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Combining indicator species and key environmental and management factors to predict restoration success of degraded ecosystems

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ABSTRACT

When evaluating the success or failure of ecological restoration projects, practitioners need to verify success within the first few years of the monitoring process to apply corrective measures if necessary or to reclaim environmental down payment where required. This could be achieved with ecological indicators, if they can be easily and routinely measured and are representative of the complexity of the restored ecosystems. We used peatlands restored after horticultural peat extraction in eastern Canada to test a methodological approach that predicts restoration success early after restoration implementation. The goal of restoration of these extracted peatlands is to re-establish a moss carpet typically dominated by *Sphagnum* mosses, the main peat-accumulating plant group in these northern ecosystems. Vegetation in a total of 152 plots in 41 peatlands restored after peat extraction activities and distributed across a span of 600 km was monitored every 2 years since the third year after restoration. The plots were clustered in three restoration outcome categories: *Sphagnum*-dominated, bare peat-dominated and *Polytrichum*-dominated, according to their characteristic vegetation composition at the time of the latest survey for each plot (4–11 years since restoration). Second, vegetation composition in the same plots from the earliest survey, 3 years since restoration, and key environmental and management variables such as summer temperature, effectiveness of ditch blockage, season of restoration works and delay in P fertilization were analyzed using linear discriminant analysis (LDA) to obtain the combination of parameters that best discriminated between the restoration outcome categories. LDA correctly classified 71% of the plots of a calibration database (for which 75% of the sectors were used) and 75% of a validation database (for which 25% of the sectors were used) into the three categories. The obtained LDA models can be used to allocate new plots to one of the restoration outcome categories by providing a series of linear equations (classification functions) that are computed from the combination of ecological indicators. One additional and recently restored peatland was used to illustrate application of these equations of the LDA model to predict future restoration outcome and subsequently adapt management strategies. Such a LDA model provides an unequivocal (i.e., one new plot assigned to one and only one restoration outcome category) prediction of success based on multiple but simple, easily recognizable indicators and spares managers the complex task of interpreting many individual predictors for establishing a clear diagnosis.

1. Introduction

The evaluation of success in restoration projects is a key step to ensure an optimal, adaptive management strategy (Walker et al., 2007; Shafroth et al., 2008; Suding, 2011). The challenge is to develop protocols that carefully assess the fate of restored ecosystems and provide practitioners with unambiguous tools to determine success or failure (Hobbs, 2005; Wohl et al., 2005; Bernhardt et al., 2007). Specifically, tools that can predict success early (i.e., months or a few years) after restoration works, based on simple, easily-recognizable indicators, would constitute great methodological advances in the field of restoration ecology (Herrick et al., 2006). This is of critical importance because degraded ecosystems usually recover slowly, a process that can only be evaluated comprehensively on the basis of longer term monitoring (Palmer et al., 2005; Kondolf et al., 2007). Predicting future restoration outcome from early monitoring data would enable rapid evaluation of the need for additional works to rectify undesired successional trajectories. This would both reduce monitoring cost and increase restoration efficiency. Surprisingly,

Abbreviations: IndVal, indicator value index; LDA, linear discriminant analysis; RDA, redundancy analysis.

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however, we were unable to find any studies that have focused specifically on developing predictive tools to evaluate restoration success at early stages of the recovery process.

Ecological indicators, which are easily identifiable surrogates of ecosystem conditions (Niemi and McDonald, 2004), have been widely applied to monitor site conditions following disturbances and have been used recently to describe restoration outcomes (Ottonetti et al., 2006; Fagan et al., 2010; Cristofoli et al., 2010; Bachand et al., 2014). However, since indicators are designed to reveal the conditions and evolution of ecosystems based on simplified estimators such as the presence of a particular species, they may fail to integrate the full complexity or multi-dimensional nature of an ecosystem (Dale and Beyeler, 2001). In the context of ecological restoration, this could bias the evaluation process. For example, González et al. (2013) have recently shown that, while it is possible to identify plant species that are significant indicators of restoration success, variations in frequency and cover of these indicator species are very small between different categories of restoration outcomes, making it difficult to confirm recovery 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. Multiple environmental and management factors can be also associated to different success categories in restoration projects and therefore may help to anticipate restoration outcomes (Bay and Sher, 2008; González and Rochefort, 2014). But again, integrating these factors into a predictive comprehensive model would facilitate the implementation of adaptive management strategies. Tools that unequivocally identify success by considering the entire restored community as well as environmental and management variables would be of great help in prediction of restoration success.

Multivariate analyses can be used effectively to develop integrative tools for evaluating success since they make it possible to synthesize environmental information, thereby explaining most system variability on fewer dimensions. Among the panoply of existing multivariate techniques, linear discriminant analysis (LDA, Fisher, 1936; Rao, 1948, 1952) is one of the few that can be used specifically for prediction purposes, although it has seldom been applied for this aim in ecology (Legendre and Legendre, 2012), especially in the evaluation of restoration projects (but see Syvaranta et al., 2008 and Lorite et al., 2010).

We combined several indicator species, as well as key environmental and management variables, through LDA modeling to predict success in attaining desired trajectories shortly (3 years) after restoration work (i.e., application of the restoration technique). The ultimate objective was to develop an analytical approach for unequivocally predicting success early in restoration projects, based on a set of parameters that can be measured easily, such as plant species cover or meteorological parameters. In other words, vegetation, environmental and management data recorded at the third year post-restoration served to predict the future outcome of restoration. Restoration projects after peat extraction activities for horticultural use in bogs of eastern Canada were used to illustrate this methodological approach.

2. Methods

2.1. Study sites

The goal of peatland restoration after horticultural peat extraction activities in Canada is to re-establish a moss carpet typically dominated by *Sphagnum* mosses, which is able to reinitiate self-regulatory mechanisms, and eventually restore the peat accumulation function (Rochefort, 2000). Since the late 1990s, a collaborative partnership between the horticultural peat industry and the Peatland Ecology Research Group based at Université Laval, Quebec, Canada has resulted in the restoration of 41 extracted peatlands in the provinces of Quebec and New Brunswick, ranging in size from 1 to 30 ha and spread over an area of 166,400 km^2 (Table 1). They may be located 2–5 km apart within the same peatland complex, or in different peatlands (Fig. 1). The sites were restored by the moss layer transfer technique, in the following steps: (1) re-shaping field topography, (2) spreading plant diaspores, including *Sphagnum* mosses previously collected from a donor site, (3) spreading straw mulch to protect diaspores by improving micro-climatic conditions and preventing desiccation of plant fragments, (4) blocking drainage ditches and (5) in some cases, fertilizing with phosphorus, to favor colonization by plants that nurse *Sphagnum* mosses (Quinty and Rochefort, 2003; Rochefort et al., 2003; Rochefort and Lode, 2006; Graf et al., 2012).

2.2. Post-restoration monitoring program

To document the evolution of the vegetation community after restoration, permanent plots measuring 5 m × 5 m were established in each restored peatland, the number differing between them as a function of peatland size, heterogeneity of the establishing vegetation and local constraints. A total of 152 plots were established in the 41 restored peatlands. 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 for the monitoring program to facilitate species identification, since some, especially developing mosses, are difficult to distinguish at earlier stages of their development, and to ensure data was recorded for well-established plants, not ungrounded fragments. At the last survey, the longest time since restoration was 11 years and the shortest was 4 (only one peatland, Table 1), but all met the condition of having been monitored at least twice (a first time: 3 years since restoration and a second time: more than 3 years since restoration), allowing us to conduct retrospective analyses of the vegetation composition. Vascular plants (trees, ericaceous and other shrubs and herbs: forbs and graminoids) were identified to the species level (or higher taxonomic level when this was impossible) and the ground covered by their vertical projection, as well as bare peat cover, were visually estimated within four 1 m × 1 m quadrats situated systematically within each permanent plot. Cover of all bryophyte species and lichens was recorded in 20 quadrats of 25 cm × 25 cm that were also systematically distributed within each permanent plot. A total of 64 lichens, bryophytes and vascular plant species were recorded; due to difficulties experienced during field identification, 15 taxa were identified to the genus level.

Information related to the environmental context and the small variations in the application of the restoration technique ("management" hereafter) was also collected at each restored peatland. Among a wide array of parameters, we selected for this study those that were shown to have a key influence on the outcome of the restoration according to González and Rochefort (2014) (Table 2). Temperature and precipitation in the summer following restoration works were obtained from the closest meteorological station (mean monthly temperature °C of July and August, Environment Canada, 2012), as high temperatures and low precipitation of the first growing season after restoration hinders *Sphagnum* recolonisation (Chirino et al., 2006; González and Rochefort, 2014). In cases where restoration was carried out in spring and summer rather than the fall, weather data for the growing season of the same year were used. The effectiveness of blockage of the secondary ditches (i.e., ditches within the restored sector *sensu* González and Rochefort, 2014) was assessed visually on a semi-quantitative basis, in increasing order of blockage

Table 1
List of 41 peatlands restored by the moss transfer technique after horticultural peat extraction.

Peatland complex name	Geographic coordinates	Size (ha)	Restoration year	Time since restoration of the restored peatland at the time of the last vegetation survey	Number of permanent plots	Observed restoration outcome (% of plots)
Baie-Sainte-Anne	47°01′05″N 64°52′46″W	12	2000	10	6	B (66) S (17) P (17)
Bois des Bel	47°58′03″N 69°25′44″W	12	2000	9	9	S (66) B (22) P (11)
Chemin du Lac	47°45′47″N 69°31′34″W	3	1997	11	6	S (50) B (50)
Chemin du Lac	47°45′42″N 69°31′36″W	1	1999	10	2	S (100)
Chemin du Lac	47°45′39″N 69°31′35″W	2	2000	10	4	S (100)
Chemin du Lac	47°45′37″N 69°31′30″W	3	2001	10	3	S (100)
Chemin du Lac	47°45′51″N 69°31′31″W	5	2002	7	4	S (50) B (50)
Chemin du Lac	47°45′41″N 69°31′09″W	11	2003	7	4	S (50) B (50)
Inkerman Ferry	47°42′12″N 64°49′02″W	3	1997	9	9	B (89) S (11)
Inkerman Ferry	47°42′21″N 64°49′07″W	7	2008	5	5	B (100)
Kent	46°18′32″N 65°08′11″W	5	2001	10	4	S (100)
Kent	46°18′42″N 65°08′36″W	8	2007	4	4	B (75) S (25)
Kent	46°18′40″N 65°08′09″W	7	2008	5	4	B (100)
Kent	46°18′28″N 65°08′04″W	4	2008	5	3	S (100)
Kent	46°19′03″N 65°08′16″W	2	2008	5	2	S (50) B (50)
Kent	46°18′55″N 65°08′22″W	3	2008	5	1	S (100)
Kent	46°18′51″N 65°08′16″W	7	2008	5	4	B (75) S (25)
Maisonnette	47°49′43″N 65°02′02″W	11	2000	10	9	B (55) S (33) P (11)
Maisonnette	47°49′37″N 65°01′50″W	9	2006	5	6	S (50) P (50)
Pointe-Lebel	49°07′03″N 68°11′25″W	4	2004	7	8	P (100)
Pokesudie	47°48′47″N 64°46′20″W	14	2006	5	5	B (60) S (20) P (20)
Pokesudie	47°48′42″N 64°46′02″W	9	2008	5	4	B (75) S (25)
Saint-Charles-de-Bellechasse	46°44′53″N 70°59′46″W	1	1999	10	3	S (66) B (33)
Sainte-Marguerite (Section E)	48°48′29″N 72°10′57″W	15	2000	10	1	S (100)
Sainte-Marguerite (Section K)	48°48′23″N 72°10′48″W	10	2000	10	2	S (100)
Sainte-Marguerite (Section AA)	48°49′29″N 72°10′47″W	10	2001	10	2	P (100)
Sainte-Marguerite (Section E)	48°48′45″N 72°11′13″W	10	2001	10	1	S (100)
Sainte-Marguerite (Section G)	48°49′06″N 72°10′52″W	10	2001	10	2	S (100)
Sainte-Marguerite (Section K)	48°48′11″N 72°10′38″W	17	2001	10	1	P (100)
Sainte-Marguerite (Section L)	48°48′07″N 72°10′54″W	18	2001	10	1	S (100)
Sainte-Marguerite (Section AA)	48°49′28″N 72°10′46″W	10	2002	10	3	P (100)
Sainte-Marguerite (Section H)	48°48′33″N 72°10′12″W	12	2002	7	2	P (100)
Sainte-Marguerite (Section J)	48°48′21″N 72°10′27″W	27	2002	7	3	P (66) B (33)
Sainte-Marguerite (Section AA)	48°49′24″N 72°10′37″W	21	2003	7	2	P (100)
Sainte-Marguerite (Section DD)	48°48′45″N 72°10′51″W	30	2003	7	3	P (100)
Sainte-Marguerite (Section F)	48°48′36″N 72°11′31″W	15	2003	7	2	S (50) B (50)
Sainte-Marguerite (Section AA)	48°49′22″N 72°10′22″W	21	2004	7	2	P (100)

Table1 (*Continued*)

Peatland complex name	Geographic coordinates	Size (ha)	Restoration year	Time since restoration of the restored peatland at the time of the last vegetation survey	Number of permanent plots	Observed restoration outcome (% of plots)
Saint-Modeste	47°50′01″N 69°27′51″W	1	1997	9	4	B (50) P (50)
Saint-Modeste	47°50′02″N 69°27′50″W	1	1997	9	2	S (100)
Verbois	47°50′24″N 69°26′41″W	9	2005	5	6	P (66) S (33)
Verbois	47°50′16″N 69°26′22″W	7	2006	5	4	P (75) S (25)
					Total = 152	

S – Sphagnum-dominated, B – Bare peat-dominated, P – Polytrichum-dominated plots.
Success categories were assigned according to k-means partitioning of residualized post 4–11 years vegetation matrix (see text).

effectiveness: 1 – clean ditches; 2 – less than 50% of ditch cross-section collapsed; 3 – more than 50% collapsed; or 4 – completely infilled or not identifiable. More effective blockage was recently shown to favor *Sphagnum* establishment (González and Rochefort, 2014). Restoration in spring was a qualitative variable with two possible values: yes, restored in spring and no, restored in either summer or fall. It was not intended to represent a phenological or climatic variable, but rather to reflect the different site disturbance that may have arisen from working on it with heavy machinery in spring; when the ground (bare peat) was more likely to be wet due to snowmelt and thus especially prone to mechanical disturbance (e.g., rutting by caterpillar tracks or tires), which in turn could have a negative influence on the plant community colonizing the restored peatland (González and Rochefort, 2014). Finally, the delay in phosphorus fertilization 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 – no fertilizer application. Phosphorus fertilizer is most commonly applied in shorter delays where serious frost heaving is observed, to promote colonization by the moss *Polytrichum strictum* (Quinty and Rochefort, 2003; Sottocornola et al., 2007), which can help to stabilize the peat substrate (Groeneveld and Rochefort, 2005).

2.3. Data processing and statistical analyses

Plant cover values obtained in the quadrats were averaged for each permanent plot to obtain a database with one row per plot and year of survey and one column per species. For each permanent plot, data collected the third year after restoration and from the last year surveyed were selected to build two vegetation matrices: post 3 years and post 4–11 years of dimensions 152×78 and 152×79 (row $\times$ species), respectively.

Our analytical approach included two steps: (1) we classified each plot into different restoration outcome categories; (2) we then searched the combination of indicator species cover and environmental and management variables at early stages of the recovery process that best predicted the success categories.

(1) In the first step, to control for the effect of different sector time since restoration at the time of their last survey (Table 1), a redundancy analysis (RDA) was run to remove the effect of year since restoration from the post 4–11 years matrix. A Hellinger

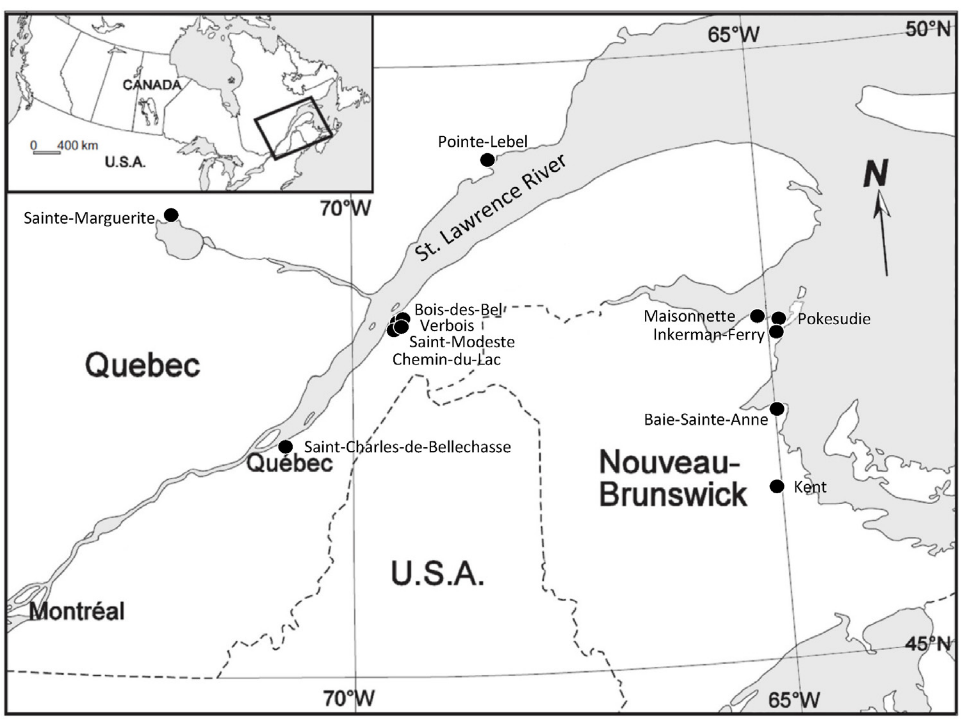

Fig. 1. Location of the 12 peatlands restored by the moss transfer technique in the eastern Canadian provinces of New Brunswick and Quebec.

Table 2
Key environmental and management variables to predict the outcome of restoration in the 41 peatlands restored by the moss transfer technique. See the text for codification of blockage of secondary ditches and delay in P fertilization.

Peatland complex name	Restoration year	Blockage of secondary ditches	Temperature in summer (Jul–Aug) (°C)	Precipitation in summer (mm)	Delay in P fertilization (yr)	Restoration in spring[a]
Baie-Sainte-Anne	2000	4	20.1	137	4	No
Bois des Bel	2000	4	17.1	195	0	No
Chemin du Lac	1997	4	16.7	148	2	No
Chemin du Lac	1999	4	16.6	181	4	No
Chemin du Lac	2000	4	17.1	195	4	No
Chemin du Lac	2001	4	17.6	95	4	No
Chemin du Lac	2002	4	16.5	204	4	No
Chemin du Lac	2003	4	16.8	669	4	No
Inkerman Ferry	1997	4	18.7	183	1	No
Inkerman Ferry	2008	4	18.0	135	4	No
Kent	2001	3	18.4	162	0	No
Kent	2007	4	19.3	181	4	No
Kent	2008	2	18.7	326	4	No
Kent	2008	4	18.7	326	4	No
Kent	2008	1	18.7	326	4	No
Kent	2008	1	18.7	326	4	No
Kent	2008	4	18.7	326	4	No
Maisonnette	2000	3	19.7	114	2	No
Maisonnette	2006	4	18.0	201	0	No
Pointe-Lebel	2004	3	16.3	212	0	Yes
Pokesudie	2006	4	18.0	201	0	No
Pokesudie	2008	4	18.0	135	0	No
Saint-Charles-de-Bellechasse	1999	2	17.5	176	0	No
Sainte-Marguerite (Section E)	2000	4	16.7	210	0	No
Sainte-Marguerite (Section K)	2000	2	16.7	210	0	Yes
Sainte-Marguerite (Section AA)	2001	1	16.7	210	0	Yes
Sainte-Marguerite (Section E)	2001	3	16.7	210	0	Yes
Sainte-Marguerite (Section G)	2001	N.D.	16.7	210	0	Yes
Sainte-Marguerite (Section K)	2001	3	17.2	140	0	No
Sainte-Marguerite (Section L)	2001	2	17.2	140	0	No
Sainte-Marguerite (Section AA)	2002	1	17.2	140	0	Yes
Sainte-Marguerite (Section H)	2002	3	16.7	159	1	No
Sainte-Marguerite (Section J)	2002	2	16.7	159	5	No
Sainte-Marguerite (Section AA)	2003	1	16.7	159	0	Yes
Sainte-Marguerite (Section DD)	2003	1	16.2	142	0	No
Sainte-Marguerite (Section F)	2003	2	16.7	159	0	Yes
Sainte-Marguerite (Section AA)	2004	1	16.2	142	0	Yes
Saint-Modeste	1997	4	16.7	148	4	No
Saint-Modeste	1997	4	16.7	148	0	No
Verbois	2005	4	16.8	118	4	No
Verbois	2006	4	16.7	284	4	No

N.D.: No data.
[a] Restoration could be conducted in spring, summer or fall and have an influence on the resulting plant community due to the effects of heavy machinery working on wet bare peat following spring snowmelt (see text), being summer and fall better seasons to obtain a *Sphagnum*-dominated plant community (González and Rochefort, 2014).

transformation was applied to species cover in order to account for the occurrence of double zeros (Legendre and Gallagher, 2001). The significance of the RDA was assessed using a permutation test with 9999 randomized runs (Legendre and Legendre, 2012). The residuals of the RDA were classified into k groups by a k-means partitioning that maximized the Calinski–Harabasz criterion (Milligan, 1996). The species composition of each group was explored to assign a restoration outcome category to each of the obtained k groups. Success was defined as the re-establishment of a *Sphagnum* carpet typical of bogs, but the expected plant cover and composition could not be defined in more detail before implementing the clustering of plots. In other words, success was defined qualitatively *a priori* and quantitatively *a posteriori*.

(2) We then conducted a linear discriminant analysis (LDA) with the post 3 years matrix and key environmental and management variables to find the best combination of ecological indicators 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 restored sectors were the observations, species cover in the post 3

year matrix and the environmental and management variables were the descriptors, and the restoration outcomes categories defined after examining vegetation composition in the post 4–11 year matrix were the 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 and 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 received the highest score. In our case, the LDA model, and particularly its classification functions, served as a tool to forecast the restoration outcome category to which a newly restored plot is most likely to belong.

Since a higher number of observations than the number of predictors plus the number of groups is recommended (Ter Braak, 1987), our analysis included only environmental and management variables that played a key role in explaining peatland restoration success (González and Rochefort, 2014) and those species that had an a priori high discrimination power between success categories (González et al., 2013). The choice of these species was assessed by indicator value indices in the post 3 year matrix (IndVal Dufrêne and Legendre, 1997). The IndVal combines the species' relative abundance with its relative frequency of occurrence to statistically determine species associated to one or several particular site categories. The significance of the indicator value of each species was assessed by a randomization procedure with 9999 permutations (Legendre and Legendre, 2012). The cover of each of the selected species by IndVal in the post 3 year matrix was $\ln(x+1)$ transformed before computing the LDA, in order to decrease the heterogeneity of the within-group covariance matrices (Borcard et al., 2011). LDA models were calibrated using 75% of the sectors (31 sectors), which were randomly chosen and included 119 plots. The remaining 25% (10 sectors including 33 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 set 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 2.14.0) software (R Development Core Team, 2011). More precisely, RDA and k-means partitioning were run using the functions "rda" and "cascadeKM" of the "vegan" package (Oksanen et al., 2011); the IndVal indices were computed using the function "multipatt" of the "indicspecies" package (De Caceres and Legendre, 2009); and LDA was computed using the function "lda" in the "MASS" package (Venables and Ripley, 2002).

2.4. Applying the lda model to predict the fate of newly-restored peatland

Finally, once the LDA model was calibrated and validated, we used one "new" additional peatland recently restored in 2009 to illustrate the use of the model to predict restoration success. This 8-ha restored peatland was located in the Pointe Lebel peatland complex (49°08′50′′N 68°15′22′′W, Fig. 1). The success predictions were done on six plots whose vegetation was surveyed in 2012 (third year after restoration) and information on key environmental and management variables was collected as required by the model. Subsequently, we considered management alternatives. As during calibration and validation operations, raw data (IndVal species cover, %) from the newly-restored peatland were $\ln(x+1)$ transformed, and then, together with the key environmental and management variables, multiplied by the corresponding weights of the classification functions. The success category whose classification function received the highest score was assigned to each new plot.

3. Results

3.1. Classifying restored peatlands 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 only explained 4.5% of the variability in the species composition of the Post 4–11 years vegetation matrix (RDA, permutation test, 9999 runs, $F = 8.1388$, $P < 0.001$). Well-established 3 years after restoration, the community's species composition remained rather stable throughout the study period, and changes were probably due to differences in species' architecture and growth rate rather than species turnover. Woody species with slow growth rates, such as *Chamaedaphne calyculata* and *Ledum 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), had the highest positive correlation with plots restored longer time ago; bare peat and *Eriophorum vaginatum*, one of the few species that can spontaneously colonise peatlands after peat extraction activities (Campbell et al., 2003), appeared more often at the more recently restored sites.

Once the effect of sector "time since restoration" was removed, k-means partitioning separated the 152 plots into three categories. A first category of 67 plots was primarily dominated by *Sphagnum rubellum* (mean cover = 26%), *Eriophorum vaginatum* (mean cover = 31%), and *Polytrichum strictum* (mean cover = 9%) (Fig. 2). This category was thus defined as *Sphagnum*-dominated restoration. A second category of 44 plots, characterized by a low moss cover (mean cover = 26%, Fig. 2) and a mean cover of bare peat of almost 50%, was considered as bare peat-dominated restoration. A third category of 41 plots was almost exclusively dominated by *Polytrichum strictum* (mean cover = 52%, Fig. 2). The dominant moss of this category has been recognized as nurse species for the establishment of *Sphagnum* and other typical bog species, due to their capacity to stabilize disturbed substrates and improve microclimatic conditions (Groeneveld and Rochefort, 2005; Groeneveld et al., 2007). Only long-term follow-up would determine whether the few *Sphagnum* colonies in these plots will eventually outcompete *P. strictum* (Groeneveld and Rochefort, 2002). It should be noted that, although "time since restoration" was removed from our analyses, *Polytrichum*-dominated plots were not among the ones restored more recently (Table 1). However, at this point, these plots appear to be settling into an alternative stable state (Beisner et al., 2003) for which additional human intervention would be recommended to promote the development of the desired *Sphagnum* carpet. On the other hand, 10 years of *Polytrichum*-moss establishment and growth contributes to form a dense and thick carpet accumulating about 5 mm of *Polytrichum*-moss fiber per year (Rochefort, field observation). The thickness of the *Polytrichum*-moss carpet accumulated since restoration (newly accumulated biomass) is very easy to determine as the top limit of the residual peat deposit is clearly identifiable. This could be also a good restoration outcome if mostly substrate stabilisation and C sequestration functions are considered as goals.

3.2. Building a lda model to predict restoration success early in the monitoring process

The IndVal method identified a total of 20 species as indicators of the different success categories, based on vegetation cover data collected at the third year after restoration (post 3 year matrix). However, we only considered the five species with an IndVal > 0.40

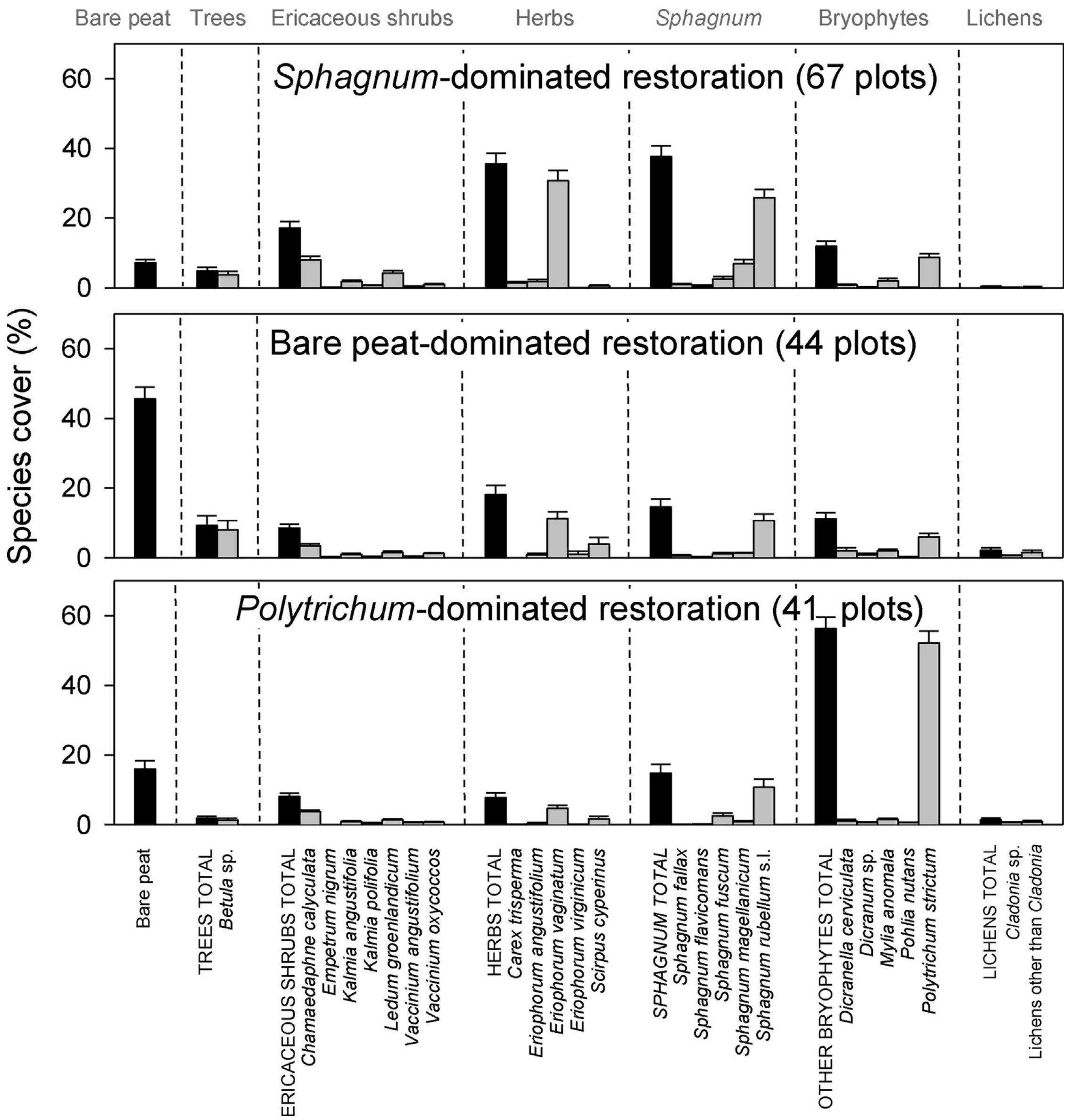

Fig. 2. The most abundant (mean cover >1% at any of the success categories) species classified by life form in the 152 permanent plots of 41 peatlands restored 4–11 years ago and clustered in 3 restoration outcome categories after k-means partitioning: *Sphagnum*-dominated, bare peat-dominated and *Polytrichum*-dominated plots. Plots where the species was not present were also taken into account for calculation of species cover.

Table 3
List of species with an *a priori* high discriminant power among success categories according to IndVal methodology (Dufrêne and Legendre, 1997). For each species *j* in each restoration outcome category, IndVal computes the product of two values, A_{kj} and B_{kj}. A_{kj} is a measure of specificity based on abundance values whereas B_{kj} is a measure of fidelity computed from presence data. $IndVal_{kj}$ ranges from 0 (species *j* not present in any of the objects of the restoration outcome category *k*) to 1 (species *j* present only in objects of restoration outcome category *k* and in all of them). IndVal analyses were conducted for the vegetation data at the third year since restoration (post 3 year vegetation matrix in the text).

	Life form	IndVal	*P*-value	Absolute cover ± SE (%)[a]	Specificity	Fidelity
Sphagnum-dominated restoration (67 plots)						
Sphagnum spp.	*Sphagnum*	0.48	0.005	12.7 ± 1.6	0.48	1.00
Eriophorum vaginatum L.	Herbs	0.56	<0.001	16.6 ± 2.1	0.60	0.94
Bare peat-dominated restoration (44 plots)						
Lichens	Lichens	0.43	0.001	0.2 ± 0.0	0.54	0.80
Polytrichum-dominated restoration (41 plots)						
Polytrichum strictum Brid.	Bryophytes	0.63	<0.001	24.9 ± 2.6	0.63	1.00
Chamaedaphne calyculata (L.) Moench	Ericaceous shrubs	0.50	<0.001	1.6 ± 0.2	0.50	1.00

[a] Plots where the species was not present were also taken into account for calculation of absolute cover.

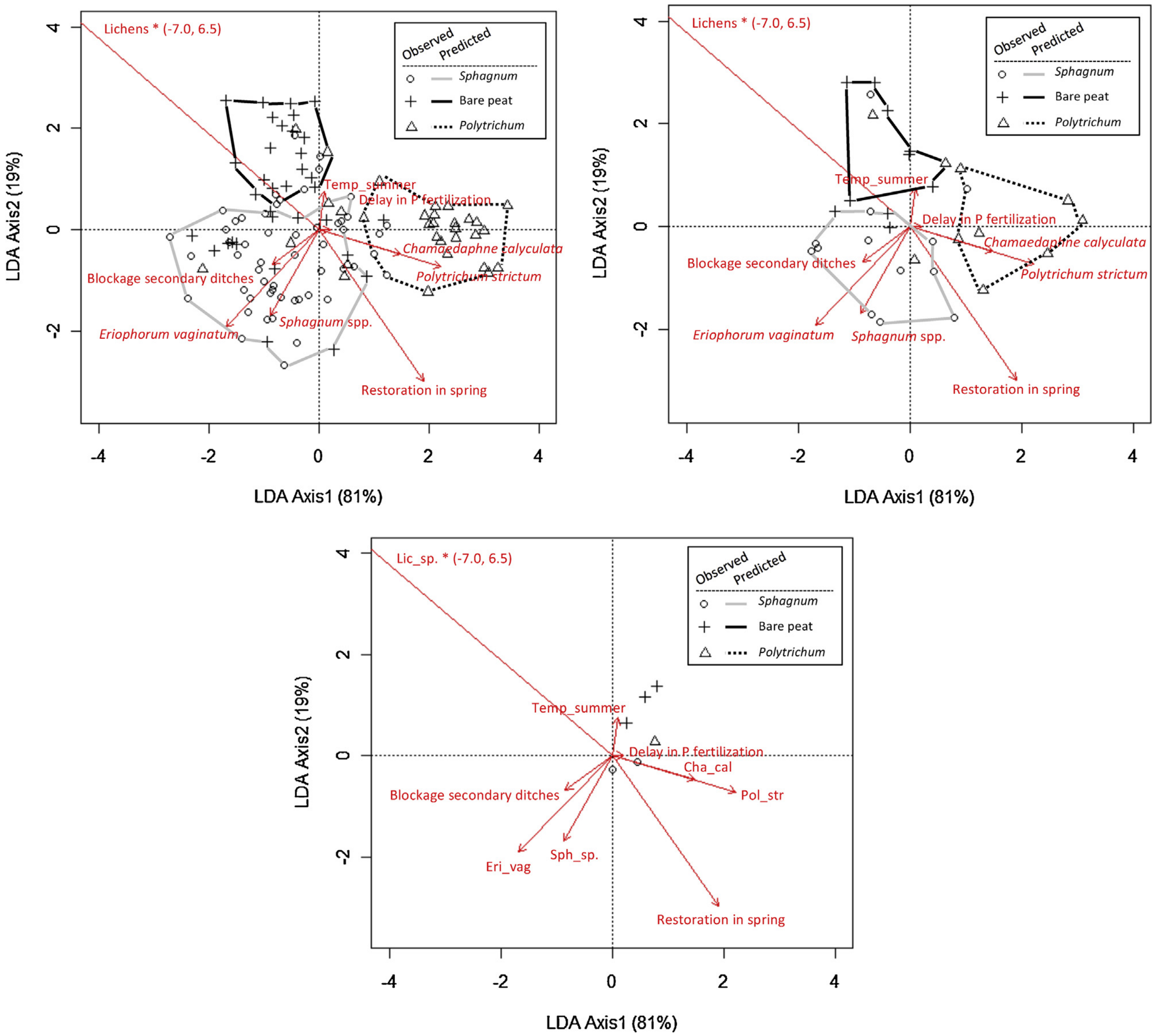

Fig. 3. Linear discriminant analysis (LDA) of success categories based on ln(x + 1) transformed species abundance 3 years after restoration work. LDA was conducted with four environmental and management variables that play a key role in explaining restoration success (González and Rochefort, 2014; Table 2) and five species with an *a priori* high discriminant power as selected by IndVal > 0.40 and $P < 0.01$ (González et al., 2013; Table 3). Vector length has been multiplied by 3.5 to improve visual clarity. All plots within the limits of each polygon were assigned to the corresponding restoration outcome category using the classification functions. (a) Calibration step (75% of the sectors, 31 sectors including 119 plots) and (b) validation step (25% of the sectors, 10 sectors including 33 plots) and (c) application phase (6 plots set up at one newly-restored extracted peatland, Table 3). Note that the percentages of plots that were correctly classified were used to calculate the accuracy of the model (71% for calibration data and 75% for validation data).

and $P < 0.01$ (Table 3). Such a restrictive threshold was considered necessary to discard less frequent and more regional species, which could have biased the models by having a disproportionate weight. LDA is not a method specifically designed for species abundance, which generally deviates from multinormality. By working only with strong indicator species, we considered those that deviated least from normality, thereby obtaining a more robust model that still exhibited a high level of accuracy.

The best LDA model correctly classified 71% of the plots: 78, 56 and 74% of the *Sphagnum*-dominated, bare peat-dominated and *Polytrichum*-dominated plots of the calibration data (Fig. 3a) and 75% of the validation data: 85, 70 and 70% (Fig. 3b). For example, from the ten plots identified as *Polytrichum*-dominated plots in the validation dataset (triangles in the Fig. 3b), two were predicted as bare peat-dominated restoration, one as *Sphagnum*-dominated and the remaining seven were correctly classified (polygons, Fig. 3b). The first LDA axis divided *Polytrichum*-dominated plots from the *Sphagnum*-dominated and bare peat-dominated plots, while the second axis mainly divided bare peat-dominated from *Sphagnum*-dominated plots (Fig. 3a,b). Not surprisingly, the five species assigned by IndVal contributed positively to the restoration outcome category (arrows in Fig. 3 pointing in the direction of the group that species represented according to IndVal). The key environmental and management variables were also in accordance with our expectations. Higher summer temperatures during the first year post restoration discriminated the bare peat-dominated category from the other two success categories, a more efficient blockage of the secondary ditches was related to *Sphagnum*-dominated restoration and restoring in spring favoured the establishment and development of *P. strictum*-dominated communities. Precipitation in summer was not included in the models for having a very low discriminant power, despite being ecologically relevant to explain success in restored peatlands, with wetter summers related to a higher cover of *Sphagnum* (González and Rochefort, 2014). The delay in P fertilization played a marginal role, but it improved the accuracy of the models and was kept in.

3.3. Applying the lda model to predict the fate of a newly-restored peatland

Finally, the LDA model was used as a tool to forecast the outcome of one additional peatland restored in 2009 after horticultural peat extraction, and surveyed 3 years later in 2012. Feeding the LDA discriminant functions (Appendix A) with the ln $(x+1)$ transformed vegetation data and the key environmental and management variables, we were able to predict the position of the six plots surveyed in those sectors along the gradients given by the LDA axes. Using the classification functions (Appendix B), we predicted the expected restoration outcome only 3 years after work was completed (*Sphagnum*-dominated, 2 plots; bare peat-dominated, 3 plots; *Polytrichum*-dominated, 1 plot; Fig. 3c).

4. Discussion

4.1. Ecological indicators combined by LDA can predict restoration outcomes

By combining several indicator species with key environmental and management information, LDA can produce predictive models that account for more of the complexity existing in ecosystems than indicators considered individually. This spares practitioners the dilemma of interpreting several indicators simultaneously with thresholds demanding expert knowledge (González et al., 2013) and contributes to the need of finding systematic, objective and standard evaluation criteria to determine success of completed projects (Palmer et al., 2005; Bernhardt et al., 2007; Kondolf et al., 2007).

The practitioner's in-the-field and computation efforts will be greatly facilitated by the fact that the LDA model only included a selection of several species or higher level taxa easily identifiable in the field, and a few meteorological and management variables which are easy to document as well. Moreover, raw plant cover data requires only a logarithmic transformation before feeding the linear equations (discriminant and classification functions, Appendix A and B). We believe that simplifying the evaluation process in this way, without compromising its quality, represents a major contribution for any adaptive management strategy. For example, the model predicted different restoration outcomes for the six plots randomly sampled across the newly-restored peatland that we used for illustrative purposes. The lack of success (50% of the plots being bare-peat dominated and 16% being *Polytrichum*-dominated, Fig. 3c) may be due to unsatisfactory re-profiling (step 1 of the moss layer transfer technique), or to water or wind blow of *Sphagnum* propagules and plant fragments soon after introduction (step 2). In such cases, the required interventions might consist of targeted actions, such as the construction of small hydrological structures (dams, berms) followed by the manual introduction of *Sphagnum*, or in case of occurrence of frost heaving, a more careful application of straw mulch and phosphorus fertilization to enhance peat stabilization by *P. strictum* establishment (steps 3 – mulch application and 4 – optionally, P fertilization; Groeneveld and Rochefort, 2002, 2005).

4.2. Further considerations to use LDA models in prediction of restoration success

The LDA methodological approach presented in this paper is applicable to any restoration project having a specific goal for which clear success categories may be defined. In our example, we used clustering to define success categories, but even abundance of key species could be used to facilitate the work of restoration practitioners. With a less systematic definition of success, a reduction in the accuracy of the LDA predictive models would be expectable, but models would be equally legitimate. Success does not necessarily have to be represented by a static desired final stage, but can be a successional trajectory towards a self-regulating functional ecosystem. For example, dominance by a keystone species such as *Sphagnum* in restored peatlands would favour the long-term recovery of the acrotelm and accumulation of peat (van Breemen 1995; Rydin and Jeglum, 2013; Graf and Rochefort, 2014). This is compatible with the emerging view of restoration that advocates for a more pragmatic focus on recovering ecological processes and successional trajectories rather than targeting a specific ecosystem structure or components (targeted restoration, Dufour and Piégay, 2009 process-based restoration, Beechie et al., 2010 intervention ecology, Hobbs et al., 2011; open-ended restoration, Hughes et al., 2011 etc.). However, regardless of how success is defined, it must be evaluated quantitatively (Bernhardt et al., 2007). Accepting a dynamic definition of success also implies that success categories may change over time. For example, some of the plots defined as *Polytrichum*-dominated may become successful or failed beyond the time span covered by the post-restoration monitoring of this work (González and Rochefort, 2014). But even in that case, our LDA model still provides an unequivocal prediction of success, since the model assigns one and only one category (*Sphagnum*-dominated, bare peat-dominated or *Polytrichum*-dominated) to each plot for the period 4–11 year.

The second condition for applying the proposed approach is the presence of a post-restoration monitoring program that has collected plant cover data of several restoration projects at least twice over time, so that retrospective analyses can be conducted to find the best combination of indicators of success. We believe this type of monitoring data often exist but efforts to gather data dispersed in different research groups or non-profit organizations will have to be made. In the case study of peatlands restored after peat extraction activities, plant composition after restoration is generally determined very rapidly ("time since restoration" effect was low); restoration success can thus be evaluated with confidence at the early stages of a monitoring program. This observation is of great importance, because it guarantees the reliability of predictive models based on plant data collected soon after restoration work. In ecosystems naturally subjected to higher disturbances than peatlands, such as river floodplains, greater unpredictability of successional trajectories may be expected, and success could probably not realistically be predicted shortly after project implementation (Hughes et al., 2005, 2011; Kondolf et al., 2007).

Third, it is worth mentioning that while our LDA model is valid for peatlands restored after horticultural peat extraction activities in Eastern Canada, future models must be calibrated using local restoration outcomes, species and ecological indicators of each ecosystem and world region. We anticipate, however, that local LDA models will be probably best fitted with analog species and similar key environmental and management variables if the same restoration method (moss layer transfer technique) is the one chosen for restoration.

Finally, we recommend that highly-accurate post-restoration monitoring programs continue after predictive LDA models have been built, so that models can be improved in the future with data covering longer time periods, more sites and wider geographic areas.

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Appendix A.

Scores of linear discriminant functions. In order to find the position of the plots (including newly-restored plots) into the canonical space of our LDA model (Fig. 3), raw data for the species cover (%) needed to be $\ln(x+1)$ transformed and the mean value of the corresponding species subtracted before being multiplied by each coefficient. For the key environmental and management variables, only subtract the mean value before multiplying by each coefficient is necessary, as no transformations were applied. Means ($\ln(x+1)$ transformed for species cover, %) were obtained from the calibration dataset. Code for restoration in spring: 1 – restored in spring, 0 – no restored in spring.

	LDA1	LDA2	Means
Chamaedaphne calyculata (L.) Moench	0.4227	−0.1338	0.5931
Eriophorum vaginatum L.	-0.4806	-0.5433	1.5832
Lichens	-1.9865	1.8697	0.1318
Polytrichum strictum Brid.	0.6319	-0.2056	2.0110
Sphagnum spp.	-0.2504	-0.4827	1.8682
Blockage secondary ditches	-0.2402	-0.1940	3.286
Temperature in summer (°C)	0.0279	0.2155	17.63
Delay in P fertilization (years)	0.0595	0.0007	1.513
Restoration in spring	0.5456	-0.8524	0.1597

Appendix B.

Scores of classification functions to predict success category of plots. Each plot is assigned to the success category corresponding to the function receiving the highest score. Raw data (species cover, %) need to be $\ln(x+1)$ transformed before being multiplied by the corresponding species weight.

	Sphagnum-dominated	Bare peat-dominated	*Polytrichum*-dominated
Constant	−436.222463	−437.6453241	−437.745850
Chamaedaphne calyculata (L.) Moench	19.941864	19.7452415	20.849501
Eriophorum vaginatum L.	−1.934537	−2.5388147	−3.314788
Lichens	−41.773772	−39.3729441	−45.418111
Polytrichum strictum Brid.	23.204962	22.9044345	24.558950
Sphagnum spp.	1.348233	0.7958316	0.529222
Blockage secondary ditches	13.363857	13.1541889	12.712903
Temperature in summer (°C)	43.161492	43.4154813	43.333634
Delay in P fertilization (years)	5.218321	5.2138817	5.355788
Restoration in spring	44.302351	43.2396380	45.133533

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