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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.
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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

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