ± 0.4	0	-
Beckmannia syzigachne*	0	-	0	-	2	0.1 ± 0.0
Bidens cernua*	0	-	0	-	7	0.4 ± 0.1
Bidens frondosa*	0	-	3	0.3 ± 0.2	0	-
Calamagrostis canadensis	1	0.3 ± 0.0	8	1.0 ± 0.6	2	0.5 ± 0.3
Carex aquatilis	1	2.5 ± 0.0	5	4.7 ± 0.8	2	3.9 ± 2.1
Carex brunnescens	1	1.5 ± 0.0	1	0.1 ± 0.0	8	22.2 ± 11.9
Carex canescens	6	5.8 ± 1.3	1	1.0 ± 0.0	1	1.3 ± 0.0
Carex disperma	0	-	1	0.5 ± 0.0	2	0.4 ± 0.1
Carex flava	0	-	0	-	1	0.3 ± 0.0
Carex hystericina*	0	-	0	-	1	1.3 ± 0.0
Carex limosa	0	-	1	0.5 ± 0.0	0	-
Carex magellanica	1	3.8 ± 0.0	1	2.5 ± 0.0	0	-
Carex oligosperma	14	6.8 ± 2.1	15	2.3 ± 0.8	18	3.8 ± 1.2
Carex rostrata	0	-	1	0.3 ± 0.0	0	-
Carex trisperma	8	3.8 ± 1.3	9	0.8 ± 0.4	1	0.5 ± 0.0
Carex utriculata	0	-	0	-	5	3.4 ± 2.5
Chamerion angustifolium	2	0.3 ± 0.2	8	1.3 ± 0.7	2	0.4 ± 0.3
Cirsium arvense*	0	-	0	-	2	0.9 ± 0.4
Coptis trifolia	1	0.1 ± 0.0	0	-	0	-
Drosera rotundifolia	39	0.3 ± 0.0	28	0.4 ± 0.0	18	0.4 ± 0.1
Eleocharis palustris	0	-	0	-	2	4.3 ± 3.8
Elymus trachycaulus*	0	-	0	-	1	0.3 ± 0.0
Epilobium canum*	0	-	1	0.9 ± 0.0	1	1.4 ± 0.0
Epilobium ciliatum*	0	-	0	-	1	0.3 ± 0.0
Epilobium ciliatum ssp. glandulosum*	0	-	0	-	1	0.1 ± 0.0
Equisetum arvense	3	12.3 ± 5.8	3	8.1 ± 3.9	1	0.5 ± 0.0
Eriophorum angustifolium	48	18.1 ± 3.1	6	2.6 ± 1.9	20	2.4 ± 0.6
Eriophorum vaginatum var. spissum	94	31.6 ± 2.0	79	7.5 ± 1.1	66	8.3 ± 1.4
Eriophorum virginicum	9	0.4 ± 0.1	15	2.9 ± 2.5	7	2.5 ± 1.0

Species	Freq.	Cover	Freq.	Cover	Freq.	Cover
Euthamia graminifolia	5	2.4 ± 1.0	10	2.1 ± 0.8	11	0.6 ± 0.2
Gramineae species	0	-	1	0.1 ± 0.0	1	0.1 ± 0.0
Geocaulon lividum	0	-	1	0.1 ± 0.0	0	-
Hieracium species*	1	0.3 ± 0.0	5	0.8 ± 0.5	2	0.4 ± 0.2
Hordeum jubatum*	0	-	1	0.5 ± 0.0	5	1.8 ± 0.6
Hypericum virginicum*	1	4.3 ± 0.0	0	-	1	0.1 ± 0.0
Juncus brevicaudatus	3	4.6 ± 4.4	15	1.0 ± 0.4	25	3.4 ± 0.8
Juncus bufonius	4	6.8 ± 6.1	3	0.3 ± 0.1	3	0.8 ± 0.2
Juncus effusus	1	0.5 ± 0.0	1	8.3 ± 0.0	0	-
Juncus nodosus	0	-	0	-	1	0.1 ± 0.0
Lycopus uniflorus	2	0.5 ± 0.0	5	0.5 ± 0.1	8	0.4 ± 0.2
Phleum pratense*	0	-	0	-	1	4.4 ± 0.0
Phragmites australis*	0	-	0	-	6	3.3 ± 2.6
Poa palustris*	0	-	1	0.1 ± 0.0	3	0.9 ± 0.4
Poa other than P. palustris*	0	-	1	2.4 ± 0.0	0	-
Potentilla nivea*	0	-	3	0.3 ± 0.0	1	0.1 ± 0.0
Potentilla norvegica*	0	-	1	0.3 ± 0.0	5	0.2 ± 0.1
Ranunculus acris*	1	0.4 ± 0.0	0	-	1	0.3 ± 0.0
Rhynchospora alba	1	0.1 ± 0.0	0	-	21	5.7 ± 1.2
Rumex acetosella*	0	-	3	0.1 ± 0.0	0	-
Rumex occidentalis*	0	-	1	2.8 ± 0.0	2	0.2 ± 0.1
Sarracenia purpurea	19	0.7 ± 0.1	9	1.0 ± 0.7	8	0.3 ± 0.1
Scirpus atrovirens	2	0.8 ± 0.6	1	1.9 ± 0.0	0	-
Scirpus cyperinus	23	10.1 ± 2.5	27	6.1 ± 2.1	16	4.7 ± 2.6
Solidago rugosa	5	0.7 ± 0.4	5	1.8 ± 1.0	1	0.3 ± 0.0
Solidago other than S. rugosa	0	-	3	0.4 ± 0.1	0	-
Sonchus arvensis*	0	-	1	0.1 ± 0.0	0	-
Sonchus asper*	0	-	1	0.6 ± 0.0	8	1.7 ± 0.7
Symphyotrichum boreale*	0	-	0	-	2	0.3 ± 0.1
Symphyotrichum falcatum*	0	-	0	-	1	1.8 ± 0.0
Symphyotrichum novae-angliae*	0	-	0	-	3	1.1 ± 0.7
Taraxacum officinale*	0	-	0	-	2	0.3 ± 0.2
Triglochin palustris	0	-	0	-	1	0.3 ± 0.0
Typha latifolia*	3	2.5 ± 2.4	0	-	20	2.8 ± 1.0
Vaccinium vitis-idaea	0	-	3	1.7 ± 0.6	2	2.4 ± 0.6
Other herbs	12	2.3 ± 1.7	15	2.2 ± 1.7	3	0.3 ± 0.0

Species	Freq.	Cover		Freq.	Cover	Freq.	Cover
Ericaceae	99	14.7 ± 1.3		100	9.1 ± 0.9	84	6.4 ± 1.1
Andromeda polifolia var. *latifolia*	*17*	*1.6 ± 0.6*		*26*	*0.9 ± 0.2*	*23*	*1.0 ± 0.2*
Chamaedaphne calyculata	*94*	*7.6 ± 0.8*		*92*	*4.9 ± 0.7*	*71*	*4.1 ± 0.7*
Empetrum nigrum	*10*	*1.4 ± 0.3*		*4*	*0.9 ± 0.2*	*3*	*0.2 ± 0.0*
Gaultheria hispidula	*4*	*0.5 ± 0.0*		*0*	-	*0*	-
Gaylussacia baccata	*0*	-	-	*3*	*0.7 ± 0.1*	*7*	*1.4 ± 0.4*
Kalmia angustifolia	*77*	*1.9 ± 0.3*		*65*	*1.4 ± 0.2*	*30*	*1.2 ± 0.4*
Kalmia polifolia	*60*	*0.8 ± 0.1*		*73*	*0.7 ± 0.1*	*52*	*0.8 ± 0.1*
Rhododendron canadense	*47*	*0.6 ± 0.1*		*10*	*0.6 ± 0.1*	*9*	*0.9 ± 0.5*
Rhododendron groenlandicum	*79*	*3.4 ± 0.6*		*81*	*1.8 ± 0.3*	*45*	*1.3 ± 0.4*
Rhododendron other than *R. canadense* and *R. groenlandicum*	*2*	*0.6 ± 0.3*		*4*	*0.4 ± 0.1*	*0*	-
Vaccinium angustifolium	*25*	*1.1 ± 0.3*		*27*	*1.1 ± 0.2*	*5*	*0.9 ± 0.8*
Vaccinium macrocarpon	*6*	*0.8 ± 0.2*		*3*	*0.2 ± 0.1*	*1*	*0.1 ± 0.0*
Vaccinium myrtilloides	*4*	*1.8 ± 0.8*		*8*	*0.2 ± 0.1*	*0*	-
Vaccinium oxycoccos	*89*	*1.8 ± 0.3*		*83*	*1.2 ± 0.2*	*64*	*1.0 ± 0.2*
Shrubs	29	4.0 ± 1.0		28	3.8 ± 1.3	37	6.9 ± 1.8
Aronia melanocarpa	*11*	*0.9 ± 0.3*		*3*	*0.3 ± 0.2*	*5*	*0.2 ± 0.1*
Ilex mucronata	*1*	*2.0 ± 0.0*		*0*	-	*0*	-
Myrica gale	*14*	*5.1 ± 1.6*		*0*	-	*2*	*0.4 ± 0.1*
Rubus chamaemorus	*0*	-		*3*	*0.1 ± 0.0*	*0*	-
*Rubus idaeus******	*1*	*2.3 ± 0.0*	-	*0*	-	*0*	-
Rubus other than *R. chamaemorus* and *R. idaeus*	*3*	*1.0 ± 0.5*		*1*	*5.0 ± 0.0*	*0*	-
Salix species	*6*	*5.1 ± 2.8*		*19*	*4.6 ± 1.8*	*31*	*8.0 ± 2.0*
Spiraea alba var. *latifolia*	*1*	*2.0 ± 0.0*		*10*	*0.9 ± 0.3*	*1*	*3.0 ± 0.0*
Trees	69	5.6 ± 0.9		62	3.3 ± 0.7	43	2.9 ± 0.7
Abies balsamea	*1*	*0.5 ± 0.0*		*0*	-	*0*	-
Alnus species	*14*	*2.5 ± 0.6*		*6*	*1.3 ± 0.5*	*0*	-
Betula species*	*54*	*5.8 ± 1.0*		*42*	*2.4 ± 0.6*	*24*	*2.8 ± 0.7*
Larix laricina	*18*	*1.0 ± 0.3*		*13*	*0.5 ± 0.2*	*8*	*0.6 ± 0.3*
Picea mariana	*19*	*0.8 ± 0.1*		*14*	*2.9 ± 1.4*	*15*	*1.5 ± 0.3*
Picea other than *P. mariana*	*3*	*0.6 ± 0.2*		*8*	*1.4 ± 0.7*	*1*	*0.5 ± 0.0*
*Pinus banksiana**	*0*	-		*3*	*0.6 ± 0.4*	*1*	*0.1 ± 0.0*
Populus species*	*4*	*0.6 ± 0.2*		*15*	*2.0 ± 0.9*	*14*	*2.0 ± 0.8*
Prunus species*	*1*	*0.5 ± 0.0*		*0*	-	*0*	-

the visual estimates in the permanent plots; while the last two were the sums of all *Sphagnum* spp. and *Polytrichum* spp. identified in the 12 quadrats of 25 cm^2, transformed to the seven-point scale used for the plant strata data to improve normality and homogeneity of the within-group covariance matrices (Legendre & Legendre 2012, Borcard *et al.* 2011). The choice of descriptors was based on differences between restoration outcome categories and previous research (González *et al.* 2013, 2014; González & Rochefort 2014). The 'bare peat and litter' stratum was not used as one of the descriptors to avoid circularity, as it was already used in the k-means clustering. Having a low number of descriptors will also facilitate the task of the restoration practitioner when evaluating the success of restoration, by reducing the amount of information to be collected in the field. A sixth descriptor (6: time since restoration in years) was added when running the LDA models because it was shown to have an effect on vegetation composition in the previous step (RDA) and, therefore, we anticipated that it could also have some effect on the plant strata.

LDA models were calibrated using 75 % of the restoration sites (49 restoration sites), which were randomly chosen within each region and year since restoration and included 205 plots. The remaining 25 % (17 restoration sites including 69 plots) were used to validate the model. Calibration and validation were performed by comparing the observed vs. the predicted restoration outcome categories of the respective (75 % and 25 %) sets of plots. The accuracy of the calibration and validation datasets was defined as the percentage of objects correctly classified by the classification functions.

All analyses were carried out using R (version 3.2.4) software (R Development Core Team 2017). More precisely, RDA and k-means partitioning were run using the functions "rda" and "cascadeKM" of the "vegan" package (Oksanen *et al.* 2011); and LDA was computed using the function "lda" in the "MASS" package (Venables & Ripley 2002).

RESULTS

Classification of restoration sites into restoration outcome categories

The "time since restoration" of the restored peatlands had a significant but small effect on vegetation composition, as time since restoration explained only 1.6 % of the variability in the species composition of the vegetation matrix (RDA, permutation test, 9999 runs, F = 5.424, P < 0.001). With at least five years since restoration, differences in the plant communities between restoration sites outweighed differences within restoration sites due to change over time. The small percentage of variability in vegetation explained by time since restoration was probably due to differences in architecture and growth rate between species. Woody species with slow growth rates such as *Chamaedaphne calyculata* and *Rhododendron groenlandicum*, and hummock species that usually expand more slowly such as *Sphagnum fuscum* (Pouliot *et al.* 2011, Rochefort *et al.* 2013, Poulin *et al.* 2013, González *et al.* 2014), were most positively correlated to time since restoration. The 'bare peat and litter' component and *Eriophorum vaginatum*, one of the few species that can spontaneously colonise peatlands after peat extraction activities (Tuittila *et al.* 2000, Campbell *et al.* 2003), occupied more surface area at the more recently restored sites.

The k-means partitioning performed on the residuals of the RDA separated the 274 plots into three restoration outcome plant categories, namely '*Sphagnum*-cottongrass', '*Polytrichum-Sphagnum*' and 'Low cover-diverse peatland plants'. Overall, differences in frequency and cover of the species present could be subtle across restoration outcomes plant categories (Table 1; González *et al.* 2013). This underscores the importance of combining species when assessing restoration outcomes (González *et al.* 2014). The first category included 109 plots and was characterised by a dense moss carpet having a cover of 46 % on average for all plots (frq. = 100 %), with 78 % of the carpet dominated by *Sphagnum* mosses (36 % cover). The *Sphagnum* moss carpet was dominated by species of the subgenus Acutifolia where *Sphagnum rubellum* was the most common species for practically all plots (frequency of occurrence = 98 %; mean cover = 24 %). The dominating *Sphagnum* moss carpet was often associated with the cottongrass species *Eriophorum vaginatum* (frq. = 94 %; cov. = 32 %) and *Eriophorum angustifolium* (frq. = 48 %; cov. = 18 %), and with a lower but relatively constant presence of *Polytrichum strictum* (frq. = 85 %; cov. = 9 %). This category was defined as the '*Sphagnum*-cottongrass' community (Table 1). A second category of 78 plots was characterised by a dense moss carpet of 68 % cover on average with 60 % of the carpet dominated by *P. strictum* (frq. = 100 %; cov. = 41 %) and a good presence of *Sphagnum* species (34 % of the moss carpet), again dominated by the Acutifolia sub-genus (frq. = 94 %; cov. = 21 %). This category was defined as the '*Polytrichum-Sphagnum*' community (Table 1). A third category of 87 plots was mainly bare of vegetation ('Bare peat and litter': median cover = 51–75 %), but with *E. vaginatum*, *P. strictum* and *S. rubellum* present in more than half of the plots at a cover 8 %, 7 % and 5 % respectively. This category was defined as 'Low cover-diverse peatland plants' community (Table 1). The restoration sites did not group by region but, rather, by restoration outcome categories. However, there were small regional differences in the proportion of restoration sites and plots corresponding to each restoration outcome. For example, there was higher occurrence of 'Low cover-diverse peatland plants' in the western region.

Building the LDA model to declare restoration success in a time window of 5–10 years post-restoration

The LDA model correctly classified 91 % of the calibration data: 93, 86 and 93 % of the '*Sphagnum*-cottongrass', '*Polytrichum*-*Sphagnum*' and 'Low cover-diverse peatland plants' plot categories, respectively (Figure 1a); and 93 % of the validation data: 93, 91 and 95 % of plots per category in the same sequence (Figure 1b). For example, from the 23 plots predicted as '*Polytrichum*-*Sphagnum*' in the validation dataset (dotted black polygon, Figure 1b), 21 were correctly classified (triangles in Figure 1b) and only one of the '*Sphagnum*-cottongrass' and one of the 'Low cover-diverse peatland plants' plots were incorrectly predicted (circle and cross, respectively, in Figure 1b). The first LDA axis divided 'Low cover-diverse peatland plants' plots from '*Sphagnum*-cottongrass' and '*Polytrichum*-*Sphagnum*' plots, while the second axis mainly divided '*Sphagnum*-cottongrass' from '*Polytrichum*-*Sphagnum*' plots (Figure 1a, b). Not surprisingly, the total cover of *Polytrichum* and *Sphagnum* spp. contributed most to the discrimination between the two categories dominated by peatland mosses and the 'Low cover-diverse peatland plants' category (arrows in Figure 1). Herbs and ericaceous shrubs were also coupled to moss-dominated plots, while only trees and time since restoration ("age" in Figure 1) discriminated plots in the direction of 'Low cover-diverse peatland plants' communities. *Polytrichum* and *Sphagnum* spp. helped to discriminate *Sphagnum*-cottongrass from *Polytrichum*-*Sphagnum* plots along the second axis (red arrows in Figure 1) but the total cover of herbs (positively related to *Sphagnum*-cottongrass plots) was even more important. This was not surprising, as *Eriophorum* species were much more abundant in *Sphagnum*-cottongrass plots than in *Polytrichum*-*Sphagnum* plots as explained above. The structure of the LDA model is provided in the Appendix: discriminant functions (Table A1) and classification functions (Table A2).

DISCUSSION

Defining success from restoration outcome categories

Once a surveyed plot from a restored peatland has been assigned to a restoration outcome category, as would be done using the declaration tool developed in this project, how do you declare success? To answer this question we must examine the plant communities of the restoration outcome categories using two approaches. The first approach is to rely on the criteria proposed by regulating agencies, which usually stem from knowledge developed by experts having wide field experience of natural, degraded or restored peatlands. The second approach is to conduct a comparison with reference ecosystems of the region, but this does not take into account the notion of trajectory - the comparison is more static in time. Nevertheless, there are still some principles that need to be met to launch a degraded peatland towards successful recovery. From Chirino *et al*. (2006), for instance, we learn that if *Sphagnum* moss establishment is very low (less than 4 %) after the first growing season, recovery will remain very slow in subsequent years. On the other hand, if at least 5 % cover of *Sphagnum* mosses associated with *Polytrichum strictum* (around 15 to 20 % cover) is reached in the first year of establishment, a good trajectory can be expected. However, it is not recommended to declare success only one year after restoration because climate can still greatly influence the outcome. Evaluation after a minimum of five years post-restoration is often best, as recommended for other types of restoration (Wortley *et al*. 2013, González *et al*. 2015).

In this study, the restored sites were evaluated 5–10 years post-restoration and outcomes were compared to 159 natural peatlands in eastern Canada (L. Rochefort, unpublished data). Among the three restoration outcome categories, the ***Sphagnum*-cottongrass category** had the highest cover of *Sphagnum*. The overall cover was 36 % for the restored sites (Table 1) whereas the average *Sphagnum* moss cover is 84 % in natural peatland sites. This represents a 43 % recovery of the *Sphagnum* layer usually found in natural peatlands. The *Sphagnum* carpet of the plots belonging to this restoration outcome was associated with 11 % of peatland bryophytes (Table 1). This bryophyte abundance is similar to the 9 % found in natural peatlands. The co-dominant cottongrass species (*Eriophorum vaginatum*; 32 % cover) of the community still has a relatively high coverage value post-restoration when compared to the usually less

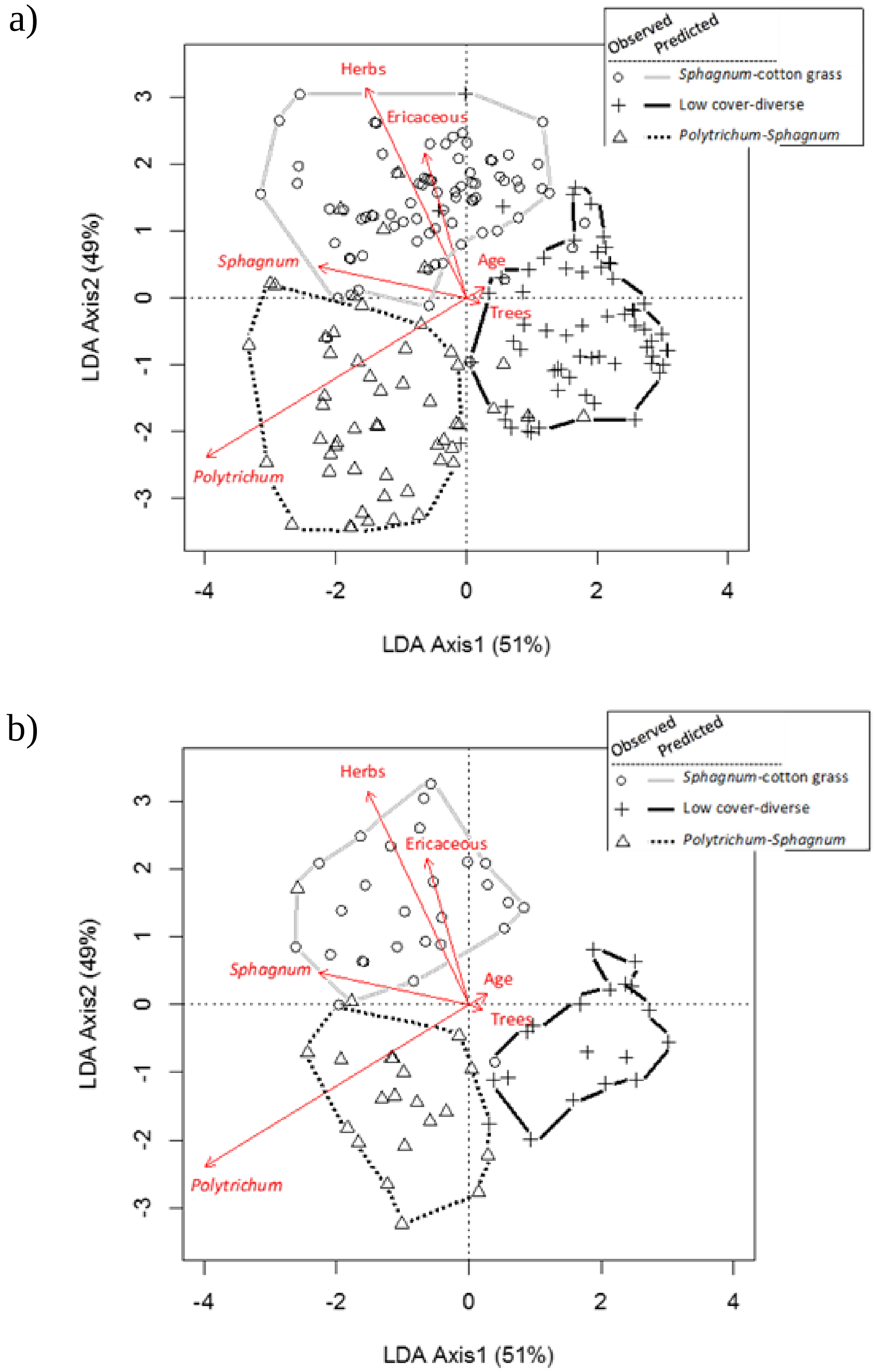

Figure 1. Linear discriminant analysis (LDA) of restoration outcome categories based on a set of readily measurable vegetation descriptors (seven-point ordinal scale) and years since the end of restoration work (Age). Vector length has been multiplied by 4.5 to improve visual clarity. All vegetation plots within the limits of each polygon were depicted in the bidimensional space using the discriminant functions (Table A1 in Appendix) and assigned to the corresponding restoration outcome category using the classification functions (Table A2). (a) Calibration step (75 % of the restoration sites; 49 restoration sites including 205 plots) and (b) Validation step (25 % of the restoration sites; 17 restoration sites including 69 plots). Note that the accuracy of the model was assessed on the basis of the percentages of these plots that it classified correctly (91 % for calibration data and 93 % for validation data).

than 15 % cover in natural peatlands. This is not of much concern as *E. vaginatum* is known to flower readily in recently restored *Sphagnum* peatlands, to dominate between five and eight years post-restoration, then to decline as the *Sphagnum* carpet develops (Rochefort *et al.* 2013). Consequently, we regard the *Sphagnum*-cottongrass community as one of the most successful scenarios given that these restored plots follow the vegetation recovery of Bois-des-Bel (BDB) research station, where it is known that a positive carbon sequestration function had returned 14 years post-restoration (Nugent *et al*. 2018). The ***Polytrichum-Sphagnum* category** is also declared a good restoration outcome because of its excellent total bryophyte cover (68 % on restored plots, see Table 1, compared to 92 % in natural sites), which is dominated by *Polytrichum strictum* (41 %) and *Sphagnum* mosses (23 %) and represents a 74 % recovery of the bryophyte layer compared to natural peatlands. The dominance of *Polytrichum strictum* over *Sphagnum* mosses in the early stages of recovery post-restoration or after fire is well known (Groeneveld *et al*. 2007, Benscoter & Vitt 2008, Rochefort *et al*. 2013). The third restoration outcome, **Low cover-diverse peatland plant category**, was the least successful of the three, having recovered only 14 % of the bryophyte layer (including 8 % of the Sphagna, Table 1) compared to natural peatlands (92 %). Nevertheless, sites belonging to this category can still lead to a peatland ecosystem given enough time, as shown by Gonzalez & Rochefort (2014), for two reasons: first, because the category is well recolonised with diverse taxa present in the other two categories and in natural peatlands; and secondly because of the absence of invasive species and the low presence of ruderal species not typical of peatland ecosystems (Total non-peatland species frq. = 60 % and cov. = 5 %, Table 1). However, when a site falls into this category, it should be viewed as a warning (raising a flag) to do a more comprehensive assessment of the site to evaluate whether some landscape constraints to the restoration process are evident and could be rectified (failed dams or berms for rewetting the sites, erosion, gullying, water ponding, beaver activity, etc.).

Is restoration meeting expectations?

In evaluating restoration projects, restoration practitioners are increasingly adopting goals that are morally valuable and pragmatic rather than ones that strictly reproduce historical pre-disturbance states (Rohwer & Marris 2016). Therefore, declaring success depends on the goals of the restoration project and is highly context dependent. In Canada, a general goal has been to return the characteristic function of carbon sequestration to peatlands that have been degraded by the extraction of either peat (Rochefort 2001, Nugent *et al.* 2018) or oil (wellsites and associated facilities; Environment & Parks 2015).

The restoration outcome categories would together rate the restoration success, 5–10 years post-restoration, for disturbed extracted peatlands in Canada at close to 70 %. The 70 % value is the combination of all plots from both '*Sphagnum*-cottongrass' and '*Polytrichum-Sphagnum*' categories (109 + 78) compared to all plots surveyed across Canada (274). Furthermore, even the third category defined by this study ('Low cover-diverse peatland plants' community) may be judged a relatively positive restoration outcome if the goal is to exclude invasive exotic and non-peatland plants, and knowing that the target community can still develop slowly (Gonzalez & Rochefort 2014). Nevertheless, this restoration outcome needs further investigation in terms of the factors impeding recovery.

In Canada, only two provinces so far have official guidelines for assessing the efficiency of restoration projects: New Brunswick (Government of New-Brunswick 2001) and Alberta (Environment & Parks 2015). In both cases, they demand that a mix of bryophytes, Sphagna and vascular plant strata must dominate the system, and they consider the notions of species richness and desirable versus undesirable species. When our dataset is evaluated in terms of these criteria, around 70 % of the plots (again, the '*Sphagnum*-cottongrass' and '*Polytrichum-Sphagnum*' categories) meet the efficiency criteria whereas, as when using natural peatlands as a reference, the plots from the 'Low cover-diverse peatland plants' category raise questions.

From an applied perspective, our work will allow local stakeholders, peatland managers and provincial regulators to establish their desired levels of success and gauge the effectiveness of industrial restoration actions 5–10 years post-restoration by means of a tool that is readily applicable. Indeed, by considering only plant strata and number of years since restoration, restoration outcome categories can be determined unequivocally. We believe our experimental approach could be applied to other ecosystem types as well.

How to apply the declaration tool?

The LDA model can be used to assign a restoration outcome category to a plot that was not used in calibration or validation of the model by feeding the LDA classification functions (Table A2) with the plant strata descriptors and the time since restoration. The classification function that obtains the highest score determines the restoration outcome category for the plot under examination. The LDA discriminant functions (Table A1) are also fed with the plant strata descriptors and the time since restoration, to predict the position of the plot along the gradients given by the LDA axes (Figure 1). Depicting the plot position in the bi-dimensional space helps in determining how close the plot is to the other restoration outcome categories. This is important as it can offer clues to any adaptive management that may be needed. For example, two new plots may be predicted as "*Sphagnum*-cottongrass" but one may be located closer to the 'Low cover-diverse peatland plants' predicted area (solid black polygons, Figure 1) than the other. This may indicate that the vegetation recovery of the former plot needs to be monitored more closely than the latter, as there is a higher risk that it will deviate from the desired trajectory.

It is worth mentioning that a large number of sites was used to build our LDA model. Monitoring of a large number of sites is not frequent in restoration ecology because of budgeting and logistic constraints (González *et al*. 2015). LDA is sensitive to a lack of normality, which is common in species cover data, and for this reason we recommend working only with dominant species or plant groups.

ACKNOWLEDGEMENTS

Financial support was provided through the Industrial Research Chair in Peatland Management funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canadian Sphagnum Peat Moss Association (CSPMA) and its members. The first author received an Excellence Grant for postdoctoral studies from Université Laval. We thank Roxane Andersen, Vicky Bérubé, Claire Boismenu, Stéphanie Boudreau, Suzanne Campeau, Sandrine Hogue-Hugron, Josée Landry, Marie-Claire LeBlanc, Luc Miousse, François Quinty and Claudia St-Arnaud for their various contributions to leading and coordinating the numerous students who assisted with field surveys and laboratory data entry, managing the long-term database, and verifying numerous plant identifications.

REFERENCES

Bachand, M., Pellerin, S., Côté, S.D., Moretti, M., De Cáceres, M., Brousseau, P.M., Cloutier, C., Hébert, C., Cardinal, E., Martin, J.L. & Poulin, M. (2014) Species indicators of ecosystem recovery after reducing large herbivory density: comparing taxa and testing species combinations. *Ecological Indicators*, 38, 12–19.

Benscoter, B.W. & Vitt, D.H. (2008) Spatial patterns and temporal trajectories of the bog ground layer along a post-fire chronosequence. *Ecosystems*, 11, 1054–1064.

Bernhardt, E.S., Sudduth, E.B., Palmer, M.A., Allan, J.D., Meyer, J.L., Alexander, G., Follstad Shah, J., Hassett, B., Jenkinson, R., Lave, R., Rumps, J. & Pagano, L. (2007) Restoring rivers one reach at a time: results from a survey of U.S. river restoration practitioners. *Restoration Ecology*, 15, 482–493.

Bérubé, V. & Rochefort, L. (2018) Production and decomposition rates of different fen species as targets for restoration. *Ecological Indicators*, 91, 105–115.

Bonnett, S.A.F., Ross, S., Linstead, C. & Maltby, E. (2009) *A Review of Techniques for Monitoring the Success of Peatland Restoration*. Natural England Commissioned Report (NECR) 086, Natural England, Sheffield, UK, 179 pp. Online at: http://eprints.uwe.ac.uk/21937, accessed 21 Mar 2019.

Borcard, D., Gillet, F., & Legendre, P. (2011) *Numerical Ecology with R*. Springer-Verlag, New York, 306 pp.

Campbell, D.R., Rochefort, L. & Lavoie, C. (2003) Determining the immigration potential of plants colonizing disturbed environments: the case of milled peatlands in Quebec. *Journal of Applied Ecology*, 40, 78–91.

Environment & Parks (2015) *Reclamation Criteria for Wellsites and Associated Facilities for Peatlands* (October 2015). Land Policy Branch, Alberta Government, Edmonton, Canada, 142 pp.

Fisher, R.A., (1936) The use of multiple measurements in taxonomic problems. *Annals of Eugenics*, 7, 179–188.

González, E., Rochefort, L., Boudreau, S., Hugron, S. & Poulin, M. (2013) Can indicator species predict restoration outcomes early in the monitoring process? A case study with peatlands. *Ecological Indicators*, 32, 232–238.

González, E., Rochefort, L., Boudreau, S. & Poulin, M. (2014) Combining indicator species and key environmental and management factors to predict restoration success of degraded ecosystems. *Ecological Indicators*, 46, 156–166.

González, E. & Rochefort, L. (2014) Drivers of success in 53 cutover bogs restored by a moss layer transfer technique. *Ecological Engineering*, 68, 279–290.

González, E., Sher, A.A., Tabacchi, E., Masip, A. & Poulin, M. (2015) Restoration of riparian vegetation: A global review of implementation and evaluation approaches in the international, peer-reviewed literature. *Journal of Environmental Management*, 158, 85–94.

Government of New Brunswick (2001) *A Provincial Policy on Peat Mining: A Total Development Strategy for the New Brunswick Peat Resource Sector*. Minerals, Policy and Planning Division, Department of Natural Resources and Energy, Fredericton, 10 pp.

Graf, M.D. & Rochefort, L. (2016) A conceptual framework for ecosystem restoration applied to industrial peatlands. In: Bonn, A., Allott, T., Evans, M., Joosten, H. & Stoneman, R. (eds.) *Peatland Restoration and Ecosystem Services: Science, Policy and Practice*, Cambridge University Press, 192–212.

Groeneveld, E.V.G., Massé, A. & Rochefort, L. (2007) *Polytrichum strictum* as a nurse-plant in peatland restoration. *Restoration Ecology*, 15, 709–719.

Herrick, J., Schuman, G.E. & Rango, A. (2006) Monitoring ecological processes for restoration projects. *Journal for Nature Conservation*, 14, 161–171.

Hughes, F.M.R., Colston, A. & Mountford, J.O. (2005) Restoring riparian ecosystems: the challenge of accommodating variability and designing restoration trajectories. *Ecology and Society*, 10(1): 12, 22 pp.

Legendre, P. & Gallagher, E.D. (2001) Ecologically meaningful transformations for ordination of species data. *Oecologia*, 129, 271–280.

Legendre, P. & Legendre, L. (eds.) (2012) *Numerical Ecology*. Third English edition, Elsevier Science, Amsterdam, 1006 pp.

Milligan, G.W. (1996) Clustering validation: results and implications for applied analyses. In: Arabie, P., Hubert L.J. & De Soete, G. (eds.) *Clustering and Classification*, World Scientific Publication, River Edge, NJ, 341–375.

Nugent, K., Strachan, I.B., Strack, M., Roulet, N. & Rochefort, L. (2018) Multi-year net ecosystem carbon balance of a restored peatland reveals a return to carbon sink. *Global Change Biology*, 24, 5751–5768.

Oksanen, J., Guillaume Blanchet, F., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Henry, M., Stevens, H. & Wagner, H. (2011) *Vegan: Community Ecology Package*. R package version 2.0-2. Online at : http://CRAN.R-project.org/package =vegan.

Poulin, M., Andersen, R. & Rochefort, L. (2013) A new approach for tracking vegetation change after restoration: a case study with peatlands. *Restoration Ecology*, 21, 363–371.

Pouliot, R., Rochefort, L. & Karofeld, E. (2011) Initiation of microtopography in revegetated cutover peatlands. *Applied Vegetation Science*, 14, 158–171.

Quinty, F., & Rochefort, L. (eds.) (2003) *Peatland Restoration Guide*. Second edition, Canadian Sphagnum Peat Moss Association, 106 pp.

R Development Core Team (2017) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Online at: http://www.R-project.org/

Rao, C.R. (1948) The utilization of multiple measurements in problems of biological classification. *Journal of the Royal Statistical Society. Series B (Methodological)*, 10, 159–203.

Rao, C. R. (1952) *Advanced Statistical Methods in Biometric Research*. John Wiley & Sons, New York, 390 pp.

Rochefort, L. (2000) Sphagnum: A keystone genus in habitat restoration. *New Frontiers in Bryology and Lichenology*, 103, 503–508.

Rochefort, L., Quinty, F., Campeau, S., Johnson, K. & Malterer, T. (2003) North American approach to the restoration of *Sphagnum* dominated peatlands. *Wetlands Ecology and Management*, 11, 3–20.

Rochefort, L., Isselin-Nondedeu F., Boudreau, S. & Poulin, M. (2013) Comparing survey methods for monitoring vegetation change through time in a restored peatland. *Wetlands Ecology and Management*, 21, 71–85.

Rohwer, Y. & Marris, E. (2016) Renaming restoration: conceptualizing and justifying the activity as a restoration of lost moral value rather than a return to a previous state. *Restoration Ecology*, 24, 674–679.

Sottocornola, M., Boudreau, S. & Rochefort, L. (2007) Peat bog restoration: Effect of phosphorus on plant re-establishment. *Ecological Engineering*, 31, 29–40.

Suding, K. (2011) Toward an era of restoration in ecology: successes, failures, and opportunities ahead. *The Annual Review of Ecology, Evolution, and Systematics*, 42, 465–487.

Ter Braak, C.J.F. (1987) Ordination. In: Jongman, R.H.G., ter Braak, C.J.F. & van Tongeren, O.F.R. (eds.) *Data Analysis in Community and Landscape Ecology*. Centre for Agricultural Publishing and Documentation (Pudoc), Wageningen, The Netherlands; re-issued in 1995 by Cambridge University Press, UK, 324 pp.

Tuittila, E.S., Rita, H., Vasander, H. & Laine, J. (2000) Vegetation patterns around *Eriophorum vaginatum* L. tussocks in a cut-away peatland in southern Finland. *Canadian Journal of Botany*, 78, 47–58.

Venables, W.N. & Ripley, B.D. (eds.) (2002) *Modern Applied Statistics with S*. Fourth edition, Springer, New York, 498 pp.

Waddington, J.M., Strack, M. & Greenwood, M.J. (2010) Toward restoring the net carbon sink function of degraded peatlands: Short-term response in CO_2 exchange to ecosystem-scale restoration. *Journal of Geophysical Research*, 115, G01008.

Wortley, L., Hero, J.M. & Howes, M. (2013) Evaluating ecological restoration success: a review of the literature. *Restoration Ecology*, 21, 537–543.

Submitted 29 Oct 2017, final revision 05 Feb 2019
Editor: Ab Grootjans

Author for correspondence: Professor Line Rochefort, Peatland Ecology Research Group and Centre d'Études Nordiques, Département de phytologie, Faculté des sciences de l'agriculture et de l'alimentation, 2425, rue de l'Agriculture, Université Laval, Québec G1V 0A6, Canada.
Tel: +1 418 656 2131 ext. 2583; Fax: +1 418 656 7856; E-mail: line.rochefort@fsaa.ulaval.ca

Appendix

Table A1. Scores of linear discriminant functions. In order to find the positions of the plots (including newly-restored plots) within the canonical space of our LDA model (Figure 1), subtracting the mean value of each vegetation descriptor before multiplying by each coefficient is necessary. Means were obtained from the calibration dataset. Vegetation descriptors data must be entered in a seven-point ordinal scale: 0 – absence, 0.5 – presence, 1 – 1-10 %, 2 – 11-25 %, 3 – 26-50 %, 4 – 51-75 % and 5 – 76-100 %.

	LDA1	LDA2	Means
Trees	0.04633	-0.01722	0.83
Ericaceous shrubs	-0.14144	0.47994	1.34
Herbs	-0.33957	0.69836	2.60
Polytrichum spp.	-0.88398	-0.52980	1.55
Sphagnum spp.	-0.50353	0.10415	1.74
Time since restoration (years)	0.06143	0.03403	7.21

Table A2. Scores of classification functions to predict the restoration outcome categories of plots. Each plot is assigned to the restoration outcome category corresponding to the function receiving the highest score. Vegetation data must be transformed to a seven-point ordinal scale (0 = absent, 0.5 = present, 1 = 1–10 %, 2 = 11–25 %, 3 = 26–50 %, 4 = 51–75 % and 5 = 76–100 %) before being multiplied by the appropriate score.

	Sphagnum-cottongrass	*Polytrichum*-*Sphagnum*	Low cover-diverse peatland plants
Constant	-20.97470	-17.7811	-11.19025
Trees	0.99760	1.0168	1.13553
Ericaceous shrubs	-0.51513	-1.8529	-1.69992
Herbs	4.45949	2.6065	2.42625
Polytrichum spp.	2.22077	4.4256	1.12400
Sphagnum spp.	1.19484	1.2355	-0.15544
Time since restoration (years)	2.48899	2.3441	2.57019