Restoration and Reclamation of Boreal Ecosystems

Attaining Sustainable Development

DALE H. VITT
Department of Plant Biology and Center for Ecology, Southern Illinois University, Carbondale, IL, USA

JAGTAR S. BHATTI
Canadian Forest Service, Northern Forestry Centre, Edmonton, AB, Canada

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town,
Singapore, São Paulo, Delhi, Mexico City

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by
Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9781107015715

First published 2012

Printed and bound in the United Kingdom by the MPG Books Group.

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data
Restoration and reclamation of boreal ecosystems : attaining sustainable
development / [edited by] Dale Vitt, Jagtar Bhatti.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-107-01571-5 (hardback)
1. Taiga ecology. 2. Rain forest ecology. 3. Rain forest conservation.
4. Taiga conservation. 5. Forest ecology. I. Vitt, Dale H. (Dale Hadley), 1944–
II. Bhatti, J. S. (Jagtar S.)
QH541.5.T3V55 2012 577.3′7–dc23 2012015310

ISBN 978-1-107-01571-5 Hardback

Contents

Contributors — *page* viii
Preface — xiii

Part 1
Utilizing natural regimes as models for reclamation and restoration — 1

1 The changing boreal forest: Incorporating ecological theory into restoration planning — 3
DALE H. VITT AND JAGTAR S. BHATTI

2 Disturbance and the peatland carbon sink in the Oil Sands Administrative Area — 13
R. KELMAN WIEDER, MELANIE A. VILE, KIMBERLI D. SCOTT, DALE H. VITT, ERIN BRAULT, MICHELLE HARRIS, AND STEPHEN B. MOWBRAY

3 Regional-scale modeling of greenhouse gas fluxes — 23
PAVEL JURUŠ, PETR MUSILEK, YAQIONG LI, AND JAMES RODWAY

4 Reclamation and restoration of boreal ecosystems: attaining sustainable development: Modeling and mapping vegetation type by soil moisture regime across boreal landscapes — 56
DOUG HILTZ, JOYCE GOULD, BARRY WHITE, JAE OGILVIE, AND PAUL ARP

Nyberg, J. (1985). *Predicting Red Huckleberry Biomass from Plant Dimensions and Percent Cover*. Research Branch, Ministry of Forests, Victoria, BC. Publication No. WHR-18.

Schaffer, W., Beck, B., Beck, J., Bonar, R., Hunt, L. (1999). *Northern Goshawk Reproductive Habitat: Habitat Suitability Index Model, Version 3*. Foothills Model Forest, Hinton, AB.

Skinner, D. L. (1996). *Habitat Suitability Models for the Suncor Study Area*. Report by Westworth, Brusnyk and Associates for Suncor Energy Ltd., Ft. McMurray, AB.

Turcotte, I., Quideau, S. A., Oh, S. W. (2009). Organic matter quality in reclaimed boreal forest soils following oilsands mining. *Organic Geochemistry*, **40**, 510–519.

Welham, C. (2004). *Deriving Multipliers and Nutrient Regime Classes for the Land Capability Classification System using the Ecosystem Simulation Model, FORECAST*. Final report in partial fulfillment of CEMA Contract No. 2003-0007.

Welham, C. (2005a). *Evaluating a Prescriptive Approach to Creating Target Ecosites using D-Ecosites as a Test Case*. Final report in partial fulfillment of CEMA Contract No. 2004-0014.

Welham, C. (2005b). *Evaluating Existing Prescriptions for Creating Target Ecosites using the Ecosystem Simulation Model, FORECAST: Implications for Ecosystem Productivity and Community Composition*. Final report in partial fulfillment of CEMA Contract No. 2005-0025.

Welham, C. (2006). *Evaluating Existing Prescriptions for Creating Target Ecosites using the Ecosystem Simulation Model, FORECAST: Implications for ecosystem productivity and Community Composition in Reclaimed Overburden*. Final report in partial fulfillment of CEMA Contract No. 2006-0030.

MARTHA D. GRAF, VICKY BÉRUBÉ, AND LINE ROCHEFORT

12

Restoration of peatlands after peat extraction

Impacts, restoration goals, and techniques

INTRODUCTION

In North America peat is extracted mainly for horticultural purposes. Weakly decomposed *Sphagnum* peat is the best horticultural peat; therefore, in the order of 25,000 ha (past and present combined) of *Sphagnum*-dominant peatlands (primarily bogs) are affected by this industry (Environment Canada, 2010). To promote long-term extraction, a minimal peat depth of 2 m and area of 50 ha is encouraged, although not obligatory. Peatlands close to infrastructures, like roads and electricity, are more economical to develop. Additionally, most exploited peatlands are close to human settlements so that labor needs can be met. Peat extraction is an important economic activity in non-urban areas (Keys, 1992; Daigle and Gautreau-Daigle, 2001; Rochefort 2001). This has created a disequilibrium where most disturbed peatlands are located in southern Canada and the northern peatlands remain mostly untouched by industry (Rochefort, 2001). However, new developments in mining, forestry, and the oil and gas industry have begun to disturb northern peatlands (Schneider and Dyer, 2006; Turetsky and St. Louis, 2006).

The most significant areas of peat extraction in North America are in the provinces of Quebec, New Brunswick, and Alberta. An impact assessment of horticultural peat industries on peatlands showed a total of 24,000 ha have been used for peat extraction since the settlement of Canada (Environment Canada, 2010). The last data provided by the Canadian Sphagnum Peat Moss Association showed that 14,000 ha of peatlands were still in production in 2006. Consequently, production

Restoration and Reclamation of Boreal Ecosystems, ed. Dale Vitt and Jagtar Bhatti. Published by Cambridge University Press.

has ceased on a total of 3900 ha. As of 2006, 1800 ha were restored or were being restored or reclaimed. Finally, from 2007 to 2011, the industry is projecting restoration or reclamation of 3100 ha of peatlands affected (Canadian Sphagnum Peat Moss Association, personal communication). Peatland restoration attempts to resolve the conflict between the economic value and the environmental value of peatlands by allowing the return of ecological functions after peat extraction to restore a wetland habitat in the landscape (Rochefort and Lode, 2006).

SCOPE AND TOPICS OF THIS CHAPTER

The restoration of boreal peatlands affected by peat extraction has already been thoroughly reviewed by other authors (Price et al., 2003; Rochefort et al., 2003; Rochefort and Lode, 2006). This chapter will give a brief overview of the topics already discussed in these previous works. Our aim is to report this information in such a way that is easily accessible to practitioners. We will focus on fen restoration research, as it is extremely pertinent to the recent expansion of the oil and gas industry in northern Alberta. Lastly, we will review how applicable these restoration techniques are to restoration of peatlands affected by other land uses, such as the oil and gas industry and forestry.

Abandoned peatlands with deep layers of residual organic matter are referred to as "cutover" peatlands. "Cutaway" peatlands are where most peat has been removed by industrial means and will often show part of the exposed mineral soil. This terminology will be used throughout this chapter to distinguish the two types of abandoned peatlands.

PEAT EXTRACTION

Modern, large-scale peat extraction is carried out using large vacuums pulled by tractors, which remove thin layers of dry peat at every passage (Figure 12.1A). Peat extraction is carried out in six steps. First, a drainage system is installed by digging deep drainage canals around the area to be extracted and drainage ditches every 30 m. Second, the vegetation layer (acrotelm) including trees, shrubs and *Sphagnum* moss is removed to expose the peat below. Then, each peat field is profiled into a dome-shape to improve drainage (Figure 12.1B). The extraction and pilling of the peat, including the packing, transformation, and delivery are the next steps. Finally, when the upper peat layers have been extracted and mineral ground is exposed or a more decomposed, sedge–peat layer (hereafter referred to as fen peat) is reached, the extraction activities are abandoned because of the low horticultural quality of this peat. Ecosystem

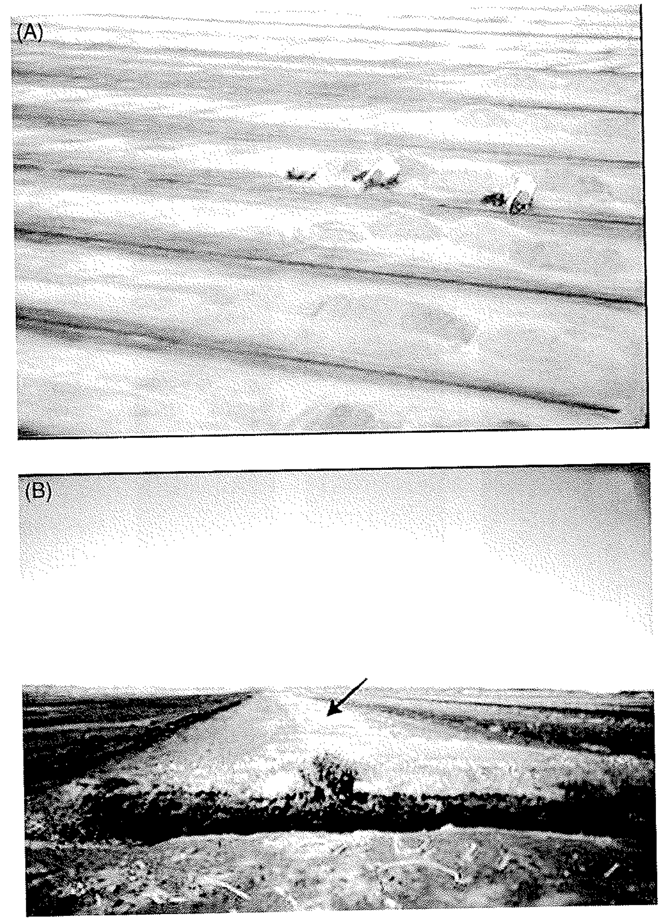

Figure 12.1. Photographs illustrating the extent of the disturbance to a peatland when vacuum-milled. (A) shows the vacuum machines being pulled by tractors. (B) shows the dome-shaped contour of the peat field (arrow), which facilitates the drying and drainage of the peat. (Photographs by M. Poulin of Peatland Ecology Research Group.)

restoration or rehabilitation is then planned (Keys, 1992; Daigle and Gautreau-Daigle, 2001; Rochefort, 2001).

HOW PEAT EXTRACTION IMPACTS PEATLANDS

Drainage and removal of acrotelm

Peatlands are composed of a two-layered (diplotelmic) soil structure; the upper layer is the acrotelm and the lower layer is the catotelm

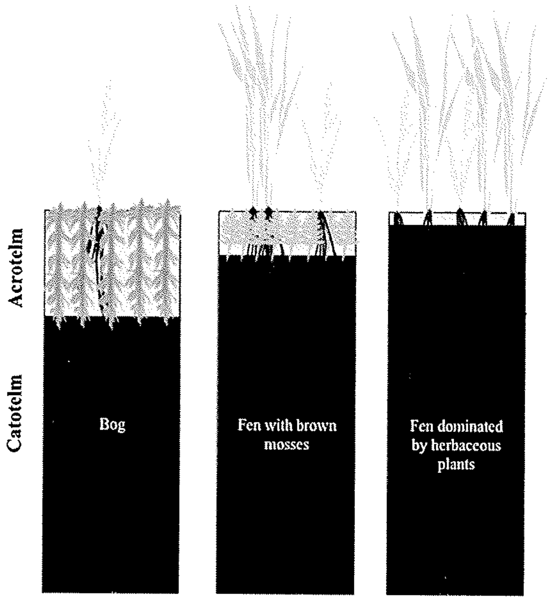

Figure 12.2. The acrotelm and catotelm of bogs and fens. The acrotelm layer is thickest in bogs and thinner in fens. It is virtually nonexistent in fens dominated by herbaceous plants. It is not known how important the acrotelm layer is in the hydroregulation and the carbon-accumulating capacity of fens.

(Figure 12.2). The acrotelm is the uppermost layer of the peat deposit and is composed of live and slightly decomposed vegetation. It is characterized as having a variable water content, high hydraulic conductivity, periodic aeration, and intense biological activity (Ingram, 1978; Ivanov, 1981). The acrotelm contains a propagule bank and has the capacity to regenerate within a few years if a thin part of the top layer is burned by fire (Wieder et al., 2009) or removed mechanically (Rochefort and Campeau, 2002; Rochefort et al., 2003). The catotelm, the lower level of more decomposed peat, is characterized by constant water content, very low hydraulic conductivity, and anaerobic conditions. Natural peatlands rely on this structure to regulate water storage and discharge, thus creating constantly saturated conditions that are ideal for carbon storage (Price et al., 2003). Carbon is sequestered by the submergence of organic matter at the base of the acrotelm, or as seen from the opposite perspective, by the thickening of the catotelm (Clymo, 1984).

The removal of the acrotelm strongly affects the water storage capacity, the magnitude of evaporation losses, as well as soil processes,

including carbon storage (Price et al., 2003). Drained peat undergoes subsidence in the unsaturated zone and compression in the saturated zone, which changes the soil pore structure. The peat is further compacted by the numerous passages of machinery. The change in pore structure decreases the water storage capacity and hydraulic conductivity, which exacerbates the fluctuation of the water table (Price et al., 2003). Compression and oxidation can decrease hydraulic conductivity by 75% (Price et al., 2003). The dark color of exposed peat from the catotelm increases surface temperatures and, indirectly, evaporation. All of these factors create conditions that are unfavorable to the establishment of typical peatland plant communities, especially bryophytes (Sagot and Rochefort, 1996).

Increase in pH and peat contamination from mineral soil

In some cases, peat companies remove the entire *Sphagnum* peat layer, leaving either more decomposed fen peat, or in some extreme situations, the part of mineral soil. This residual peat is richer in minerals and higher in pH than the preexisting bog (Wind-Mulder et al., 1996; Wind-Mulder and Vitt, 2000; Graf et al., 2008). Therefore, returning the site back to its previous state is nearly impossible and restoration toward a fen or marsh ecosystem is encouraged. The richer residual peat or the mineral soil allows for the establishment of spontaneous vegetation. These sites are mainly revegetated by wetland species, but peatland species, especially bryophytes and sedges, usually do not reestablish (Graf et al., 2008). They are also more susceptible to be colonized by invasive species (Zedler and Kercher, 2004). The species and cover of the spontaneous vegetation will impact the restoration approach.

Surface instability

Soil erosion caused by water and wind is a common problem in unvegetated areas (Tallis 1987; Quinty and Rochefort 2000). Snowmelt, heavy rains, and periodic flooding can form gullies and move soil sediments away, burying plants and blocking drainage ditches. Peat oxidation on exposed peat areas affects plants by slowly exposing their roots (Waddington and McNeil, 2002).

Rewetted sites are often plagued by surface instability in the form of needle-ice formation. This phenomenon, known as frost heaving, has been recognized as a major factor limiting plant reestablishment on bare peat. Frost heaving not only damages plants, but also destroys the structure of surface peat and contributes to the process of deflation (Groeneveld and Rochefort, 2002). Frost heaving is most destructive to seedlings and bryophytes because they lose contact with the soil surface and become prone to desiccation. If a plant survives its frost heaving period, it has a much better chance of surviving to a productive age. Surface instability is best combated by the use of straw mulch or a nurse plant, as discussed later.

RESTORATION GOALS

In North America, the central goal of peatland restoration after peat extraction is the return of a peat-accumulating system (Rochefort, 2000; Gorham and Rochefort, 2003). Modelization of restored sites showed that this goal could be reached within 20 years (Lucchesse et al., 2010). In order to achieve this long-term goal, the short-term aims are the reestablishment of: (1) a plant cover dominated by bryophytes and specifically for bog restoration; and (2) diplothelmic hydrological layers, which ensure the return of important peatland functions. The return of other ecosystem functions, like biodiversity (flora and fauna composition and ecosystem structure) biogeochemical cycling, and resistance to invasive plants are also important (Gorham and Rochefort, 2003; Rochefort, 2000).

A bryophyte-dominated plant cover is important to the peatland's ecosystem functioning (Vitt, 2000). *Sphagnum* is especially important to acrotelm hydroregulation because the loosely woven, expansible surface creates the capacity to store a large amount of water (Clymo and Hayward, 1982). It is not known to what extent brown mosses are important to fen hydrology. Mosses, both *Sphagnum* and brown mosses, are a major contributor to peat accumulation (Vitt, 2000). *Sphagnum* mosses and some species of brown mosses possess properties that create an acidic, nutrient-poor, heat-insulating, and slowly permeable environment ideal for peat accumulation (Andrus, 1986; van Breemen, 1995).

RESTORATION TECHNIQUES

Bog restoration

As peat extraction has mainly affected bogs, these peatlands have been the focus of restoration research. Over 20 years of restoration experiments in North America have shown that three active restoration measures are essential to successful bog restoration: (1) plant reintroduction, (2) the application of a protective mulch cover, and (3) the rewetting of the site by blocking drainage ditches and surface preparation (Rochefort et al., 2003; Rochefort and Lode, 2006). The essential steps of the moss layer transfer method will be discussed in more detail in the following sections.

Vegetation introduction

Reintroducing plant fragments in the form of diaspores is an essential step to restoring *Sphagnum*-dominated peatlands. Natural regeneration on cutover peatlands occurs very slowly and is not sufficient to restore the ecological functions of a peatland (Salonen, 1987; Bérubé and Lavoie, 2000; Campbell et al., 2003; Lavoie et al., 2003; Poulin et al., 2005). Many peatlands are void of vegetation after as much as 30 years of abandonment (Poulin et al., 2005), even though spores of mosses and the seeds of various ericaceous shrubs and trees are often abundant in residual peat (Campbell et al., 2000). As moss spores germinate only under specific and constant conditions (Clymo and Duckett, 1986), the reintroduction of fragments has proven to be the only viable alternative for restoring a *Sphagnum* carpet on a short-term basis. Once a *Sphagnum* carpet has been established, it is not necessary to reintroduce other peatland plants, as many will establish from the diaspore bank or will immigrate from residual peatlands in the proximity (Rochefort and Lode, 2006). Important features of successful reintroduction of bog vegetation are outlined as follows:

- *Sphagnum* should occupy a large percentage of the ground cover (>50%) at the donor site (Rochefort et al., 2003). Species such as *S. fuscum*, *S. rubellum*, and *S. angustifolium* should be target species, as they show excellent regeneration capacities (Campeau and Rochefort, 1996; Rochefort et al., 2003).
- Fragments from the top 10 cm of the vegetation surface are recommended as donor material because regeneration potential drops with increasing depth (Campeau and Rochefort, 1996; Rochefort and Lode, 2006).
- A donor site: restoration site ratio of 1:10 to 1:15 (depending on the original moss cover) is recommended to optimize establishment while minimizing donor site damage (Rochefort et al., 2003).
- Restoration should be kept in mind when planning extraction, as the acrotelm of new extraction sites can be used as donor material.
- These techniques can be carried out mechanically using locally available tractors and manure spreaders (see Figure 12.3) in order to restore large areas of cutover peatlands.

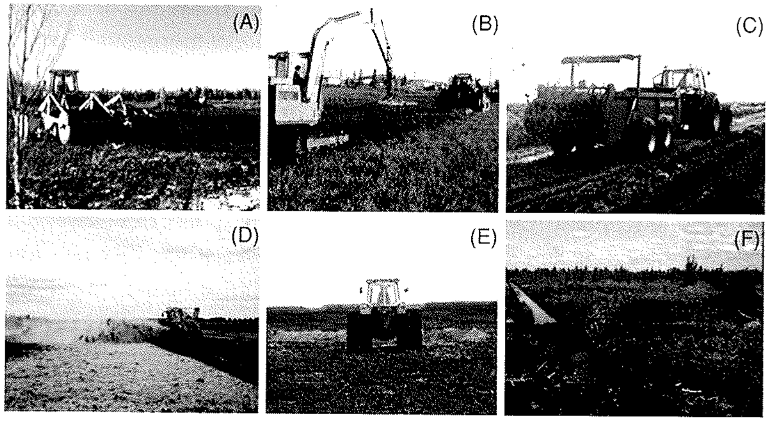

Figure 12.3. The six main mechanical steps: (A) site preparation, (B) diaspora collection, (C) spreading donor vegetation, (D) mulch application, (E) optional fertilization, and (F) blocking drainage ditches for the Sphagnum moss layer transfer approach to restore milled peatlands. (Photographs taken by the Peatland Ecology Research Group.)

- Material collection should be carried out in late autumn or early spring when the ground is frozen to minimize damage to the donor sites. If the material is collected at this time, the donor sites regenerate quickly (Rochefort and Campeau, 2002; Rochefort et al., 2003).

Application of mulch and nurse plants

Once the diaspore fragments have been introduced, a protective mulch cover should be applied as quickly as possible to protect fragments from desiccation (Sagot and Rochefort, 1996; Price et al., 1998). Although many forms of mulch have been tested (clear plastic cover, shading screens, snow fences, commercial mulchs), straw proved to be the most economic and effective mulch. The density of the mulch layer should be such that light can pass through it to reach the plant fragments, but thick enough to create an air layer.

Including nurse plants in restoration plans has been shown to improve the microclimate and increase the establishment of *Sphagnum* (Boudreau and Rochefort, 1999; Groeneveld et al., 2007). A common nurse plant for bog restoration is *Polytrichum strictum*, a pioneer moss species that can establish in the harsh conditions of a bare peat surface. Hence, here the restoration works in three successional steps: first, straw mulch improves the microclimate, aiding the establishment of

Polytrichum mosses, and is also an effective measure against frost heaving during the first two years post-restoration; second, a live mulch, such as *P. strictum*, grows thicker and protects the ground as the mulch decomposes and becomes less effective (Groeneveld et al., 2007). Eventually, *P. strictum* will be outcompeted by *Sphagnum* moss, starting plant autogenic succession.

In order to increase *P. strictum* establishment, fertilization with low doses (15 g m^{-2}) of phosphate rock may be carried out (Figure 12.3), although it is not mandatory. The use of fertilization remains a site-specific decision, dependent on the exposure to frost heaving, the probability of invasion by non-peatland invasive plants, and the inherent properties of a specific site (Sottocornola et al., 2007).

Rewetting

Restoring the hydrological regime is necessary for the establishment of target vegetation, nutrient cycling, and increasing energy capture rates of wetlands (Mitsch and Gosselink, 2000). However, simply rewetting a peatland is not an adequate measure to restore the hydrology, as fundamental soil properties are altered during peat extraction (Price et al., 2003). A restoration site should be seen as a new environment with new physical properties, especially in the upper peat layers (Rochefort and Lode, 2006). A number of techniques used to restore peatland hydrology are outlined as follows:

- Blocking drainage ditches is an important step in restoring wetland hydrology (Cooper et al., 1998; Price et al., 2003). This simple step will retain surface water and elevate the ground water level.
- Creating depressions and altering the basin morphology is common for the construction of wastewater wetlands and has also been suggested for peatland restoration (Wheeler and Shaw, 1995; LaRose et al. 1997).
- Shallow retention basins (<20 cm) increase soil moisture and the water table, thereby improving the establishment and growth of *Sphagnum* mosses in bog restoration projects (Price et al., 2002; Campeau et al. 2004).
- Berms, bunds, terracing and polders hold surface water and precipitation on site and are important in retaining snowmelt water in the spring on cutover peatlands with uneven topography (Price et al., 2003).
- The use of mulch or nurse plants increases the moisture level of the microclimate on the peat surface by increasing the relative

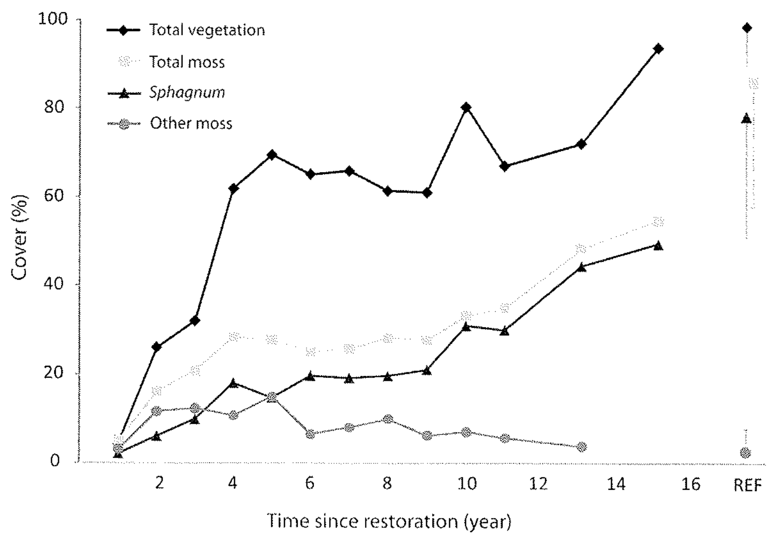

Figure 12.4. Plant cover (%) in function of years since restoration at nine restored sites over 15 years of monitoring. The restored sites are located at Rivière-du-Loup peatland (47°45′N; 69°31′W) where 3.8 ha were restored in year 1995 and monitored with 120 quadrats of 25 cm × 25 cm, 3.0 ha in 1997 with 120 quadrats, 1.2 ha in 1999 with 40 quadrats, 1.6 ha in 2000 with 80 quadrats, 2.4 ha in 2001 with 60 quadrats, 3.6 ha in 2002 with 60 quadrats, 12 ha in 2003 with 80 quadrats, 8 ha in 2005 with 120 quadrats, and 7 ha in 2006 with 80 quadrats, which were last surveyed in 2010.

humidity near the surface and decreasing the evaporation loss compared to a bare peat site (Groeneveld and Rochefort, 2002; Price et al., 2003).

- Border and pipe irrigation can be used to maintain water levels (Rochefort, 2001; Richert et al., 2000). However, such measures, as they are costly, are best used in a *Sphagnum* culture system. Additionally, moving water and sedimentation will impair the establishment of mosses (Quinty and Rochefort, 2000).
- Trees that established spontaneously on the site increase the evapotranspiration of the site (Fay and Lavoie, 2009). In times of critically low water levels, trees may be cut to maintain water levels.

Monitoring

Monitoring is an important part of the restoration process to evaluate if restoration goals have been met or to find adaptive strategies if the restoration trajectory needs to be corrected. The plant recovery of nine restored bog sites is presented in Figure 12.4 as an example of monitoring

for the flora. The nine sites were restored by the same peat company within a 15 km^2 peatland, following the method illustrated in figure 12.3 and sites were not necessarily adjacent. The mean of the nine recovery curves are shown as compared to the mean of seven reference ecosystems of the regions.

FEN RESTORATION

Research on restoring a fen plant community after peat extraction in North America is relatively new (Cooper and MacDonald 2000; Cobbaert et al., 2004; Graf and Rochefort 2008a). Restoring fens is a great challenge because of the complexity of the hydrology and the wide variety of fen plant communities. The approaches are believed to be similar to bog restoration, although the techniques used to apply them may differ. In the next section, we explore some techniques that can be used to restore residual fen peat.

Vegetation introduction

Unlike bog residual peat, cutover peatlands are spontaneously colonized by wetland plants (Famous et al., 1991; Graf et al., 2008); however, typical fen species, such as Cyperaceae and brown moss species, remain virtually absent even in rewetted sites (Graf et al., 2008). Active reintroduction is necessary for these species to reestablish.

Cobbaert et al., (2004) and Graf and Rochefort (2008a) reintroduced fen vegetation using the moss layer transfer method. The fen surface layer is the first 10–15 cm of the soil and includes the seed bank, rhizomes, and diaspores if mosses are present. This method is similar to the vegetation reintroduction used for bog restoration described in the previous section. This method proved to be successful in establishing a *Sphagnum* carpet for the restoration of poor and moderate-rich fens (Graf and Rochefort, 2008a). In a greenhouse experiment, nine poor and moderate fen bryophyte species regenerated better under shade (50% shade) and when the water level was just below the surface (Graf and Rochefort, 2008b). Mälson and Rydin (2007) tested regeneration capacities of brown mosses found in rich fens; these mosses also reproduce vegetatively when diaspores are introduced and covered with protective layers.

Extensive research on restoring of fen plant communities on former agricultural lands has been carried out in Europe (Wheeler and Shaw, 1995; Pfadenhauer and Grootjans, 1999; Kratz and Pfadenhauer, 2001; Lamers et al., 2002). This research is not entirely transferable to milled peatlands, as the desired state is often one of extensive agricultural use or semi-natural, and damage to the European peatlands is often more severe (Graf and Rochefort, 2008a). However, some fen restoration techniques have been tested on cutaway peatlands.

The hay transfer method is often used for restoring fen communities of former agricultural lands (Pfadenhauer and Grootjans, 1999). This technique is ideal for the restoration of large sites, as it is mechanized and relatively inexpensive. Additionally, it has been shown to be effective for reintroducing both vascular plants and bryophytes (Jeschke and Kiehl, 2006). The hay transfer method involves mowing a donor site, when the desired seeds are ripe yet still attached to the stalks, and then transferring the fen "hay" directly onto the restoration site. On European experimental plots, 50%–71% of the fen species were transferred using this method (Patzelt, 1998). In order to ensure success using this technique, a donor:recipient ratio should be 1:1, meaning 1 ha should be mown for the restoration of 1 ha of wetland. The number of species transferred can be augmented if the donor site is diverse, several donor sites are used, and mowing and introduction is done at different times during the vegetation season.

When the moss layer transfer and hay transfer methods were compared directly, the former showed a higher reestablishment of peatland plants (Graf and Rochefort, 2008a). After three vegetation seasons, the percentage cover for *Sphagnum centrale* was $\sim$ 20% on plots where moss layer transfer had been applied and <1% for the hay transfer and control plots (Graf and Rochefort, 2008a). Similarly, the percentage cover for *Carex* species was 10% on the moss layer transfer plots and <1% for the hay transfer and control plots. The moss layer transfer was more effective because it includes fresh seeds, the seed bank, rhizomes, and moss fragments.

For moss layer and hay transfer methods, the availability of donor sites is a limitation. When brown moss species are dominant, a fen has a shallow acrotelm, and the removal of the first 10 cm can expose the peat. Care must be taken when using machinery to take off the diaspore material. However, when the site is undrained and the deeper rhizomes remain untouched, the regeneration of former vegetation occurs quickly. Another option is to search for peatlands that have been highly disturbed or destroyed by new anthropogenic developments, in order to cultivate the material for future restoration projects. For donor sites that are very sensitive or have a high conservation status, the hay transfer method is more appropriate, as it is much less intrusive than the moss layer transfer method. Unlike North American fens, mowing European fens is possible because many have been partially drained for extensive agriculture. The choice of a donor site and the use of light machinery must be done carefully to guarantee the success of this method.

If vascular plants are the focus of revegetation efforts, seeding is another option for reintroducing fen species. Seeding plants is an easy and relatively inexpensive option; however, this technique often produces poor results for wetland plants (Patzelt, 1998; Cooper and MacDonald, 2000; Cronk and Fennessy, 2001). Field germination trials and survival of eight common fen species described in Cooper and MacDonald (2000) only succeeded with *Triglochin maritima*, with a germination rate of 59%. Plugs from seedlings, rhizomes, and stem cuttings were a more effective method, with higher survival rate. Seeds can be collected by hand from nearby sources or purchased from specialty nurseries. Ideally, seeds should be regional to ensure that they are genetically adapted to the local conditions (Falk et al., 2006; Cooper et al., 2008). The timing of collection is vital, as seeds should be collected as they mature, but before they fall to the ground. After collection, close attention must be paid to species-specific requirements for storage and germination. The methods for storing seeds can greatly affect their viability (van der Valk et al., 1999). Baskin and Baskin (1996), Middleton (1999), and Cooper et al. (2008), provide detailed information on the storage and germination requirements of wetland species. Among factors that influence germination and survival rate, there are the seedbed preparation (vegetation cover, microtopography, soil stability), water table depth and variation during the growth season, soil physicochemistry, and the presence of mycorrhizae.

Transplantation is often used for plants that do not establish well from seeds, as is the case for many wetland species (Cronk and Fennessy, 2001). Mature plants tend to be more tolerant of the extreme environmental conditions (Middleton, 1999) found in peat extracted peatlands. Rhizomatous species propagate quickly and extensively. Transplanting of rhizomes or plugs of plants has been an effective technique for establishing a wide assortment of wetland species (van der Valk et al., 1999; Cooper and MacDonald, 2000; Kratz and Pfadenhauer, 2001). In Cooper and MacDonald (2000), seedlings and rhizome transplants of *Carex aquatilis* and *C. utriculata* showed over 50% of survival after three growth seasons. Many of these plants had ten or more shoots from clonal growth. It indicates that one or two plugs per meter square are enough to colonize in a reasonable time frame. A major limitation to this approach is the cost and the labor required. It should be avoided when a large area is to be restored or the budget is limited. Overall, seeding and transplantation can be seen as complementary to the moss layer transfer technique. Seeding and transplantation can be used in places where machinery cannot go or when the peat must be stabilized quickly to avoid erosion.

Using fertilizer for restoration projects can have both positive and negative effects on the development of the restored site. Fertilization may aid the establishment of aggressive, fast-growing plants that can persist for a long time after invasion (D'Antonio and Chambers, 2006), or it may help the reintroduced plants to establish in a harsh environment to stabilize peat soil. Fertilizer should play an important role in fen restoration, as vascular plants are a dominant component of fen vegetation communities. However, little research has been carried out on which fertilizer and what doses are ideal for poor, moderate-rich, and rich fens. The prolific research on European fen meadow restoration does not cover the topic of fertilization as these sites are usually "too rich" to allow fen vegetation to compete. Graf and Rochefort (2008a) showed a higher establishment of *Carex* species on plots that were lightly fertilized with phosphate rock. The dose used in this study, 15 g m^{-2}, is the same amount used for bog restoration and is most certainly not the optimal dose for fen vascular plants. More research is needed on this topic.

Application of mulch

As mentioned previously, if the peatland is not readily restored after abandonment of activities, spontaneous vegetation grows quickly. Depending on the technique used for restoration, mulch application may be an option. If moss layer or hay transfer methods are employed, the peat surface must be refreshed to remove the biological crust. This step also removes the spontaneous vegetation. As discussed previously, straw mulch application is then mandatory. On the other hand, if a site has a high cover of spontaneous vegetation, mulch application is not essential to protect the introduced mosses. In fact, these herbaceous plants can act as a nurse plant, improving moss establishment by improving the microclimatic conditions. It is essential for the mosses to be introduced by hand and put under the canopy of herbaceous plants. A large herbaceous plant, *Scirpus cyperinus*, was shown to be associated with a significantly higher establishment of bryophytes than under straw mulch (Graf et al., 2008). However, prolonged monitoring is necessary to determine if, over time, tall, tussock-forming species can compete with moss cover due to light competition.

Nurse plants should increase fen restoration success, as cutaway peat surface also undergoes instability. Current research is still preliminary and identifying an effective nurse plant species is not obvious. While paleoecological analysis of bogs showed that *P. strictum* is a pioneer species after disturbances like fire events (Lavoie et al., 2001; Benscoter et al. 2005), answering this question is harder in fen systems as fires are rare and most paleological work did not focus on fens.

Rewetting

Fen hydrology is more complicated than bog hydrology because it is connected and dependent on its surrounding environment (Mitsch and Gosselink, 2000). Water levels should be less variable in fen systems than bog systems as there is a constant water input. In order to achieve true fen hydrology on a restored site, it is necessary for the site to be hydraulically connected to the immediate landscape. Additionally, minimal water quality requirements must be respected for the long-term development of fen plant communities. The hydrology of a restoration site and the surrounding areas must therefore be understood before restoration measures can be planned. In this respect, restoring a bog's hydrology is more straightforward.

In the case of cutaway peatlands, we have found that the water level is often so close to the surface that drainage canals are no longer effective. Cutaway peatlands that were no longer being drained were always quickly revegetated with predominantly wetland species (Graf et al., 2008). Therefore, often no active steps must be taken to restore the local hydrology, as the sites are wet enough to support wetland and fen plants. This does not mean that the regional hydrology (i.e., groundwater flow through the site) has been restored; returning a site back to a true fen requires hydrological connectivity with the adjacent landscape. The presence of drainage ditches is often a major obstacle because it stops the water flow. However, filling all the ditches is not a good solution. The peat inside the ditches does not have the same physical properties and will still block underground water flow, although it could improve the surface water flow. The topography is also an important aspect to consider. A slight slope in the right direction can improve surface and groundwater movement; alternatively, it can also create erosion problems. Introducing vegetation can moderate erosion.

In establishing a sustainable fen system, hydrology is the principal concern. Restoring fen hydrology is the greatest challenge of the whole restoration project. Each restoration site is unique, one method will likely not fit most situations, although it is theoretically possible. More research on rewetting techniques must be done and long-term monitoring continued in order to determine the best approaches to restoring fen hydrology.

Can these techniques be transferred to other disturbances?

Forestry, oil, gas, and *in situ* oil sands development have impacted northern Alberta's wetlands through the construction of roads, pipelines, seismic lines, power transmission lines, and well pads (Turchenek, 1990; Forest, 2001). These disturbances lead to the removal or disturbance of the acrotelm, compaction of the catotelm due to drainage and equipment passage, and possible contamination from pipeline or well pad leaks.

Techniques developed to restore cutover and cutaway peatlands are highly pertinent to the restoration of peatlands affected by forestry and energy sector disturbances. The environmental conditions of cutover peatlands are in many ways harsher than the environmental conditions of wetlands affected by forestry and *in situ* disturbances (see Table 12.1). Peat extraction leaves large flat expanses (up to 300 ha) of drained, compacted peat with no plant propagules (Poulin et al., 2005). While forestry and *in situ* disturbances also create areas that are drained, compacted, and void of vegetation, the surrounding peatlands are left intact. Therefore, perhaps restoring the hydrology will be enough as a seed bank and local seed sources are often present.

Open-pit oil sand mining creates a greater disturbance because the entire landscape is removed to access the oil sands layers beneath (e.g., a deep hole up to 350 feet). When peatlands are recreated in the post-mined landscape, the same revegetation stategies can be used as have been for cutover peatlands. The success of revegetation schemes will rely mainly on the ability to create a true fen hydrology in the post-mined landscape.

The following points from research on restoring cutover peatlands could decrease the impact on peatlands affected by other land uses:

- When disturbing these areas (road or pipeline construction), remove the acrotelm for later restoration use or for immediate restoration of decommissioned installations.
- Work in the winter when the peat is frozen.
- The return to a functional ecosystem (which accumulates peat) is possible when all restoration activities (vegetation reintroduction, rewetting, mulching) have been completed. However, restoration and/or creation is a long-term project; therefore, monitoring is

Table 12.1. *A comparison of two types of disturbance affecting boreal wetlands. Can the techniques developed to restore cutover peatlands be used to restore peatland affected by energy sector disturbances?*

Disturbance	Peat extraction	Construction of seismic lines, pipelines, roads, and well pads
Problems	Extensively drained Drainage ditches are placed every 30 m across the peatland Compaction Tractors are continually driven across the peatland No seed bank	Locally drained Surface and subsurface water flow is impeded (by roads and pipelines) Local compaction No seed bank (roads and well pads) Possible soil and water contaminated by hydrocarbons or mineral soil (pipelines, roads, and well pads)
Size of disturbance	Large (up to 300 ha)	Small • Well pads: circa 1 ha • Linear disturbances: 6–30 m wide and several km long
Duration of disturbance	20–40 years	40–50 years
Short-term restoration/remediation goals	Vegetation layer dominated by bryophytes Diplotelmic hydrology	Equivalent land capability. Can be restored as: • wetland • agricultural land • forested land
Long-term goal of restoration/remediation	Return of the ecosystem's peat accumulating function	Return of an ecosystem functionally and structurally similar to the previous ecosystem.

very important to understanding the processes and to follow the succession trajectory.

- Restoration of the hydrology is key to the return of ecosystem function as typical peatland species or communities cannot establish and survive long term without it. Minimal disturbance of the hydrological system should be targeted.
- Linear disturbances should be parallel to the water flow of the landscape to avoid decreasing the hydraulic connectivity of a fen.
- Peatland archives can give clues about community establishment after disturbance (Lavoie et al., 2001). A closer look at peatland history can help in selecting the best plant communities with which to work.
- Importance of pioneer species for persistence of plant communities over time and to restart plant community autogenic processes.

CONCLUSIONS

Research on restoring ecosystems is a relatively new field in ecology. It is a good opportunity to learn about the ecosystem, as an understanding of the components and their processes is necessary for successful restoration. Restoration of cutover and cutaway peatlands is a challenge because of the extreme impacts of peat extraction activities. After the abandonment of extraction, the damage is permanent. Depending on the conditions of the peat (peat type, depth, physicochemistry), bog or fen restoration can be targeted. Studies have shown us that in both types of peatlands, active intervention is required to return an extracted peatland back to a functioning, peat-accumulating system. Vegetation must be reintroduced and mulch protected, and the site must be rewetted. Unlike open pit oil sand mining or other mining industries, peat extraction leaves a peat body to work with. The creation of peatland systems therefore requires a good understanding of its ecology. Continuing research on peatland restoration gives managers tools with which to face the challenges involved in restoration.

ACKNOWLEDGMENTS

Studies on the ecological restoration of peatlands in North America have been supported throughout the years by the Natural Sciences and Engineering Research Council (NSERC) of Canada in partnerships with the horticultural peat industry and grants from the provincial governments of Québec and New Brunswick.

REFERENCES

Andrus, R. (1986). Some aspects of *Sphagnum* ecology. *Canadian Journal of Botany*, **64**, 416–426.

Baskin, C. C. and Baskin, J. M. (1996). *Seeds – Ecology, Biogeography, and Evolution of Dormancy and Germination*. Toronto, ON: Academic Press.

Benscoter, B. W., Wieder, R. K., Vitt, D. H. (2005). Linking microtopography with post-fire succession in bogs. *Journal of Vegetation Science*, **16**, 453–460.

Bérubé, M. È. and Lavoie, C. (2000). The natural revegetation of a vacuum-mined peatland: eight years of monitoring. *Canadian Field-Naturalist*, **114**, 279–286.

Boudreau, S. and Rochefort, L. (1999). Établissement de sphaignes réintroduites sous diverses communautés végétales recolonisant les tourbières après l'exploitation. *Écologie*, **30**, 53–62.

Campbell, C., Vitt, D. H., Halsey, L. A., et al. (2000). Net primary production and standing biomass in northern continental wetlands. Northern Forestry Centre, Edmonton, AB, Information report No. NOR-X-369.

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

Campeau, S. and Rochefort, L. (1996). *Sphagnum* regeneration on bare peat surfaces: field and greenhouse results. *Journal of Applied Ecology*, **33**, 599–608.

Campeau, S., Rochefort, L., Price, J. S. (2004). On the use of shallow basins to restore cutover peatlands: plant establishment. *Restoration Ecology*, **12**, 471–482.

Clymo, R. S. (1984). The limits to peat bog growth. *Philosophical Transactions of the Royal Society of London B*, **303**, 605–654.

Clymo R. S. and Duckett, J. G. (1986). Regeneration of *Sphagnum*. *New Phytology*, **102**, 589–614.

Clymo, R. S. and Hayward, P. M. (1982). The ecology of *Sphagnum*. In A. J. E. Smith, ed., *Bryophyte Ecology*. London, UK: Chapman and Hall, pp. 229–289.

Cobbaert, D., Rochefort, L., Price, J. (2004). Experimental restoration of a fen plant community after peat mining. *Applied Vegetation Science*, **7**, 209–220.

Cooper, D. J. and MacDonald, L. H. (2000). Restoring the vegetation of mined peatlands in the southern Rocky Mountains of Colorado, USA. *Restoration Ecology*, **8**, 103–111.

Cooper, D. J., MacDonald, L. H., Wenger, S. K., Woods, S. W. (1998). Hydrologic restoration of a fen in Rocky Mountain National Park, CO, USA. *Wetlands*, **18**, 335–345.

Cooper, D., Wolf, E., Gage, E. (2008). Appendix D. Plant establishment for wetland reclamation: a review of plant establishment techniques and species tolerances for water level and salinity. In M.L. Harris, ed., *Guideline for Wetland Establishment of Reclaimed Oil Sands Leases*. (2nd edn. Fort McMurray, AB, Alberta Envirionment, Canada.

Cronk, J. K. and Fennessy, M. S. (2001). *Wetland Plants: Biology and Ecology*. Lewis, New York, NY.

Daigle, J.-Y. and Gautreau-Daigle, H. (2001). *Canadian Peat Harvesting and the Environment*, 2nd edn. Secretariat to the North American Wetlands Conservation Council Committee, Ottawa, Canada.

D'Antonio, C. and Chambers, J. (2006). Using ecological theory to manage or restore ecosystems affected by invasive plant species. In D. A. Falk, M. A. Palmer, J. B. Zedler, eds., *Foundations of restoration ecology*. Washington, DC, USA: Island Press, pp. 260–279.

Environment Canada. (2010). National Inventory Report 1990–2008: Greenhouse gas sources and sinks in Canada. Address: http://www.ec.gc.ca/ges-ghg.

Falk, D. A., Richards, C. M., Montalvo, A. M., Knapp, E. E. (2006). Population and ecological genetics in restoration ecology. In D. A. Falk, M. A. Palmer, J. B. Zedler, eds., *Foundations of restoration ecology*. Washington, DC, USA: Island Press, pp. 14–41.

Famous, N. C., Spencer, M., Nilsson, H. (1991). Revegetation patterns in harvested peatlands in central and eastern North America. In *Peat and Peatlands: The Resource and its Utilization. Proceedings of the International Peat Symposium*, Duluth, MN, pp. 48–66.

Fay, E. and Lavoie, C. (2009). The impact of birch seedlings on evapotranspiration from a mined peatland: an experimental study in southern Quebec, Canada. *Mires and Peat*, **5**, 1–7.

Forest, S. F. (2001). Peatland management and conservation in boreal Alberta, Canada. M.Sc. , University of Alberta, Edmonton, AB.

Gorham, E. and Rochefort, L. (2003). Peatland restoration: a brief assessment with special reference to Sphagnum bogs. *Wetlands Ecology and Management*, **11**, 109–119.

Graf, M. D. and Rochefort, L. (2008a). Techniques for restoring fen vegetation on cut-away peatlands in North America. *Applied Vegetation Science*, **11**, 521–528.

Graf, M. D. and Rochefort, L. (2008b). Moss regeneration for fen restoration: field and greenhouse experiments. *Restoration Ecology*, **18**, 121–130.

Graf, M. D., Rochefort, L., Poulin, M. (2008). Spontaneous revegetation of harvested peatlands of Canada and Minnesota, USA. *Wetlands*, **28**, 28–39.

Groeneveld, E. V. G., Massé, A., Rochefort, L. (2007). *Polytrichum strictum* as a nurse-plant to facilitate Sphagnum and boreal vascular plant establishment. *Restoration Ecology*, **15**, 709–719.

Groeneveld, E. V. G. and Rochefort, L. (2002). Nursing plants in peatland restoration: on their potential use to alleviate frost heaving problems. *Suo*, **53**, 73–85.

Ingram, H. A. P. (1978). Soil layers in mires: function and terminology. *Journal of Soil Science*, **29**, 224–227.

Ivanov, K. E. (1981). Water movement in Mirelands. Translated from Russian by A. Thomson and H. A. P. Ingram. London, UK: Academic Press, p. 276.

Jeschke, M. and Kiehl, K. (2006). Auswirking von Renaturierungs- und Pflegemaßnahmen auf die Artenzusammensetzung und Artendiversität von Gefäßpflanzen und Kryptogramen in neu angelegten Kalkmagerrasen. *Tuexenia*, **26**, 223–242.

Keys, D. (1992). Canadian Peat Moss and the Environment. Issues Paper, No. 1992–3. North American Wetlands Conservation Council, Canada.

Kratz, R. and Pfadenhauer, J. (2001). *Ökosystemmanagement für Niedermoore: Strategien und Verfahren zur Renaturierung*, Ulmer Verlag, Stuttgart.

Lamers, L., Smolders, A., Roelofs, J. (2002). The restoration of fens in the Netherlands. *Hydrobiologia*, **478**, 107–130.

LaRose, S., Price, J., Rochefort, L. (1997). Rewetting of a cutover peatland: hydrologic assessment. Wetlands, **17**, 416–423.

Lavoie, C., Grosvernier, P., Girard, M., Marcoux, K. (2003). Spontaneous revegetation of mined peatlands: a useful restoration tool? *Wetlands Ecology and Management*, **11**, 97–107.

Lavoie, C., Zimmermann, C., Pellerin, S. (2001). Peatland restoration in southern Québec (Canada): a paleoecological perspective. *Écoscience*, **8**, 247–258.

Lucchese, M., Waddington, J. M., Poulin, M., et al. (2010). Organic matter accumulation in a restored peatland: evaluating restoration success. *Ecological Engineering*, **36**, 482–488.

Mälson, K. and Rydin, H. (2007). The regeneration capabilities of bryophytes for rich fen restoration. *Biological Conservation*, **135**, 435–442.

Middleton, B. (1999). Revegetation alternatives. In B. Middleton, ed., *Wetland Restoration, flood pulsing, and disturbance dynamics*. New York, NY: Wiley, pp. 191–211.

Mitsch, W. J. and Gosselink, J. G. (2000). *Wetlands*. 3rd edn. New York, NY: Wiley.

Patzelt, A. (1998). Vegetationökologische und populationsbiologische Grundlagen für die Etablierung von Magerwiesen in Niedermooren. *Dissertationes Botanicae*, **297**, 1–215.

Pfadenhauer, J. and Grootjans, A. (1999). Wetland restoration in Central Europe: aims and methods. *Applied Vegetation Science*, **2**, 95–106.

Poulin, M., Rochefort, L., Quinty, F., Lavoie, C. (2005). Spontaneous revegetation of mined peatlands in eastern Canada. *Canadian Journal of Botany*, **83**, 539–557.

Price, J. S., Healthwaite, A. L., Baird, A. J. (2003). Hydrological processes in abandoned and restored peatlands: an overview of management approaches. *Wetlands Ecology and Management*, **11**, 65–83.

Price, J. S., Rochefort, L., Campeau, S. (2002). Use of shallow basins to restore cutover peatlands: hydrology. *Restoration Ecology*, **10**: 259–266.

Price, J. S., Rochefort, L., Quinty, F. (1998). Energy and moisture considerations on cutover peatlands: surface microtopography, mulch cover and Sphagnum regeneration. *Ecological Engineering*, **10**, 293–312.

Quinty, F. and Rochefort, L. (2000). Bare peat substrate instability in peatlands restoration: problems and solutions. In L. Rochefort and J. Y. Daigle, eds., *Sustaining our peatlands. Proceedings of the 11th International Peat Congress, vol. II*. Québec City, QC, International Peat Society, Jyväskylä, Finland, pp. 751–756.

Richert, M., Dietrich, O., Koppisch, D., Roth, S. (2000). The influence of rewetting on vegetation development and decomposition in a degraded fen. *Restoration Ecology*, **8**, 186–195.

Rochefort, L. (2000). Sphagnum – a keystone genus in habitat restoration. *Bryologist*, **103**, 503–508.

Rochefort, L. (2001). Restauration écologique. In S. Payette and L. Rochefort, eds., *Écologie des tourbières du Québec-Labrador*. Québec, QC: Les Presses de l'Université Laval, pp. 449–505.

Rochefort, L. and Campeau, S. (2002). Recovery of donor sites used in peatland restoration. In G. Schmilewski and L. Rochefort, eds., *Peat in Horticulture – Quality and Environmental Challenges: IPS Symposium Proceedings (Commissions II and V)*. Pärnu, Estonia, International Peat Society, Jyväskylä, pp. 244–251.

Rochefort, L. and Lode, E. (2006). Restoration of degraded boreal peatlands. In R. K. Wieder and D. H. Vitt, eds., *Boreal Peatland Ecosystems*. Vol. 188. Berlin: Springer-Verlag, pp. 381–423.

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.

Sagot, C. and Rochefort, L. (1996). Tolérance des sphaignes à la dessiccation. *Crytogamie, Bryologie et Lichénologie*, **17**, 171–183.

Salonen, V. (1987). Relationship between the seed rain and the establishment in two areas abandoned after peat harvesting. *Holarctic Ecology*, **10**, 171–174.

Schneider, R. and Dyer, S. (2006). Death by a Thousand Cuts: Impact of in Situ Oil Sands Development on Alberta's Boreal Forest. Edmonton, AB: The Pembina Institute Publications.

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

Tallis, J. H. (1987). Fire and flood at Holme Moss: erosion processes in an upland blanket mire. *Journal of Ecology*, **75**, 1099–1129.

Turchenek, L. W. (1990). Present and potential effects of anthropogenic activities on waters associated with peatland in Alberta. Environmental Research and Engineering Department, Alberta Research Council.

Turetsky, M. R. and St. Louis, V. L. (2006). Disturbance in boreal peatlands. In R. K. Wieder and D. H. Vitt, eds., *Boreal Peatland Ecosystems*. Berlin: Springer-Verlag, pp. 359–372.

van Breemen, N. (1995). How *Sphagnum* bogs down other plants. *Trends in Ecology and Evolution*, **10**, 270.

van der Valk, A. G., Bremholm, T. L., Gordon, E. (1999). The restoration of sedge meadows: seed viability, seed germination requirements, and seedling growth of *Carex* species. *Wetlands*, **19**, 756–764.

Vitt, D. H. (2000). Peatlands: ecosystems dominated by bryophytes. In A. J. Shaw and B. Goffinet, eds., *Bryophyte Biology*. Cambridge, UK: Cambridge University Press, pp. 312–343.

Waddington, J. M. and McNeil, P. (2002). Peat oxidation in an abandoned cutover peatland. *Canadian Journal of Soil Science*, **82**, 279–286.

Wheeler, B. D. and Shaw, S. C. (1995). A focus on fens-controls on the composition of fen vegetation in relation to restoration. In B. D. Wheeler, S. C. Shaw, W. J. Fojt, R. A. Robertson, eds., *Restoration of Temperate Wetlands*. West Sussex, UK: Wiley and Sons, pp. 49–72.

Wieder, R. K., Scott, K. D., Kamminga, K. (2009). Postfire carbon balance in boreal bogs of Alberta, Canada. *Global Change Biology*, **15**, 63–81.

Wind-Mulder, H. L., Rochefort, L., Vitt, D. H. (1996). Water and peat chemistry comparisons of natural and post-harvested peatlands across Canada and their relevance to peatland restoration. *Ecological Engineering*, **7**, 161–181.

Wind-Mulder, H. L. and Vitt, D. H. (2000). Comparison of water and peat chemistries of a post-harvested and undisturbed peatland with relevance to restoration. *Wetlands*, **20**, 616–628.

Zedler, J. B. and Kercher, S. (2004). Causes and consequences of invasive plants in wetlands: opportunities, opportunists, and outcomes. *Critical Reviews in Plant Sciences*, **23**, 431–452.

ROXANE ANDERSEN

13

Importance of microbes in peatland dynamics, restoration, and reclamation

INTRODUCTION

Boreal peatlands are estimated to store up to a third of all the terrestrial carbon (C) in the form of partially decomposed organic matter (Turetsky et al., 2002; Vitt et al., 2000). Nevertheless, they are also considered one of the largest sources of atmospheric methane (CH_4) (Crill et al., 1988). Although the vast majority of boreal peatlands are still in pristine condition in North America, extensive areas have been affected by anthropogenic activities or natural disturbances, shifting some of the systems from sinks to sources of CO_2 (Turetsky et al., 2002) and altering the microbial driven processes of CH_4 production and/or consumption patterns (Andersen et al., 2006; Basiliko et al., 2003; Glatzel et al., 2004; Strack et al., 2004). Large-scale restoration of cutover peatlands (Rochefort et al., 2003) and reclamation of fens in the oil sands-affected areas (Price et al., 2010) have been developed to bring back those systems to a self-sustainable state, which requires functional microbial communities. On the other hand, an increasing number of studies unequivocally show that peatlands and their associated microbial populations will be affected in various ways by global change (Davidson and Janssens, 2006; Dorrepaal et al., 2009; Freeman et al., 2004; Mastepanov et al., 2008). Understanding the effects of disturbances, restoration, and global change on carbon and nutrient dynamics in peatlands requires explicit consideration of the complex feedbacks that occur between belowground microbial communities, aboveground communities, and their environment. This chapter will: (1) review the diversity and roles of microorganisms in natural boreal

Restoration and Reclamation of Boreal Ecosystems, ed. Dale Vitt and Jagtar Bhatti. Published by Cambridge University Press.