17 Restoration of Degraded Boreal Peatlands

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17.1 Introduction

The ecological restoration of a habitat is the process of assisting the recovery of an ecosystem that has been damaged, degraded, or destroyed (Society for Ecological Restoration Science, Policy Working Group 2004; Chap. 16). Owing to the fact that the restoration of complex wetland ecosystems to their former patterns is almost impossible, the existing wetlands or peatlands should be improved and restored as far as is possible to former wetlands within socioeconomic and environmental limiting conditions (Anonymous 1995; Wheeler 1995; Charman 2002). Environmental limitations can refer to controllable conditions, e.g., hydrological or biological management, or to uncontrollable conditions, e.g., climate (Streefkerk and Casparie 1989). Socioeconomic conditions can limit the restoration approach owing to poor economy or lack of environmental knowledge of a society. The historical conditions established by different peatland utilization systems also influence future possibilities for restoration (Girard et al. 2002). There is considerable variation in restoration costs and in the duration of the recovery process, variation that is strongly related to the scale and length of time of the changes made in the peat landscapes.

In view of these constraints, we define the general goal of peatland restoration as the return of degraded or destroyed peatland sites to wetland ecosystems. Over time and through plant succession, these wetlands should lead back to peat-accumulating ecosystems. The notions discussed in this chapter apply mostly to the boreal biome of the northern hemisphere.

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17.1.1 Goals of Peatland Restoration

The restoration of peatlands will seek to reestablish a plant cover dominated by *Sphagnum* or brown mosses depending on the substrate minerotrophy, as well as a hydrological regime typical of peatlands (Rochefort 2000). Nonetheless, the restoration process should ensure the return of functions of the ecosystem necessary to its self-perpetuity (Lode 2001). Among these functions are adequate productivity permitting the accumulation of carbon, cycling of nutrients, recovery of the vegetation structure that will favor animal and plant biodiversity, and characteristics that permit the ecosystem to resist biological invasions.

Peatland restoration is one way of reaching the objective of "no net loss" promoted by the North American council for the conservation of wetlands (Lynch-Stewart 1992) and the European community (Anonymous 1995). The no net loss objective is based on the principle that the obligatory loss of wetlands should be compensated. Compensation can be achieved by the restoration of former wetlands or the creation of new wetlands of at least the same area that perform the same functions and provide similar ecological values. Improvement and restoration should have priority over the creation of new wetlands. It is not possible to completely end disturbance of wetlands. Some disturbances occur naturally, some are from past activities, while others are unavoidable and result from human activities that are beneficial. However, attempts toward "wise use" of peatlands (Joosten and Clark 2002) via "reasonable" manmade management including conservation and nondestructive uses will hopefully increase in the near future.

The concept of peatland restoration retained in this chapter subscribes to the notion of "sustainable use" of peatlands. This means that after any type of disturbance, the peatland ecosystem and its main functions are restored back within a human lifetime, so that future generations can appreciate the presence of this special habitat, often little known by the general public. Thus, the general goal of restoration is not to renew peat as a natural resource, but rather to manage the ecosystem so as to impede its loss in certain regions or localities and maintain the biodiversity of habitats.

Mire restoration has become a central practice of nature conservation in European countries where mires have become rare (Wheeler and Shaw 1995; Wheeler et al. 1995; Lamers et al. 2002; Blankenburg and Tonnis 2004). In North America and in Europe, commitments toward peatland restoration have been adopted as a common practice among the peat industries (Rochefort and Price 2003; Vasander et al. 2003). In European countries where there is still a considerable amount of both peat resources and mires in a natural state (Estonia, Finland, Sweden, Russia), bog restoration is not the prevailing aim of peatland management. Management options are often the creation of shallow wetlands to favor bird habitats, the creation of fen-type landscapes, or the establishment of agricultural or forestry practices. But if in a particular landscape setting bogs are recognized to be important in maintaining the groundwater table, then a restoration approach is favored (Schouten et al. 2002).

17.1.2 Conservation

It would be unwise to only rely on restored peatlands as a conservation strategy for a given geographical region. Indeed we know little about how new restoration sites are recolonized by animal peatland species. To ensure the maintenance of regional biodiversity, it appears important to maintain pristine peatlands on the landscape, or at the scale of a peatland complex to preserve undisturbed fragments adjacent to extracted areas (Poulin et al. 1999; Pellerin and Lavoie 2000). The undisturbed peat deposits of mires are like a book, and through palaeoecological analyses, the history of past climate, landscape development since the last glaciation, and environmental changes can be decoded. Any peat utilization destroys these archives forever, and this is part of the reason why the spatial distribution of peatlands for conservation should be chosen with care. The preservation of natural remnants within a peatland site or complex is also recommended as it can ensure the supply of plant material for future restoration plans or as a refuge for an array of animal species while waiting for the restoration of the entire ecosystem.

17.1.3 Topics of This Chapter

Peatland restoration is a relatively new field of investigation that was the object of significant advances in the 1990s (Lode 2001; Price et al. 2003; Rochefort et al. 2003). Currently the conservation and restoration of peatlands in Europe stem from the fact that Europe has lost or degraded the major part of its peatlands. This chapter will mostly discuss the restoration of *Sphagnum*-dominated peatlands (bogs) that have been affected by peat mining (Chap. 16), but the overall approach can easily be adapted to the restoration of ombrotrophic peatlands that have been damaged by agriculture, fires, or certain types of erosion. The restoration of peatlands after forestry practices and drainage is discussed in depth by Laine et al. (Chap. 15). For the particular case of peatlands with serious erosion problems, the report on blanket mire degradation (Tallis et al. 1997) should be consulted.

The first section of this chapter overviews the extent of habitat loss in the boreal biome. The next section describes the factors influencing plant establishment on degraded peatlands, and the subsequent section gives an overview of restoration practices. Concluding sections discuss the success of recovery and end with the needs of research in peatland restoration.

17.2 Background on Habitat Loss

During the last decade, intensive work has been done in the field of peatland inventories (Pfadenhauer et al. 1993; Lappalainen 1996; Mitsch and Gosselink 2000). In spite of greatly improved overviews concerning the location of peatlands and extension, there is still lack of comprehensive and comparable data in reports at the national level (compare for instance Joosten and Clarke 2002 with Vasander et al. 2003). In spite of uncertainties in data or different definitions used, one trend is clearly observed – a trend of decreasing the area of peatlands in the world, especially in Europe (Fig. 17.1).

Owing to a long history of high population and climatic suitability for agriculture, Europe has experienced one of the largest mire losses in the world. Currently over 50 % of European peatlands have ceased to accumulate peat and almost 20 % of the original mire area no longer exists as peatland. In many countries only 1 %, or less than 1 %, of the original resources remains (Joosten and Clarke 2002).

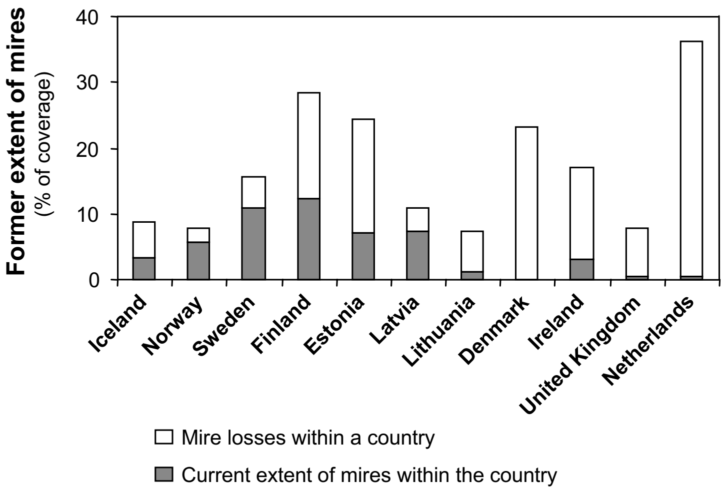

Fig. 17.1. Former extent of mires expressed as a percentage over the total area of a country (*total bars*), mire losses within a country (*white part of the bar*), and current extent of mires within a country (*shaded part of the bar*) in northern Europe, estimated after Joosten and Clarke (2002)

In Canada, it is estimated that since European colonization, close to 20 × 10^6 ha of wetlands have been affected by human activities (Rubec 1996). Out of that 20 × 10^6 ha of wetland lost, it is estimated that 1 × 10^6 ha is ombrotrophic peatlands (bogs). So far, the peat industry has been working on a total area of 17,000 ha of bogs over the country (Daigle and Gautreau-Daigle 2001). The main loss of bog habitats in North America is mostly caused by flooding from the building of dams for hydroelectricity or from agriculture, which has impacted mostly fens and wetlands. In the USA, there are 21.4 × 10^6 ha of peatlands, of which 50 % occur in Alaska in their natural state. Only about 2 % of the contiguous USA is ombrotrophic peatlands (high fiber, low-decomposition fibrists peat type; Malterer 1996), and nearly all are in their natural state.

17.3 Factors Influencing Plant Establishment on Degraded Peatlands

Sphagnum-dominated peatlands (bogs and poor fens) are characterized by a strong relationship between vegetation and hydrology (Ingram 1983; Chap. 4). Sphagnum mosses are abundant and dominant in these ecosystems and they are able to modify their physicochemical environment to the point of impeding the processes of decomposition (Clymo 1987). With time, peat accumulates, which slowly raises the peat layers above surface runoff, causing an impoverishment in mineral input as the peatlands become fed only by atmospheric precipitation (Glaser and Janssens 1986). The highly fibric and porous structure of the Sphagnum carpet can store atmospheric water and limits considerably water table fluctuations (Ingram 1983; Wheeler 1999). In natural bogs, the *Sphagnum* mosses keep the eco-hydrologic self-regulating systems favorable to their own growth (van Breemen 1995). This is the reason why so much attention has been given to the long-term reestablishment success of Sphagnum mosses during the development of restoration techniques (Money 1995; Rochefort 2000; Tuittila et al. 2003).

17.3.1 General Approach

Sphagnum mosses possess a high potential for regeneration from vegetative fragments (Table 17.1), but factors allowing this expression under field conditions have only begun to be understood. Numerous field observations show that spontaneous recolonization of peatland ecosystems by *Sphagnum* mosses is not a common phenomenon on milled peatlands (presently the most common type of abandoned peat fields). Indeed, very

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Table 17.1. Regeneration potential of different *Sphagnum* organs removed from the gametophyte in experimental conditions (adapted from Gauthier 2001)

Bibliographical source	Oehlmann (1898)			Woesler (1934)		
Species	6	7	8	2	10	2
Green part						
Apical bud						
• With leaf and branch primordia						
• Without leaf and branch primordia	+	+	+			
Whole capitulum						+
Branch of the capitulum						
• Length not specified						
• Long	+	+	+			
• Medium	+	+	+			
• Short	+	+	+	+		
Thin section of the stem between the capitulum and the first fascicle						
Stem portion						
• Not specified	–	–	–			
• Between the capitulum and the first fascicle						
• With at least 1 branch fascicle						
• Between 2 branch fascicles						
• Without leaves and branches						+
Whole branch fascicle						
Branch (type not specified)	+	+	+	+		
Divergent branch						
• With leaves						+
• Without leaves						
Pendent branch						
• With leaves						
• Without leaves						
Branch leaf						
• Origin not specified	+	+	+		+	–
• From branches of the capitulum				+		
• From divergent branches of the stem						
Brown part – stem portion						
• With at least 1 branch fascicle						
• Between 2 branch fascicles						
• Without leaves and branches						+

+ expresses a positive result and – a negative result.
1 S. magellanicum, 2 S. palustre, 3 S. papillosum, 4 S. squarrosum, 5 S. angustifolium, 6 S. cuspidatum, 7 S. fallax, 8 S. rufescens (= *S. denticulatum*), *9 S. subsecundum, 10 S. capillifolium, 11 S. rubellum, 12 S. subnitens*

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Noguchi and Muraoka (1959)	Sobotka (1976)	Poschlod and Pfadenhauer (1989)						Rochefort et al. (1995)			
1	2	3	4	6	9	11	12	1	3	5	11
								+			+
									–		
+	+	+	–	+	+	+	+				
+	+	+	+	+	+	+	+				
									+		
									+		
									+		
											+
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+	+	+	+	+	+	+	+		+		
+	+	+	+	+	+	+	+	–	+		
+	+	+	+	+	+	+	+				
+	+	+	+	+	+	+	+	–		+	+
								–		–	+
								–			
								–			
–	–	–	–	–	–	–	–				
								+		–	+
+	+	+	+	+	–	+	+				
+	+	+	+	+	–	+	–				

few postmilled peatlands that have been abandoned for the last 15–25 years have readily been recolonized by *Sphagnum* plants over extensive bare peat areas (e.g., less than 1 % in Canada; Rochefort 2001; Poulin et al. 2005).

The first years of trials to reintroduce sphagna on bare peat were unsuccessful (at the end of the 1980s and the beginning of the 1990s). All moss reintroductions were done by spreading fragments on bare peat, by either reintroducing whole *Sphagnum* individuals in wet hollows and water-filled ditches or by the transplantation of entire *Sphagnum* cores ("plugs") of different size (small cores of 10 cm × 10 cm × 10 cm or blocks of 1 m × 1 m × 50-cm depth), and resulted in dead plant material after one or two field seasons or at most they just barely survived (the large "plugs") without any spatial extension after 10 years of monitoring. *Sphagnum* moss establishment became successful only once the importance of providing a favorable humid microclimate at the interface of the air–peat surface and of protecting the vegetative moss fragments against desiccation was realized. Then it became possible to develop efficient restoration techniques.

In the first peatland restoration projects, careful attention was given to match the *Sphagnum* species and the residual substrate in terms of physicochemical conditions. Those detailed substrate characterizations were costly and now several field observations indicate that there is little relation between the specific *Sphagnum* habitat niche and its ability to colonize bare peat when working on *Sphagnum* residual peat (fibric material of von Post 4–5 or less). Usually though, *Sphagnum* material should not be reintroduced on residual sedge peat.

Ten years of restoration practices in North America have shown that there are three management interventions that are paramount to the success of *Sphagnum* establishment on bare peat surfaces: (1) the active reintroduction of plant diaspores[3]; (2) the application of a protective mulch cover; and (3) the rewetting of the site by a combination of blocking drainage and field surface preparation (ellipses in Fig. 17.2). For the sites prone to frost heaving (Groeneveld and Rochefort 2002), phosphorus fertilization is also compulsory. It is currently questioned if fertilization is needed for all restoration conditions and only long-term monitoring of projects will determine its necessity.

The following sections describe how the different factors represented in rectangles in Fig. 17.2 affect the establishment of *Sphagnum*.

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[3] Any part of a plant capable of growing as a new plant. This includes seeds and spores, but also rhizomes, stems, leaves, and branches.

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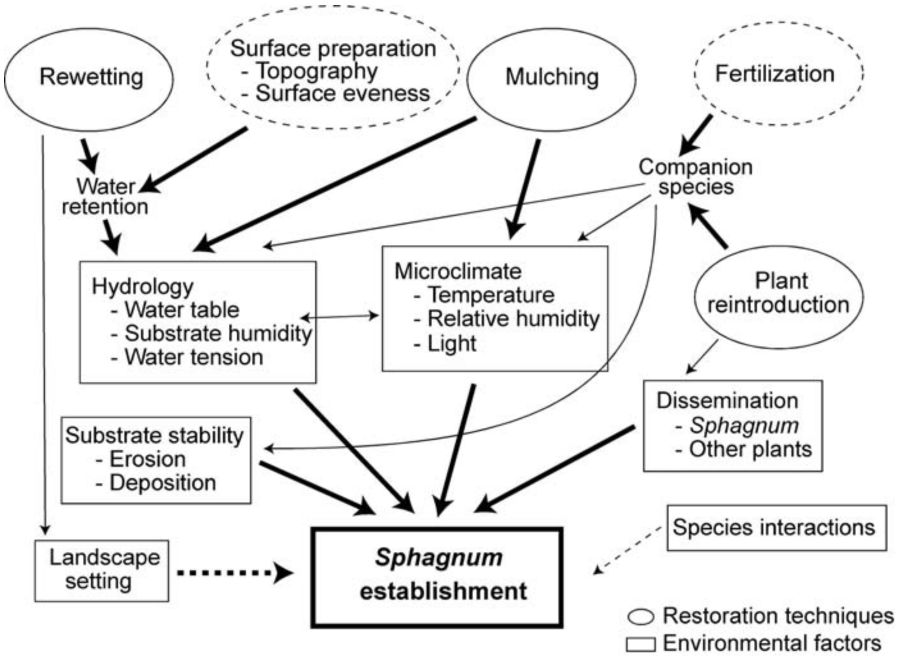

Fig. 17.2. Factors affecting the success of *Sphagnum* establishment on bare peat substrates. *Rectangles* represent the factors directly responsible for the success of moss establishment. Management practices (actions) – absolutely necessary to reestablish a moss cover when degradation is extreme such as in a cutover peatland – are represented in *ellipses*. The *dashed-line ellipse* represent optional management practices, specific of each case study, or factors suspected to be compulsory (fertilization) but still under study. The *full-line arrows* point to relationships that have often been demonstrated through several field trials; *the dashed-line arrows* are relationship still under study. (Adapted from Rochefort 2000)

17.3.2 Dissemination

It was obvious from the start that natural recolonization of milled peatlands is far from sufficient to restore a functional peatland (Salonen 1987; Desrochers et al. 1998; Bérubé and Lavoie 2000; Campbell et al. 2003; Lavoie et al. 2003; Fig. 17.3). Plant dispersal by wind to bare peat sites does not appear to be a problem. Indeed, spores of mosses, particularly *Polytrichum strictum*, seeds of several ericaceous species, notably *Kalmia angustifolia* and *Rhododendron groenlandicum;* and seeds from trees, mostly *Betula* spp. and *Picea mariana*, are easily and abundantly dispersed by wind (Soro et al. 1999; Campbell et al. 2000). That is true if the surrounding edges of the site to be rehabilitated are in a relatively natural

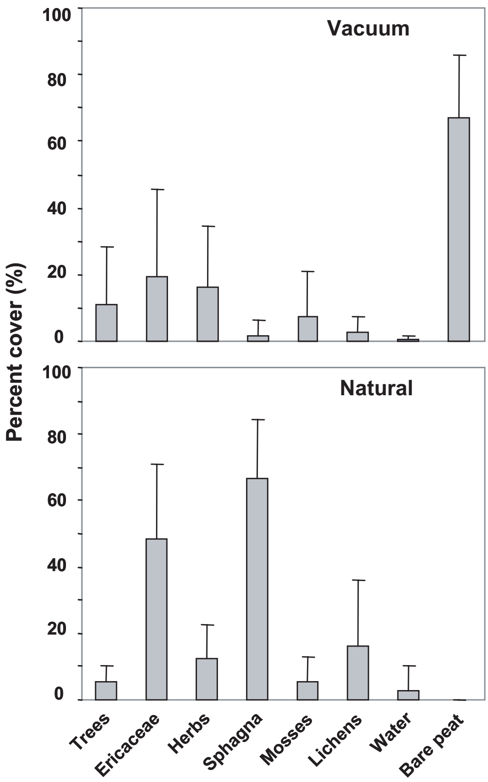

Fig. 17.3. Mean vegetation cover in 18 abandoned milled peatlands and 24 nearby natural peatlands in eastern Canada. The average age of abandonment was 11±7 years (mean ± standard deviation). Details on the methodological surveys are available from Poulin et al. (2005). Surveys in milled peatlands were conducted in 1994–1995 and those in natural peatlands were conducted in 1997 (see Poulin et al. 1999 for more details). (Adapted from Poulin et al. 2005)

state and are not dominated by invasive species such as *Betula* spp. which then can create a serious barrier to peatland plant dispersal. But usually, the discrepancies between immigration potential and the actual recolonization for several species suggest that other factors after immigration control their colonization success. In fact, it resides mostly in their inability to germinate, to establish, or to grow to maturity.

But why *Sphagnum* species are not found at all recolonizing milled peat surfaces is a key question on the road to successful restoration. A great part of the solution resides in the fact that *Sphagnum* spores seem to require very specific and stable conditions to germinate (Clymo and Duckett 1986). It is quite easy to get *Sphagnum* spores to germinate on bare peat when the peat is at a constant humidity and at 22 °C in a sealed Petri dish. But to our knowledge, no one has succeeded in germinating *Sphagnum* spores in the field. Recolonization is relatively easy with vegetative *Sphagnum* fragments when conditions are created to provide a favorable growing substrate (Poschlod and Pfadenhauer 1989; Rochefort et al. 1995). Thus, it was concluded early in the development of a restoration approach for *Sphagnum*-dominated peatlands that vegetative *Sphagnum* moss material had to be reintroduced to initiate the restoration process of abandoned milled peatlands. Once a *Sphagnum* carpet is established, it does not appear necessary to introduce other peatland plants as several will establish themselves from the diaspore bank brought in by the reintroduced *Sphagnum* plant material or they will simply immigrate from the residual fragments surrounding the restoration site and germinate. The usual biodiversity of the peatland might not be completely restored by this restoration approach, but only the long-term monitoring of restored sites will reveal if further actions are necessary.

17.3.3 Microclimate

The extreme microclimate of the bare peat surface is one of the main factors prohibiting the successful restoration of postharvested bogs. Owing to low conductivity, absence of shade, and temporary aridity, surface temperature can reach over 70 °C on bare peat surfaces, effectively disabling the establishment and recolonization of bog species (Sliva 1998). The microclimate conditions at the air–peat interface seem to be more important when the mosses are growing as isolated plants spread over the field than when growing as a uniform cover of *Sphagnum* carpets in undamaged bogs (Grosvernier et al. 1995) or in well self-recovered peat block-cutting pits (Lode 2001).

Laboratory trials have established that regenerating *Sphagnum* fragments can survive lengthy periods without a supply of water, despite the fact that they are wetland plants with little mechanism of water retention or water transport. In a study on desiccation tolerance, Sagot and Rochefort (1996) isolated *Sphagnum* fragments and left them to air dry (average temperature of 21 °C, average relative humidity, RH, of 60 %) for periods up to 61 days and then placed them in culture (for 8 weeks) in Petri dishes with nutrient solutions to determine their survival rate. The three species tested (*Sphagnum fuscum*, *S. fallax*, and *S. magellanicum*) survived quite well for periods of desiccation lasting up to 14 days, after which a sharp decline in survival was evident. But if the temperature was increased to a constant 30 or 40 °C, it appeared that most species could not survive 2 days of desiccation (six species tested; Sagot and Rochefort 1996). In fact, the ability of *Sphagnum* fragments to tolerate desiccation is directly dependent on the RH of the air to which they are exposed (Rochefort, unpublished data). At 14 % RH with an air temperature of 21 °C, survival of *Sphagnum* fragments without capitula was zero after 12 h. When the air RH was maintained at 76 %, the *Sphagnum* fragments could tolerate 3 days without a supply of water. At 94 % RH, two of the species tested could survive 28 days of no watering. In conclusion, *Sphag-*

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num fragments can survive and regenerate despite periods of several days without rain in conditions of temperature and RH averaging 21 °C and 60 %. Consequently, if a higher temperature of the residual peat surface is experienced, fragments will need to have an environment of greater RH. Abandoned peat surface conditions (in terms of temperature and RH) are known to exceed the conditions needed for the survival of *Sphagnum* fragments for a long period without rain (Price et al. 1998). It is thus imperative to use a protective device that gives preference to the survival and establishment of *Sphagnum* mosses.

The use of natural or artificial mulch is a management practice largely in use in agriculture to decrease the thermal variation of soil and to reduce evaporation (Rosenberg et al. 1983; Enz et al. 1988). A wide array of "mulching" material has been tested in peatland restoration (Rochefort 2001): polyethylene plastic cover, plastic material usually used for making snow fences, greenhouse shading screen, straw mulch, and root residues rejected by the peat screening process when baling peat. Even if in most cases moss fragments did establish themselves better under a cover rather than under no cover, the results varied greatly in efficiency between the material types used for protection. After several trials and a few years of monitoring the recovery success of different protecting materials, straw mulch proved to be the most effective protection through reducing day temperature, reducing evaporation losses, and improving soil moisture and pore water pressure (Price et al. 1998, 2003; Fig. 17.4, Table 17.2). Not only did it improve the regenerating conditions for the mosses, but it also proved to be the most economical solution.

The use of mulch might well provide a favorable humid microclimate for the mosses but it also reduces the quantity of incident light that is needed for photosynthesis and growth. Again, the requirement for light in the habitat niche might be quite different from that in the regeneration niche, especially when the moss is reintroduced as fragments. Experiments conducted in growth chambers and greenhouses (Rochefort 2001) showed that there is a decrease in *Sphagnum* regeneration from fragments only when light is cut by 80 % or more. Thus, it is possible that the potential negative effect of reducing incident light is more than counterbalanced by the amelioration of RH for the regeneration of the *Sphagnum* mosses. In fact, the photosynthetic capacity of *Sphagnum* mosses is reduced when incident light was found to be greater than 175 W m^{-2} (photoinhibition; Murray et al. 1993). Thus, the reduction of light by the straw mulch could also be beneficial, but this hypothesis remains to be tested.

Microclimate conditions for *Sphagnum* recolonization of bare peat surfaces can also be improved by the use of companion species (Grosvernier et al. 1995; Boudreau and Rochefort 1999; Tuittila et al. 2000). Vascular plants, such as the ericaceous shrubs or *Eriophorum* species, used to promote moss establishment could be interesting. One must keep in mind

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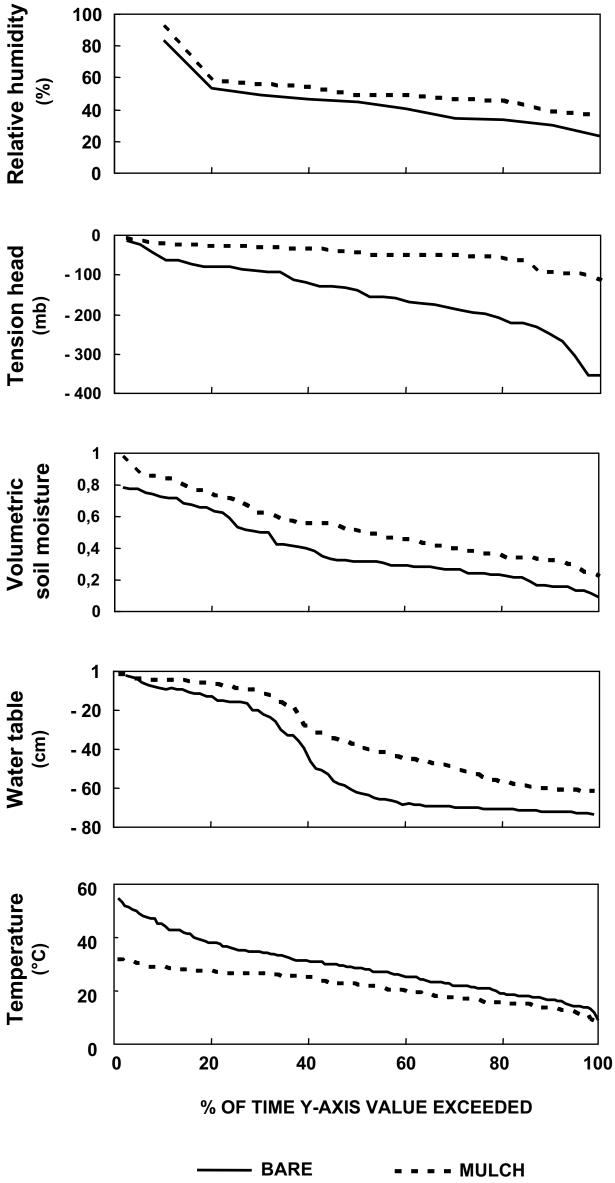

Fig. 17.4. Hydrological and microclimatic variables duration curves for bare and mulched peat substrate showing the percentage of the time the variable was greater than the level shown

that ericaceous shrubs are slow to propagate and to grow and *Eriophorum* species can be invasive and totally cover the ground. A better knowledge of their propagation and population development will be needed before they can be used effectively, although some light is now being shed in the population dynamics of *Eriophorum spissum* on abandoned peatlands (Lavoie et al. 2005a, b). Furthermore, vascular plants can enhance evapo-

Table 17.2. Average daily net radiation (Q^*), ground (Q_g) and latent heat (Q_e) flux (W m^{-2}), and evaporation (E, mm) from a bare peat surface, and a similar surface covered with straw mulch (2,250 kg ha^{-1}). Measurements are from Lac St. Jean peatland, Quebec, Canada, between June and October 1995. (Adapted from Price et al. 2003)

	Q^*	Q_g	Q_e	E
Bare peat	128.2	16.4	88.3	3.1
Mulch covered	112.0	2.2	74.2	2.6

rative losses from a site (Lafleur 1990; Spieksma et al. 1997) but water losses are from deeper in the peat profile; thus, *Sphagnum* mosses might access water directly from the surface of the bare peat in addition to direct precipitation (Price et al. 2003). In counterpart, mosses such as *Polytrichum strictum* or *Campylopus introflexus* (introduced in Ireland) are promising nursing plants (Groeneveld and Rochefort 2002). *Polytrichum* fragments or *Polytrichum* carpets can improve the microclimate over a cutover peat surface (Groeneveld and Rochefort 2005) and the survival of surrogate seedlings but the direct nursing effect to directly help *Sphagnum* establishment remains to be tested.

Similar to the restoration of *Sphagnum*-dominated peatlands, amelioration of microclimatic conditions at the air–peat interface also seems to be important for restoration of fens when plant reintroduction approach is used. A first attempt to fen restoration with Sphagna and brown mosses was done by reintroducing two different types of fen vegetation in combination with straw mulch on sedge peat (Cobbaert et al. 2004). Vegetation from natural fens was introduced as a donor diaspore bank, containing seeds, rhizomes, moss fragments, and other plant propagules. Two natural fens were chosen with contrasting vegetation types: one was dominated by mosses (*S. centrale* and *S. flexuosum* species), the other was dominated by vascular plants (*Calamagrostis canadensis)*. Even though there were problems to fully rewet the experimental site, the application of straw mulch improved the establishment success of the fen vegetation. It can be suspected that this was through the amelioration of growing conditions at the air–peat interface as for *Sphagnum* cutover peatlands.

17.3.4 Hydrology

In peatland management, it might appear easy to reverse the effects of drainage by simply rewetting. In reality, new soil profile conditions have developed after peat utilization, and these differ significantly from the natural mire soil profile of any former developmental stage (Price et al. 2003). Therefore, restoration actions, especially after peat cutting or agricultural management, should consider the restoration site as a new environment with new physical properties, especially on the upper layer of the soil column.

Starting conditions for peatland restoration are influenced by the historical management of the site and by the stratigraphy of the mire massif before human activities started. Since water is one of the main prerequisites for the development of peatlands (Chap. 13), further development of the ecosystem after restoration will be greatly influenced by two of the fundamental physical properties of the peat – porosity and hydraulic conductivity. Values of both porosity and hydraulic conductivity usually have a decreasing trend from the upper peat massif layers toward the bottom layers. This is correlated with the higher decomposition state of the vegetation debris. In most peatland areas, the bottom peat or gyttja layers act as a water seal against the underlying mineral deposits. Thus, two different aquifers are created – an upper one with free water influenced by atmospheric pressure and a lower one with water at a pressure greater than atmospheric pressure (Franzen 1985). The distribution of different porosity and hydraulic conductivity within the peat determines the water movement through the peat layer. The drained and cutaway peat massif surface therefore reflects the earlier peat hydrophysical conditions and the later degraded (by shrinkage, compaction, and oxidation) peat at the upper part of the remnant surface layer. Owing to increased mineralization, the decomposition of the peat is higher and water permeability properties lower; therefore the water table sinks far below the peat surface, especially in dry periods of the year. The supply of moisture for peat-moss growth is insufficient, which makes the substrate often unsuitable for the growth of raised bog plants (Streefkerk and Casparie 1989; Eggelsmann et al. 1993; van Seters and Price 2002; Kennedy and Price 2004). Finally, in cutover mires some of the hydrophysical attributes of the original mire are irreversibly altered (Eggelsmann et al. 1993; Schlotzhauer and Price 1999).

Here it is important to keep in mind that in natural peatlands, *Sphagnum* mosses are adapted to grow on dead, but essentially undecomposed versions of themselves. The high water storage imparted by these loosely packed, and poorly or undecomposed mosses, maintains a high and stable water table, so only a relatively small capillary rise is necessary to ensure an adequate moisture supply to the growing part of the plant. The *Sphagnum* carpet can only generate relatively weak capillary pressures within the intracellular spaces (hyaline cells) and intercellular pores (between branches and leaves of adjacent plants). Hayward and Clymo (1982) found that drainage of hyaline cells in *Sphagnum* occurred when the pore-water pressure is below about –100 mbar. The corollary of this is that *Sphagnum* plants are unable to withdraw moisture from a substrate where the pore-water pressure is lower than –100 mb. Several measurements done on terminated peat cuttings at different sites in different years reveal conditions of pore-water pressure of less than –100 mbar (–355 mbar in Price 1997; –170 mbar in Price and Whitehead 2001) to the extent that water management measures are as necessary as plant reintroduction to alleviate the problem of poor regeneration or germination and mulching to improve microclimate growing conditions (Price et al. 2003).

Hydrological conditions for restoration can be approximated from the study of old block peat cutting sites. A study of the vegetation–water–soil relationships in block peat cuttings in Sweden that were left to spontaneous recolonization in the last 30–50 years revealed the primary importance of water inundation depths and water regulation intensities in the development of different plant communities (Lode 2001). It was found that sites with reestablished (1) *Sphagnum* species (*Sphagnum* carpet) had a large range of average inundation water depths (from 0.2 to 1.0 m above the soil surface), along with small annual water level fluctuations around the year, standard deviation, SD, 1.2–2.6, (2) *E. vaginatum* had on average lower inundation levels (up to 25 cm), but more fluctuating water levels (SD 3.7–4.8), and (3) dwarf shrubs, *Pinus sylvestris*, and *Betula pubescens* accompanied by *E. vaginatum* had as a rule average groundwater level around 4–20 cm below the peat soil surface, with a relatively larger fluctuation of the water table (SD 2.3–6.9). The poorly revegetated sites had a deeper water table of 50–60 cm and a strongly fluctuating water level (SD 12–19), as a result of the functioning drainage. When the average groundwater depth was 6 cm below the surface with corresponding SDs of 4.5 the surface remained "muddy" owing to soil surface freezing and swelling events in autumn and spring, impeding young plant establishment.

The work of McNeil and Waddington (2003) in block peat cuttings in Canada also emphasizes the importance of limiting water fluctuations in restoration sites. Indeed, they found that drying and wetting cycles negatively affect *Sphagnum* net primary production and net ecosystem CO_2 exchange. *Sphagnum* and peat respiration increased 4–14-fold upon rewetting, whereas *Sphagnum* photosynthesis did not recover until 20 days of saturation. In conclusion, they suggest that restoration techniques should include the establishment of companion species to help the newly *Sphagnum* cushions to survive while a proper acrotelm, which will in turn regulate water fluctuations, is being formed.

In conclusion, milled landscapes were designed (cambered surfaces) to efficiently shed surface water quickly with usually little variation in topography over extensive areas. Furthermore, with the repeated passages of heavy machinery to extract peat, the residual peat profile is strongly compressed, and dries quickly, which then impedes the capillary water flow to the surface and to any establishing *Sphagnum* propagules. In short, the

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Table 17.3. Changes to water table, soil moisture at –2 cm, and water tension at –1 cm in basins vs. flat restored surfaces. Measurements are from Lac St. Jean peatland, Quebec, Canada. (Adapted from Price et al. 2002)

	Water table (cm)	Soil moisture (cm^3 cm^{-3})	Tension (cm)
Control (flat surface)	−27.5±13.2 (−30.2)	0.67±0.07 (0.65)	−26.4±19.3 (−25.7)
20-m basin	−0.3±10.3 (1.2)	ND	ND
10-m basin	−19.2±11.4 (−19.2)	0.80±0.05 (0.72)	−15.4±9.3 (−15.5)[a]
4-m basin	−16.1±12.1 (−16.5)	0.78±0.06 (0.71)	−8.2±11.7 (−7.4)
Mulch covered	−17.8±10.5 (−18.6)	ND	−13.5±11.0 (−13.5)

Values are means ± standard deviation, with medians in *parentheses*, collected daily between May and August 1996

ND data for this variable were not collected at this location.

[a] Data missing but generated by regression (r^2=0.92)

residual peat profile of milled extracted area is a harsher environment for spontaneous recolonization than the former block cutting method.

Site preparation for restoration of milled peatlands frequently involves the construction of berms or shallow basins to enhance peat moisture content (Wheeler and Shaw 1995; Farrell and Doyle 2003; Price et al. 2003; Table 17.3). As a consequence, *Sphagnum* reintroduced within restored areas may be subject to extended periods of flooding, particularly following snowmelt or heavy rainfall. Different *Sphagnum* species were tested to evaluate the effect of flooding on their growth and development (Rochefort et al. 2002). It was found that *Sphagnum* can physiologically tolerate and even benefit from shallow temporary flooding. Areas that tend to be temporarily flooded (lower depressions, downslope ends of sites) are also often the same areas that tend to stay wetter throughout the growing season. In such areas, establishment of reintroduced *Sphagnum* will be enhanced, as establishment success is strongly linked to the level of humidity at the peat surface during summer (Price and Whitehead 2001; Girard et al. 2002). However, it must be underlined that flooding is by no means an absolute necessity for *Sphagnum* establishment. On the contrary, severe or lengthy flooding in the field, and even limited flooding of unstabilized fine peat, can lead to erosion and peat deposition, that in turn retard or impede vegetation establishment (Quinty and Rochefort 2000; Faubert and Rochefort 2002). Thus, for successful *Sphagnum* establishment, a fine balance between rewetting and substrate stability must be found.

17.3.5 Peat Stability and Quality

17.3.5.1 Erosion

In addition to microclimate, substrate instability has been suggested as one of the potential barriers to natural recolonization of bare milled peat surfaces (Rochefort 2000). But compared with hydrology and microclimate, the role of peat surface stability in *Sphagnum* establishment has received scant attention. Peatlands for commercial uses need to be drained to allow the extraction of peat. After drainage has ceased, subsidence of these peatlands continues (Price and Schlotzhauer 1999). This subsidence is usually attributed to shrinkage, compression, and biochemical oxidation of the peat (Schothorst 1997) but wind erosion has been suspected to play a role as well (McNeil et al. 2000; Campbell 2002).

According to Eggelsmann et al. (1993), drainage and the resulting drying of the peat causes the coherent peat matrix to break down into structural units of aggregates. Although peat fibers or peat-derived aggregates are very stable and resist physically disruptive process such as ploughing, they are light in weight and therefore up to diameters of 0.5–2 mm they could be very susceptible to wind erosion. Campbell et al. (2002) have found that wind erosion during summers is not an important cause of subsidence in milled peatlands as was previously suspected. This is attributed to the crusting of the surface that makes the bare peat surfaces very resistant to wind erosion and may impede diaspore germination. This is the reason why if an extensive peat surface has been abandoned for a long time before a restorative intervention, it is recommended to refresh the surface by breaking up the crust. The scraping of the peat surface facilitates the contact between diaspores and the substrate.

Shrinkage is another component of drained peat erosion and takes place in peat surfaces as a result of high rates of evaporation (Heathwaite et al. 1993). In warm and dry periods, cracks or fissures may appear in the peat surface. These may be up to 15-cm wide and over 0.5-m deep and have height losses of 10–30 cm (Eggelsmann et al. 1993). From the experience of agricultural use of peatlands, lost of peat due to mineralization can reach up to 30 mm year^{-1} in humid regions, and in fen types mineralization can be much greater than in raised bogs (Heathwaite et al. 1993). In a cutover peatland in eastern Canada, the loss was estimated to be 6 mm year^{-1} (Waddington and McNeil 2002). In agriculture, the groundwater levels are perched to minimize the losses caused by mineralization; likewise high water levels should be maintained in cutover peatlands to impede oxidation.

Shrinkage, mineralization, wind erosion, and peat surface fires typically occur in the dry seasons of the year, whereas water-derived erosion

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Fig. 17.5. Example of a large-scale restored surface prepared with small basins. (Photograph taken by Jacques Gagnon)

occurs during intensive rain periods or flooding seasons after the winter snowmelt. Water erosion can be quite disruptive on recently restored sites (Quinty and Rochefort 2000). Compartmentalization of extensive bare peat areas or the creation of shallow basins can be effective in controlling sites prone to water erosion (Fig. 17.5).

17.3.5.2 Frost Heaving

Surfaces of milled peatlands often show an initial bumpy appearance in the spring that gets smoother with time as the summer season advances (Campbell et al. 2002). These surface irregularities appear largely connected to frost heaving (Quinty and Rochefort 2000; Fig. 17.6a). Groeneveld and Rochefort (2002) gave a description of the problem of frost heaving in cutover peatlands (Fig. 17.6b) and an array of means by which it can be diminished. Unforeseen in earlier work on peatland restoration, frost-heaving problems were exacerbated by the rewetting of former drained peatlands. As most peatlands are located in the boreal and tem-

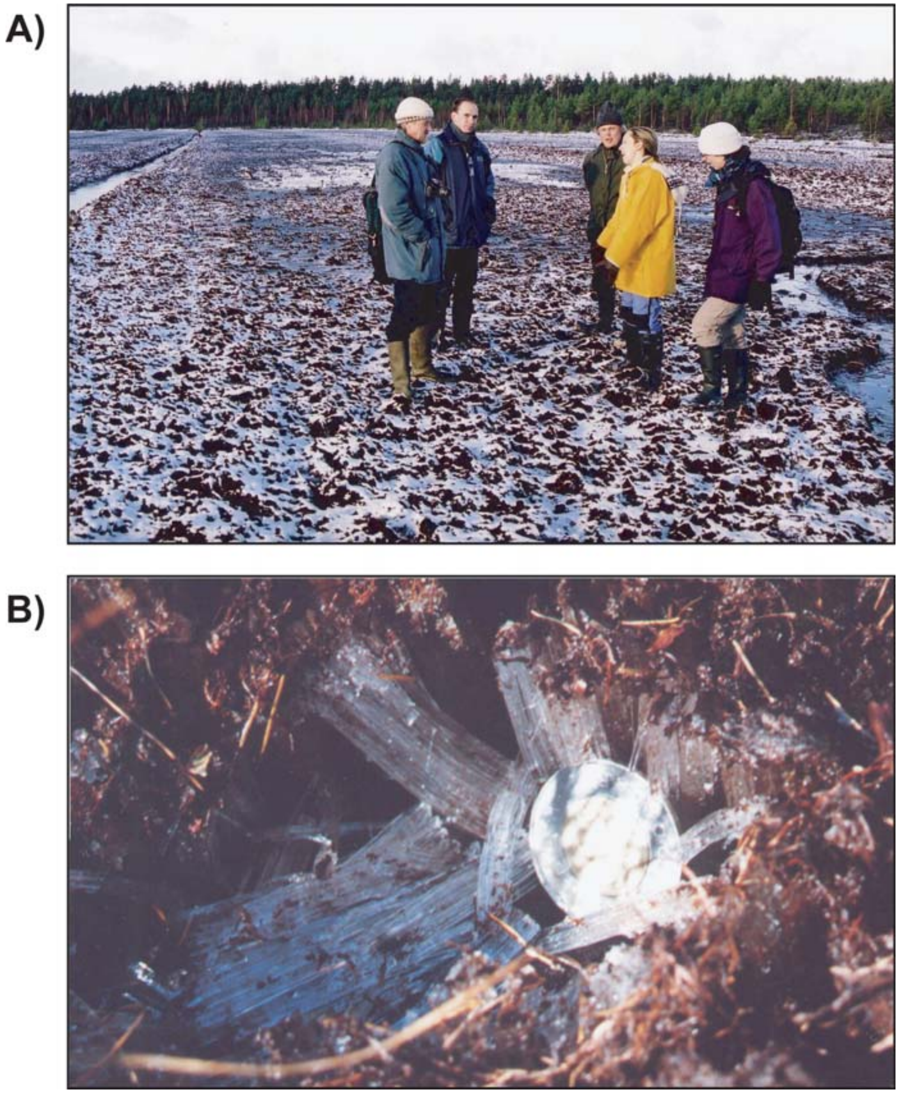

Fig. 17.6. a Extensive effect of frost heaving in an Estonian peatland (Viiru bog) after several years of no harvesting activities. **b** Ice-needle formation within peat. (**a** Photograph taken by Edgard Karofeld; **b** photograph taken by Ian Roul)

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perate zone (Lappalainen 1996) that experiences freezing weather, peat substrate instability caused by frost heaving might be among the main factors impeding total success of restoration projects. Field experiments were used to determine the effectiveness of straw mulch or the use of the moss *Polytrichum strictum* against frost heaving (Groeneveld and Rochefort 2005). Wooden dowels and seedlings of fir trees placed in a *Polytrichum strictum* carpet experienced almost no frost heaving, whereas heaving was severe on bare peat (up to 6 cm; Fig. 17.7). Straw mulch, a protective cover recommended in peatland restoration to protect *Sphagnum* diaspores against desiccation, effectively reduced heaving in the fall, but was less effective in the spring because it had partially decomposed. The *Polytrichum* carpet and the straw mulch reduced frost heaving by reducing the number of freeze–thaw cycles, by slowing the rate of ground thaw in the spring, and by reducing the unfrozen water content of the peat during the spring thaw. From these experiments, we suspect that *Polytrichum*

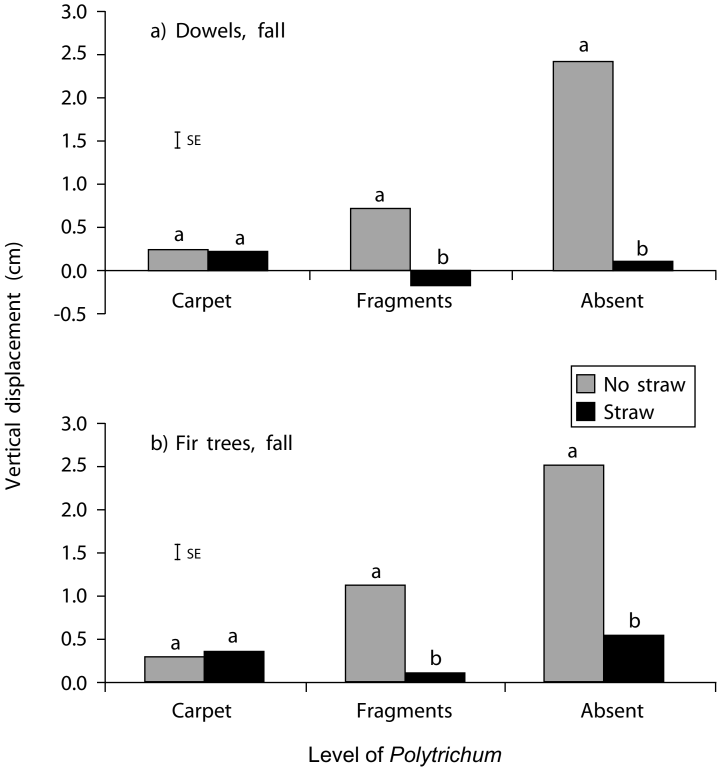

Fig. 17.7. Vertical displacement of dowels and fir trees in spring 2001 (10 months of cumulative frost heave from 24 August 2000 to 29 May 2001) due to frost heaving on an abandoned vacuum-harvested bog, Premier St-Laurent, Rivière-du-Loup, Quebec. (Adapted from Groeneveld and Rochefort 2005)

strictum could potentially be a good nursing plant for the *Sphagnum* fragments, not only in terms of stabilizing the peat surface, but also in helping to ameliorate the microclimate at the peat surface. The extent of competition between *Polytrichum strictum* and its benefactor plant, *Sphagnum*, remains unclear at this time. An interesting question is: Under what conditions does *Polytrichum strictum* enhance the establishment of *Sphagnum*, and under what conditions does competition negate the positive facilitation? Further research is needed.

17.3.6 Species Interactions

Much of the effort done in peatland restoration has been to evaluate *Sphagnum* establishment success in relation to abiotic factors (Chap. 4). Biotic interaction studies are just beginning as the implementation of large-scale restoration projects was needed to assess plant species interactions on vegetation establishment success and biodiversity.

In Europe, cotton grass (*E. vaginatum*) has been found to facilitate the establishment of other bog plant species in mined bogs (Matthey 1996; Tuitilla et al. 2000), but detailed studies conducted in North America by Lavoie et al. (2005a, b) did not provide evidence for the facilitation hypothesis. The presence of mosses or liverworts was more associated with favorable hydrological conditions than with the presence of cotton-grass cover (Fig. 17.8). Also to be noted from Fig. 17.8 is the decline in the number of cotton-grass tussocks, which is surprising given their potential long-lived tussocks and their many characteristics facilitating their invasion on bare peat (Lavoie et al. 2005a). We now know that with only minimal water management, it is possible to induce a rapid cotton-grass invasion on an abandoned milled peatland (Lavoie et al. 2005b); but once a cotton-grass cover is established it can take 60–600 years before it is succeeded by a *Sphagnum*-dominated community or other wetland vegetation types (Buttler et al. 1996; Hughes and Cymayne-Peaty 2002). Thus, if one has in mind a restoration goal of reestablishing a *Sphagum* plant cover within5 years, use of cotton grass is not a suitable restoration option as the minimal water management option using cotton-grass invasion is not suitable for a short to midterm basis (less than 100 years). But in countries where a natural source of *Sphagnum* diaspores is not readily available, cotton-grass invasions might represent a suitable restoration option.

Little is known about moss interactions. During the establishment phase, does the reintroduction of several *Sphagnum* species together benefit the biodiversity of the carpet or does it help the establishment of recalcitrant *Sphagnum* species (as noted for *S. magellanicum*; L. Rochefort, personal observation)? Or does it negatively impact the establishment success rate because of competition for resources? For answers, a long-

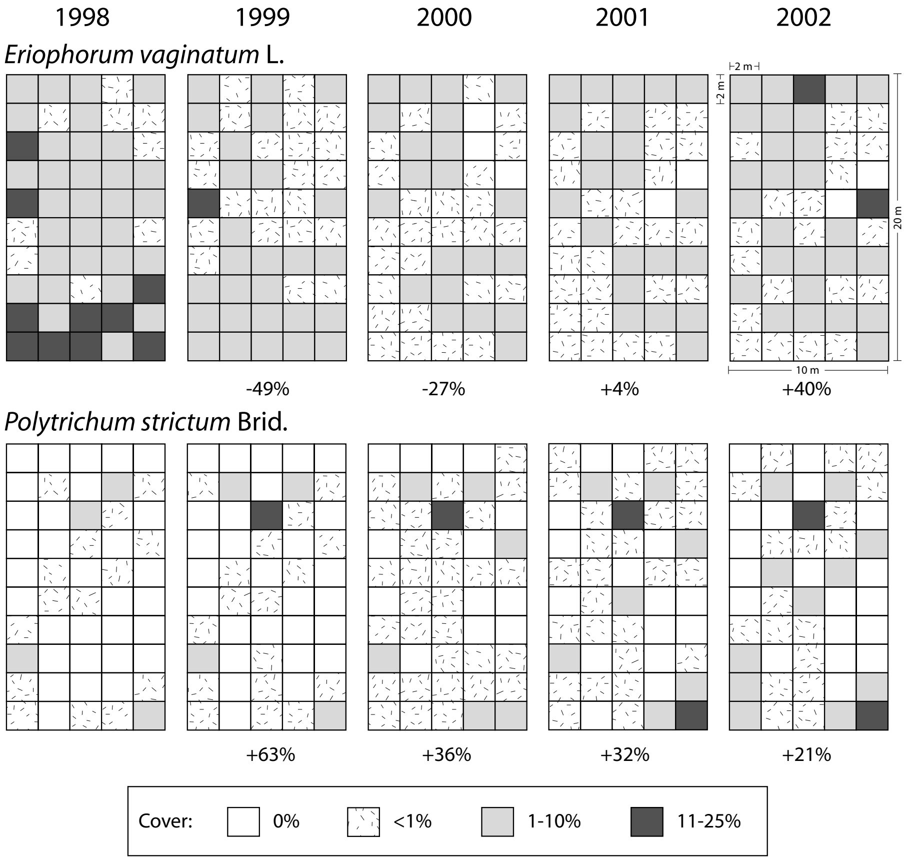

Fig. 17.8. Monitoring of the cover of *Eriophorum vaginatum* L. and *Polytrichum strictum* Brid. in a 10 m × 20 m quadrat installed in a 14-year-old abandoned vacuum-milled site over a 5-year period. See Lavoie et al. (2005a) for more details

term experiment was established in an abandoned milled peat field by Chirino and Rochefort (2000) in 1998 to assess the establishment capabilities of four species of *Sphagnum*: *S. fuscum*, *S. rubellum*, *S. magellanicum*, and *S. angustifolium*. The reintroductions were done on single species or multiple-species combinations in nine treatments. Most percentage combinations with ratios of 100, 50:50, 50:25:25, or 25:25:25:25 were applied in experimental plots of 30 m^2 in area. This was repeated six times and the development of the carpet was monitored for 4 years. It was found that *S. fuscum* and *S. rubellum* are two widespread species that easily recolonize bare peat substrates and show good success of establishment, be it in monospecific or plurispecific reintroductions. It was also found that a species like *S. magellanicum* had a greater establishment rate in the presence of *S. fuscum* or *S. rubellum* than when reintroduced in a monospe-

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cific carpet. This result is interesting because if one aims to favor the establishment of a species from the section *Sphagnum* then plurispecific reintroductions including species from the section Acutifolia should be considered. These conclusions were reached during the early development of the moss carpet. Continued monitoring is necessary to follow the evolution and specific interactions of completely closed carpets to determine the long-term establishment success.

17.3.7 Climatic Conditions

A similar long-term experiment was done to study the responses of specific *Sphagnum* species and their morphological structure in relation to interannual variations in climate (Chirino et al. 2006). In order to compare results under a variety of climatic conditions, the whole experimental setting as described earlier was repeated four times (trials), i.e., repeated in the springs of 1995, 1996, 1997, and 1998 with a 4-year follow-up for each trial. The establishment rate of the moss carpet varied according to the year, in response to climatic variations between growing seasons. Climate in the reintroduction year was particularly important in determining the long-term establishment success, mostly in terms of rainfall distribution over the growing season. The relative success of different moss species and combination of species, however, did not vary within or between trials. Thus, the species and combinations of species resulting in the highest short-term or long-term establishment rates remained the same for all trials, independent of the climatic conditions at the time of reintroduction and the season of growth. Our results showed no link between the number of species in the *Sphagnum* reintroduction mixture and successful establishment of the moss carpet. Yet successful regeneration was clearly influenced by the identity of the species chosen for reintroduction. *S. fuscum*, alone or in combination, was the species found to lead to the most extensive development of the moss carpet under the conditions tested.

17.4 Overview of Restoration Practices

Practical considerations for implementing restoration projects on a large scale have been well described by several reviews: Wheeler and Shaw (1995); Brooks and Stoneman (1997); Dupieux (1998); Blankenburg and Tonnis (2004); Schouten (2002); and Quinty and Rochefort (2003).

Thus, for this section, only general guidelines that can be applied to any peatland restoration project will be discussed.

17.4.1 Planning

Any restoration project should begin with the preparation of a restoration plan to make sure that the right options and timeframe are set up. Planning and design considerations are key elements in the success of restoration as it is essential to set the appropriate goal and objectives; it allows greater efficiency in conducting the operations and it contributes largely to the cost reduction of restoration. A good restoration plan should have two different components: site conditions, goals, and objectives and planning restoration operations.

Identification of the conditions of the site is a necessary step because site characteristics dictate the correct goal to be achieved: restoration or reclamation. The second step consists of defining the operations that need to be done, planning resources and time required, setting up a schedule, and evaluating costs. This information should include the following elements: site characteristics prior to peat extraction; hydrologic environment; topography; peat characteristics; chemical aspects; existing vegetation of the restoration site; surrounding landscape; setting the right goal; setting the right objectives; identification of a donor site (source of plant material to be reintroduced); identification of a reference site; identification of a nonrestored section (optional); and monitoring protocol.

The overall water budget should be evaluated to see if primary positive moisture conditions still exist, mostly for the case of *Sphagnum* peatland development. A hydrological approach as used by van Seters and Price (2001, 2002) should provide useful clues on restoration potential, mostly when peatlands are at the limits of their normal climatic distribution. For example, it might prove quite difficult to restore a *Sphagnum*-dominated peatland located at the edge between the prairies and the boreal forest in North America in the context of global warming. In such a case, reclamation may be a more appropriate goal, and this should be known from the beginning.

To prepare functional restoration goals, a reference ecosystem should be described as the model for planning the project, and should later serve in the evaluation of the project. Typically, the reference represents a point of advanced development that lies somewhere along the intended trajectory of the restoration (Society for Ecological Restoration Science, Policy Working Group 2004). In other words, the restored ecosystem is eventually expected to emulate the attributes of the reference, and project goals and strategies are developed in light of that expectation. The reference can consist of one or several specified locations that contain model ecosystems, written descriptions, or a combination of both. The value of the reference increases with the amount of information it contains, but every inventory is compromised by limitations of time and funding. Minimally, a baseline ecological inventory describes the salient attributes of the abi-

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otic environment and important aspects of biodiversity such as species composition and community structure. In addition, it identifies the normal periodic stress events that maintain ecosystem integrity (Society for Ecological Restoration Science, Policy Working Group 2004). With peatland ecosystems, paleoecology can also be a useful tool to define the reference ecosystem (Lavoie et al 2001; Gorham and Rochefort 2003).

The amount of work for this planning stage depends on the restoration starting conditions, and the agreed restoration end option. In many cases, financial limitations are the main factor influencing the measures planned and consequently the intensity of preparatory work. A good-quality preparatory plan should include both desk and laboratory work (literature search, climatic and hydrological data compilations, chemical analyses, computer mapping) and field work.

17.4.2 Surface Preparation

The preparation of an abandoned bare peat surface for restoration has two main purposes. One is to remove the surface crust that might have formed between the time that the extracting activities ceased and the start of the restoration project (Fig. 17.9a). A fresh peat surface will allow better contact between the newly reintroduced plant diaspores and the peat substrate as well as greater access to the soil moisture, particularly for mosses that can gain their moisture from the soil only by capillarity, because they have no roots. The second one is to prepare the surface to increase water availability and its distribution over the site to favor the establishment of the *Sphagnum* fragments.

As discussed in Sects. 17.3.3 and 17.3.4, water availability is preponderant in peatland restoration. As peat-extracted peatlands have lost their natural ability to store water and regulate water table fluctuation, management procedures must be undertaken to reduce water losses and to provide a water supply to *Sphagnum* and other introduced plants. To achieve these goals, two types of action can be undertaken: (1) redesign the surface topography and (2) blockage of the former drainage system (Fig. 17.2). Blocking the former drainage system is a necessary action (Money 1995; Rochefort 2001) as illustrated in Fig. 17.2 by the ellipse. Blocking drainage should be done only at the end of all the restoration actions to make sure that the site can support the repeated passage of machinery to the end of the restoration project. The step of blocking drainage will be discussed later.

Surface preparation includes an array of actions that can help to improve site conditions, but the implementation of any surface management needs to be decided on a case-by-case basis. If a site is naturally well supplied with water, either by an artesian aquifer or by an oceanic climate,

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Fig. 17.9. The six main mechanical steps proposed for successful restoration of milled harvested peatlands. (Photographs taken by Peatland Ecology Research Group, *PERG*)

surface preparation might not be needed much as illustrated by the discontinuous ellipse in Fig. 17.2, but this remains to be better substantiated. Among the options for surface preparation, there are (1) the reprofiling of peat fields to favor a better distribution of water (Bugnon et al. 1997); (2) the filling of ditches where convenient to facilitate the work of the machinery; (3) the building of peripheral berms to retain water in situ or act as a windbreak; (4) the building of berms across the slope or chessboard-like berms and the creation of shallow basins (Price et al. 2002, 2003; Campeau et al. 2004) that on top of acting as options 1 and 3 will prevent flooding

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over large areas and remove loose peat surface and crust; and (5) the removal of existing vegetation to reduce evapotranspiration and plant competition and to facilitate the work with machinery.

Further rationales for surface preparation options can be found in Wheeler and Shaw (1995), Quinty and Rochefort (2003), and Price et al. (2003).

17.4.3 Plant Material Choice and Spreading

Active introduction of plants is done when one wants to accelerate the formation of a new plant carpet. The most important feature of this plant carpet is the presence of *Sphagnum* mosses, which are largely responsible for the unique characteristics of peat bogs and for the accumulation of peat. Thus, the plant material that is introduced must contain an important fraction of *Sphagnum*. Species from the Acutifolia group such as *S. fuscum* or *S. rubellum* are among the best species tested so far (Rochefort et al. 2002) along with other mosses like *Polytrichum* that can contribute substantially to the success of restoration because *Sphagnum* mosses are poor primary colonizers. The quality of plant material in terms of plant species is a major factor responsible for the success of restoration. A site dominated by these plants is the best source for acquiring replacement material, while a site lacking *Sphagnum* should be discarded. The most practical and abundant source of peat bog plant diaspores is a bog itself, but there is ongoing research to develop *Sphagnum* "farms" to produce *Sphagnum* diaspores for restoration that would be very useful for countries where mires are not abundant (Joosten 1998; Campeau and Rochefort 2002; Gaudig and Joosten 2002). Ideally, plant material is collected near the site to be restored in order to minimize transportation and differences in population genetics from out-of-region donor sites.

In North America, natural remnants of harvested peatlands or small peat bogs are commonly available and accessible at short distances from restoration sites. Collection of plants consists essentially in shredding the surface vegetation and in picking it up (Fig. 17.9b). This plant material will be spread over the restoration site to form a new plant carpet. Collection of plants, when done properly, allows rapid recovery of donor sites and does not result in permanent damage (Rochefort and Campeau 2002).

The quantity of plant material to be used for restoration was determined experimentally in order to ensure rapid establishment of new plant carpets on the restored site, minimize the amount of work required for plant collection and transportation, and minimize impacts to natural sites.

The quantity of plant material for reintroduction is generally reported as a ratio of the area of the collection site to the area of the site to be restored. A ratio of 1:10–1:15 is suggested, i.e., the donor site is 10 or 15 times smaller than the area to be restored when harvested on a 6–10-cm-thick surface layer (Campeau and Rochefort 1996). Collecting only the top 5–10 cm of the surface vegetation has the advantage of favoring a rapid recovery of donor sites (Rochefort 2001). During the collection process, the plant material must be shredded to an ideal fragment size between 1 and 3 cm. If worked properly, a donor site could be used more than once on a sustainable basis.

Well-loosened fragments spread better and regenerate more successfully as they make better contact with the substrate. The root system of shrubs and sedges stays in place and moss fragments that are left behind can regenerate easily. Theoretically when spreading in the field, plant diaspores should cover the ground but not overlap. Some sedge and shrub diaspores will occur in the collected material along with the moss species and help to more quickly rehabilitate the biodiversity typical of peatlands.

The choice of donor sites should always minimize impacts to pristine sites. Whenever possible, plants should be collected on fields that are being opened for future extraction activities. Plant material of peatlands that are condemned for industrial or agricultural development should be saved for restoration projects.

Once the plants have been shredded with the help of a rotovator (Fig. 17.9b), picked up (Fig. 17.9b), and transported to the restoration site, moss fragments are spread using a standard box manure spreader (Fig. 17.9 c). Biologically, *Sphagnum* moss appears to have a lower potential of regeneration in midsummer than in spring or fall (Rochefort 2001); however this is unlikely to affect the restoration success of very wet sites as a moist substrate and a microclimate appear to be much more prevalent influencing factors. The use of heavy manure spreaders should be avoided when the ground is too soft because the machines leave deep tracks. The creation of this type of surface microtopography has proven to be detrimental to Sphagnum establishment (Price et al. 1998).

17.4.4 Diaspore Protection

Once spread on the bare peat surface, plant fragments are exposed to the sun and wind and they dry rapidly (Sagot and Rochefort 1996); hence, it is imperative to protect the newly reintroduced diaspores as soon as possible.

For peatland restoration on sites where peat instability does not appear to be a problem, the use of straw mulch alone should be sufficient (Fig. 17.9d). However, on those sites where instability is a severe problem, straw alone is not the best option. Its effect is short term, as it decomposes rapidly, seriously decreasing in efficiency after 1 year of application and being close to nil after 2 years. In these cases, the uses of a pioneer plants such as *Polytrichum strictum*, with better stabilizing capacities, become an interesting addition to restoration techniques (Groeneveld and Rochefort 2005). Straw mulch is still considered necessary, as it takes at least two growing seasons for *Polytrichum strictum* carpets to reach an appreciable size, and it also enhances the *Polytrichum* establishment.

Many other covers aimed at protecting the reintroduced *Sphagnum* fragments have been considered and tested experimentally (Rochefort 2001): clear plastic cover as used in agriculture, shading screens (Bastien 1996), plastic nets used as snow fences or construction fences of different porosity (Quinty and Rochefort 1997), root "mulch" supplied by the screening process when baling peat, ericaceous or *Eriophorum* companion species (Boudreau and Rochefort 1999), and commercial mulch such as *Curlex* and *Eromat*. Among them, the use of straw mulch was always more efficient in *Sphagnum* establishment success and proved to be the most economical option. Visually, an efficient spreading of straw mulch is when it is thick enough to create an air layer, but allows light to pass through and reach plant fragments.

17.4.5 Fertilization

Fertilization aims at facilitating plant establishment (Fig. 17.9e). In restoration experiments, it was shown that phosphorus fertilization increases the development and spreading of mosses like *Polytrichum strictum* (Sottocornola et al. 2002). This moss in turn is suspected to provide suitable conditions for the establishment and growth of *Sphagnum* fragments. Rapid colonization of bare peat substrate by *Polytrichum strictum* also helps to decrease or prevent damage caused by erosion and frost heaving phenomena. In addition to favoring mosses such as *Polytrichum strictum*, phosphorus application may help the germination and establishment of several vascular plant species typical of peatlands (Sottocornola et al. 2002). Phosphorus fertilization is a factor that plays a role in the success of plant establishment, but its usefulness still remains to be properly assessed against the drawback of favoring the growth of nonpeatland plant species. So far, the benefits appear to exceed the drawbacks.

17.4.6 Blocking Drainage and Rewetting

The objective of blocking drainage is to essentially keep water within the restoration site and also to improve the distribution of water. This action is done last, once all other restoration steps have been completed, in order to facilitate the circulation of machinery over the site (Fig. 17.9f). Still it is

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one of the essential actions (Fig. 17.2) without which *Sphagnum* will not be established. Wet humified peat cab be used to make the most efficient and impervious dams. Different experiments done within the Peatland Ecology Research Group (http://www.gret-perg.ulaval.ca) have shown repetitively the synergic effect of mulching and blocking drainage and now no further trials are done without applying these two restoration practices.

Besides blocking the drainage, many other treatments aiming at supplying water to the *Sphagnum* fragments and impeding desiccation have been tested: sprinkler irrigation, pumping water into irrigation ditches, windbreaks to retain snow on the restoration site, and surface inundation distributed by a perforated PVC pipes. All these management practices proved to be equal to mulching or did not significantly improve the *Sphagnum* establishment rate if applied in combination with mulching (Rochefort 2001). As they were costly to implement, mulching and blocking drainage remain the best options.

17.4.7 Pool Creation

Bog pools represent a characteristic feature of peat bogs in oceanic regions. Not all sites have pools, but some peatlands have hundreds of them. Pools are important because they support a wide variety of organisms that contribute to the biological richness of peatlands. Many plant and insect species are found only in or around bog pools and nowhere else in peatlands. In fact, peatlands with pools have a much greater biodiversity than peatlands without pools. Thus, the creation of pools is strongly encouraged because it increases the value of a restored peat bog, especially if the presence of pools has been seriously reduced regionally (Standen et al. 1998; Mazerolle 2001, 2003; Mazerolle and Cormier 2003).

17.4.8 Time to "Recovery"

An example of a simple monitoring program that is suggested to peatland managers after restoring a peatland is given in Quinty and Rochefort (2003) with examples of monitoring forms. We now know that it is possible to revegetate a cutover peatland with peatland plants and stabilize the surface peat substrate within 3–5 years. An example is a restoration project done in eastern Canada (Bois-des-Bel), where it was found that after 5 years of restoration, total plant cover by peatland plants was already 90 % and a moss carpet composed of *Polytrichum* and *Sphagnum* species covered 70 % of the ground. Figure 17.10 illustrates the changes observed through the years.

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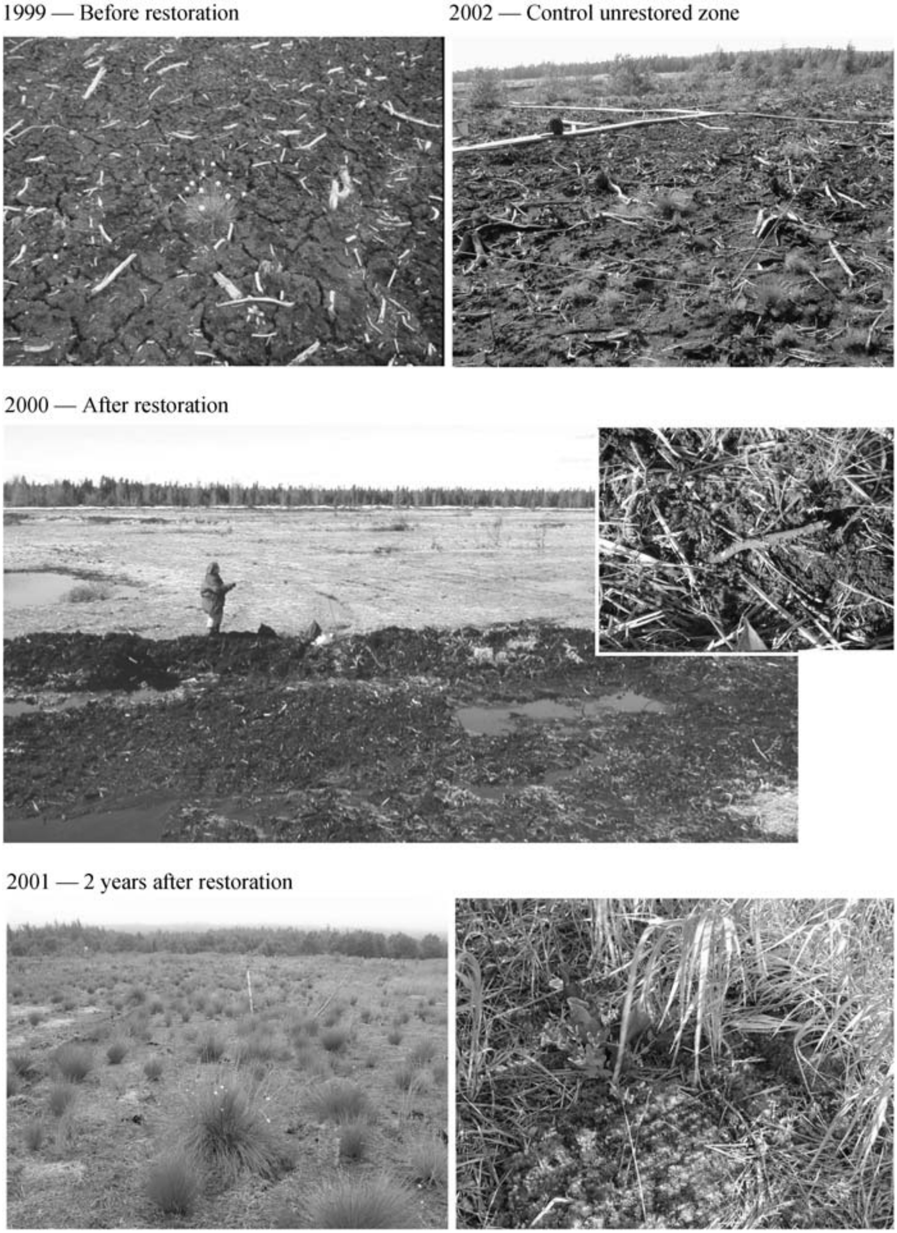

Fig. 17.10. Plant revegetation sequence of the whole ecosystem experiment at Bois-des-Bel peatland showing relatively bare peat substrate prior to restoration in 1999, the year of restoration in 2000 and four years of recovery. In 1999, prior to restoration, bare peat still covered 71 % of the ground after 20 years of abandonment. In the picture from 2002 of the control nonrestored zone, one can see much dead wood that frost-heaved to the surface with time. The picture from 2000 is a general view of the restored site covered with straw mulch atop the spread *Sphagnum* diaspores and the first pair of created pools can be seen in the foreground. In 2001, already 2 years after

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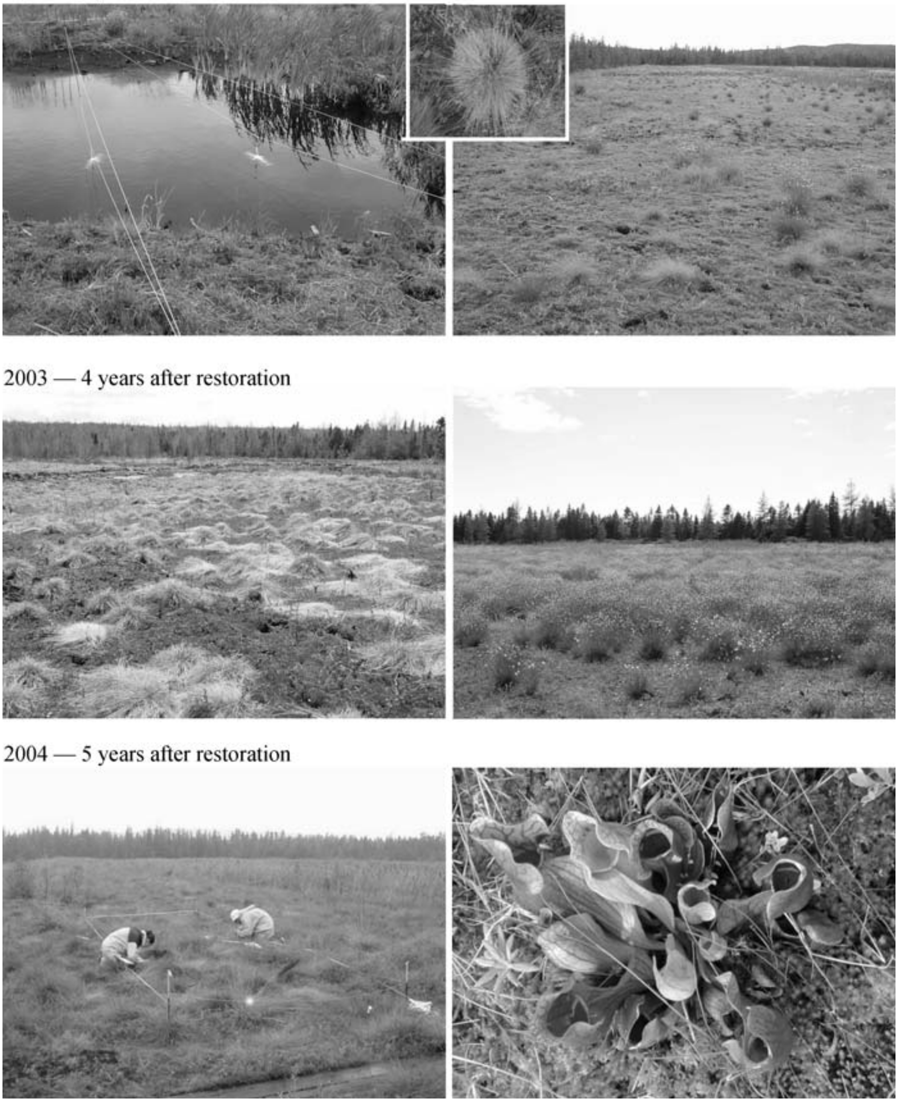
2002 — 3 years after restoration

2003 — 4 years after restoration

2004 — 5 years after restoration



restoration, the moss carpet covered 62 %, of which 22 % was composed of *Sphagnum* species; part of it is seen atop the straw mulch. In 2002, most of the ground vegetation is dominated by cotton grass (*E. spissum*) and *P. strictum*. Four years after restoration, a moss carpet dominated more and more by sphagna has developed (35 %). The survey of 2005 points to an estimate of 65 % *Sphagnum* cover and 80 % total moss cover, while *Sphagnum* cover is still below 0.2 % in the nonrestored site. (Photographs taken by PERG)

Here the success is only evaluated in terms of vegetation cover excluding nonpeatland or wetland species. It is only with a long-term monitoring program that we will be able to assess if full biodiversity is restored and if the different ecological functions have been restored in the peatland (Waddington et al. 2003; Tuittila et al. 2004).

17.5 The Future of Peatland Restoration Research

17.5.1 Climate Influence

A good restoration project will define specific goals in regard to the localization of the decommissioned site in the landscape. The effect of different climates on the success of Sphagnum establishment has received little attention as the climate within the current distribution of peatlands has been assumed to be suitable for Sphagnum regeneration. Now that several large-scale restoration projects have been undertaken since the beginning of the 1990s, it would be interesting to see if climate can be isolated as a factor that influences the success of peatland restoration.

17.5.2 Management Approach

There is a diversity of approaches and machinery that can be used to implement a restoration project. Different machinery, or timing of work in a season, can have an effect on the restoration success. As we begin to have more large-scale restoration projects, analyses of the management factors should be carried out to pinpoint less efficient practices (e.g., a machine that would mechanically shred too much of the moss material and decrease its regeneration potential during the collection or the spreading steps) and ameliorate overall restoration success.

17.5.3 Restoration of Fens

There is much experience in the restoration of fens after agricultural use in Germany and the Netherlands (Blankenburg and Tonnis 2004; Lamers et al. 2002), but little has been done so far to restore fens in milled peatlands and to reestablish brown mosses. Applying donor diaspores and straw mulch effectively increases fen plant cover and richness (Cobbaert et al. 2004) as shown in a study done on small plots (5 m × 5 m) and evaluated after a short-term recovery (2 years). Another study done in the mountains of Colorado was successful at reimplanting fen vegetation after peat mining, but the cost of the manual plantations was prohibitive (Cooper et al. 1998). So, much remains to be done in improving our abilities to understand the processes that can lead to successful fen restoration. The expertise in fen restoration needs to be improved knowing that as the peat industry ages, more and more fen type residual peat substrates will be decommissioned.

17.5.4 *Sphagnum* Farming and Nursery

Positive results in the area of *Sphagnum* cultivation in North America (Campeau and Rochefort 2002; Rochefort et al. 2003; Campeau et al. 2004) have been facilitated with comparably large interest in European peatland studies and restorations (Money 1995; Sundberg 2000), and might be a key for a new type of professional horticulture that will diminish the management pressure on natural bog landscapes (Gaudig and Joosten 2002). To create outdoor *Sphagnum* nurseries, such as in the trenches of old block peat cuttings, is an interesting option for supplying *Sphagnum* moss vegetative fragments in countries with little natural mire left and is definitely an avenue that deserves more research.

17.5.5 Creation of *Sphagnum*-Dominated Peatlands

In this era of greater environmental awareness, several stakeholders are trying to find solutions to mitigate the pollution created by industrial activities. For example, one of them is to decontaminate the polluted water caused by the piling of mine tailings such as for copper or gold extraction or to ameliorate the quality of the quality exuding from bark piles from sawmills. These tailings can be quite acidic, so it could be interesting to see if creating *Sphagnum*-dominated wetlands will be one of the processes to mitigate the polluting effect via their known ability to filter water.

The development of expertise in peatland reclamation could be useful in regions of high oil sands extraction activities. For example, in northern Alberta, Canada, the oil sands extraction activities take place in a region of abundant natural peatlands. It could be important at a regional biodiversity level to be able to recreate functional peatlands on the soils disturbed by the oil sands industry.

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17.6 Conclusions

Even though *Sphagnum* mosses are not easy plants to manipulate on artificial substrates or in nonnatural environments, it is possible to revegetate large expanses of cutover peatland at a relatively low cost (in the range of US $900–1400 per hectare). Only long term monitoring of the current restoration projects will confirm if it is possible to restore the ecological functions of the cutover peatland to bring it back to a peat-accumulating ecosystem. Fen restoration of peat fields used for agriculture has been mostly studied in central Europe but much research is needed to develop sound restoration procedures for cutover peatlands and learn how to grow true mosses. *Sphagnum* farming (cultivation in nurseries) is promising and research in that area should be promoted. Not only would it be useful for supplying plant material for reintroduction in countries with low supply, but it could prove a useful source of biomass to ameliorate growing substrates.

References

Anonymous (1995) EC Wetlands Communication. http://europa.eu.int/comm/environment/nature/docum.htm

Bastien DF (1996) Établissement et croissance des sphaignes dans une tourbière exploitée et abandonnée. MSc thesis, Université Laval, Sainte-Foy

Bérubé MÈ, Lavoie C (2000) The natural revegetation of a vacuum-mined peatland: Eight years of monitoring. Can Field Nat 114:279–286

Blankenburg J, Tonnis W (eds) (2004) Guidelines for wetland restoration of peat cutting areas – results of the BRIDGE-PROJECT. Geological Survey of Lower Saxony, Bremen, Germany

Boudreau S, Rochefort L (1999) Établissement des sphaignes réintroduites sous diverses communautés végétales recolonisant les tourbières après exploitation. Ecologie 30:53–62

Brooks S, Stoneman R (eds)(1997) Conserving bogs. The management handbook. The Stationary Office, Edinburgh

Bugnon JL, Rochefort L, Price JS (1997) Field experiments of *Sphagnum* reintroduction on a dry abandoned peatland in eastern Canada. Wetlands 17:513–517

Buttler A, Warner BG, Grosvernier P, Matthey Y (1996) Vertical patterns of testate amoebae (Protozoa: Rhizopoda) and peat-forming vegetation on cutover bogs in the Jura, Switzerland. New Phytol 134:371–382

Campbell D (2002) Comprendre la mécanique du processus de recolonisation végétale des tourbières exploitées. PhD thesis, Département de phytologie, FSAA. Université Laval, Sainte-Foy

Campbell DR, Rochefort L, Lavoie C (2000) The colonisation potential of peatland plants recolonising post-vacuum-extracted bogs. In: Rochefort L, Daigle JY (eds) Sustaining our peatlands. Proceedings of the 11th international peat congress, vol

II. Canadian Society of Peat and Peatlands, International Peat Society, Quebec City, pp 670–674

Campbell DR, Lavoie C, Rochefort L (2002) Wind erosion and surface stability in abandoned milled peatlands. Can J Soil Sci 82:85–95

Campbell DR, Rochefort L, Lavoie C (2003) Determining the immigration potential of plants colonizing disturbed environments: the case of milled peatlands in Québec. J Appl Ecol 40:78–91

Campeau S, Rochefort L (1996) *Sphagnum* regeneration on bare peat surfaces: field and greenhouse experiments. J Appl Ecol 33:599–608

Campeau S, Rochefort L (2002) Possibilities and limits to *Sphagnum* farming. In: Schmilewski G, Rocheford L (eds) Proceedings of the international peat symposium: peat in horticulture – quality and environmental challenges. A joint symposium of Commission II (industrial utilization of peat and peatlands) and Commission V (after-use of cut-over peatlands) of the International Peat Society, Pärnu, Estonia, 3–6 September 2002. International Peat Society, Jyväskylä, pp 264–269

Campeau S, Rochefort L, Price JS (2004) On the use of shallow basins to restore cutover peatlands: plant establishment. Restor Ecol 12:471–482

Charman D (2002) Peatlands and environmental change. Wiley., Chicester

Chirino C, Rochefort L (2000) Establishment response of four *Sphagnum* species on cutover peatland. In: Rochefort L, Daigle JY (eds) Sustaining our peatlands. Proceedings of the 11th international peat congress, Quebec City, Canada, 6–12 August 2000, vol II. Canadian Society of Peat and Peatlands and the International Peat Society. Edmonton, pp 694–698

Chirino C, Campeau S, Rochefort L (2006) Peatland restoration: are climatic variability and *Sphagnum* richness important? Appl Veget Sci (in press)

Clymo RS (1983) Peat. In: Gore AJP (ed) Ecosystems of the world 4A. Mires: swamp, bog, fen and moor. General studies. Elsevier, Amsterdam, pp 159–224

Clymo RS (1987) The ecology of peatlands. Sci Prog Oxford 71:593–614

Clymo RS, Duckett JG (1986) Regeneration of *Sphagnum*. New Phytol 102:589–614

Cobbaert D, Rochefort L, Price JS (2004) Experimental restoration of a fen plant community after peat mining. Appl Veg Sci 7:209–220

Cooper DJ, Macdonald LH, Wenger SK, Woods SW (1998) Hydrologic restoration of a fen in Rocky Mountain National Park, Colorado, USA. Wetlands 18:335–345

Daigle JY, Gautreau-Daigle H (2001) Canadian peat harvesting and the environment, 2nd edn. Sustaining wetlands issues paper no 2001-1. North American Wetlands Conservation Council Committee, Ottawa

Desrochers A, Rochefort L, Savard JP (1998) Avian recolonization of eastern Canadian bogs after peat mining. Can J Zool 76:989–997

Dupieux N (1998) La gestion conservatoire des tourbières de France: premiers éléments scientifiques et techniques. Espaces Naturels de France, Orleans

Eggelsmann R, Heathwaite AL, Grosse-Baukmann G, Küster E, Naucke W, Schuch M, Schweickle V (1993) Physical processes and properties of mires. In: Heathwaite AL, Göttlich K (eds) Mires. Process, exploitation and conservation. Wiley, Chichester, pp 171–262

Enz JW, Brun LJ, Larsen JK (1988) Evaporation and energy balance for bare and stubble covered soil. Agric For Meteorol 43:59–70

Farrell CA, Doyle GJ (2003) Rehabilitation of industrial cutaway Atlantic blanket bog in County Mayo, north-eest Ireland. Wetlands Ecol Manage 11:21–35

Franzen L (1985) Peat in Sweden: a method to calculate the resources. GUNI report 21, Göteborg University, Göteborg

Ecological Studies Vol 188, page proofs as of 04/21 by Kröner, HD

Faubert P, Rochefort L (2002) Response of peatland mosses to burial by wind-dispersed peat. Bryologist 105:96–103

Gaudig G, Joosten H (2002) Peat loss (*Sphagnum*) as a renewable resource – an alternative to *Sphagnum* peat in horticulture? In: Schmilewsky G, Rochefort L (eds) Peat in horticulture. Quality and environmental challenges. International Peat Society, Pärnu, pp 117–126

Girard M, Lavoie C, Thériault M (2002) The regeneration of a highly disturbed ecosystem: a mined peatland in southern Québec. Ecosystems 5:274–288

Glaser PH, Janssens JA (1986) Raised bogs in eastern North America: transitions in landforms and gross stratigraphy. Can J Bot 64:395–415

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

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

Groeneveld EVG, Rochefort L (2005) *Polytrichum strictum* as a solution to frost heaving in disturbed ecosystems: a case study with milled peatlands. Restor Ecol 13:1–9

Grosvernier P, Matthey Y, Buttler A (1995) Microclimate and physical properties of peat: new clues to the understanding of bog restoration processes. In: Wheeler BD, Shaw SC, Fojt WJ, Robertson RA (eds) Restoration of temperate wetlands. Wiley, Chichester, pp 434–450

Hayward PM, Clymo RS (1982) Profiles of water content and pore size in *Sphagnum* and peat, and their relation to peat bog ecology. Proc R Soc Lond Ser B 215:299--325

Heathwaite AI, Eggelsmann R, Göttlich KH, Kaule G (1993) Ecohydrology, mire drainage and mire conservation. In: Heathwaite AL, Göttlich KH (eds) Mires: process, exploitation and conservation. Wiley, Chichester, pp 418–484

Hughes PDM, Cymayne-Peaty L (2002) Testing theories of mire development for nutrient balance of the cotton sedge, *Eriophorum vaginatum* L. Oecologia 67:511–518

Ingram HAP (1983) Hydrology. In: Gore AJP (ed) Mires: swamp, bog, fen and moor. Elsevier, New-York, pp 67–158

Joosten H (1998) Peat as a renewable resource: the road to paludiculture. In: Maltere T, Johnson K, Stewart J (eds) Peatland restoration and reclamation, Proccedings of the 1998 international peat symposium, Duluth, Minnesota, 14–18 July 1998. International Peat Society, Jyväskylä

Joosten H, Clarke D (2002) Wise use of mires and peatlands – background and principles including a framework for decision-making. International Mire Conservation Group and International Peat Society, Finland. http://www.mirewiseuse.com

Kennedy GW, Price JS (2004) Simulating soil water dynamics in a cutover bog. Water Resour Res 40:W12410. DOI 10.1029/2004WR003099

Lafleur PM (1990) Evapotranspiration from sedge-dominated wetland surfaces. Aquat Bot 37:341–353

Lamers LPM, Smolders AJP, Roelofs JGM (2002). The restoration of fens in the Netherlands. Hydrobiologia 478:107–130

Lappalainen E (1996) General review on world peatland and peat resources. In: Lappalainen E (ed) Global peat resources. International Peat Society, Jyväskylä, pp 53–56

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

Lavoie C, Grosvernier P, Girard M, Marcoux K (2003) Spontaneous revegetation of mined peatlands: an useful restoration tool? Wetlands Ecol Manage 11:97–197

Lavoie C, Saint-Louis A, Lachance D (2005a) The vegetation dynamics of a poorly regenerated mined peatland: five years of monitoring. Wetlands Ecol Manage 13:621–633

Lavoie C, Marcoux K, Saint-Louis A, Price JS (2005b) The dynamics of a cotton-grass (*Eriophorum vaginatum* L.) cover expansion in a vacuum-mined peatland, southern Québec, Canada. Wetlands 25:64–75

Lode E (2001) Natural mire hydrology in restoration of peatland functions. Doctoral thesis, Acta Universitatis Agrivuturae Sueciae, Silvestria 234, Uppsala

Lynch-Stewart P (1992) No net loss – implementing "no net loss" goals to conserve wetlands in Canada. Sustaining wetlands issues paper 1992-2. North American Wetlands Conservation Council, Ottawa

Malterer TJ (1996) Peat resources of the United States. In: Lappalainen E (ed) Global peat resources. International Peat Society, Jyskä, pp 253–266

Matthey Y (1996) Conditions écologiques de la régénération spontanée du *Sphagnion magellanici* dans le Jura suisse. Typologie, pédologie, hydronamique et micrométéorologie. PhD dissertation, Université de Neuchâtel, Neuchâtel, Switzerland

Mazerolle MJ (2001) Amphibian activity, movement patterns, and body size in fragmented peat bogs. J Herpetol 35:13–20

Mazerolle MJ (2003) Detrimental effects of peat mining on amphibian abundance and species richness in bogs. Biol Conserv 113:215–223

Mazerolle M, Cormier M (2003) Effects of peat mining intensity on green frog (*Rana clamitans*) occurrence in bog ponds. Wetlands 23:709–716

McNeil P, Waddington JM (2003) Moisture controls on *Sphagnum* growth and CO_2 exchange on a cutover bog. J Appl Ecol 40:354–367

McNeil P, Waddington JM, Lavoie C, Price JS, Rochefort L (2000) Contemporary and long-term peat oxidation rates in a post-vacuum harvested peatlands. In: Rochefort L, Daigle JY (eds) Sustaining our peatlands. Proceedings of the 11th international peat congress, vol II. Canadian Society of Peat and Peatlands and the International Peat Society, Quebec City, pp 732–741

Mitsch WJ, Gosselink JG (2000) Wetlands, 3rd edn. Wiley, New York

Money R (1995) Restoration of cut-over peatlands: the role of hydrology in determining vegetation quality. In: Hughes J, Heathwaite L (eds) Hydrology and hydrochemistry of British wetlands. Wiley, Chichester, pp 383–400

Murray KJ, Tenhunen JD, Nowak RS (1993). Photoinhibition as a control on photosynthesis and production of *Sphagnum* mosses. Oecologia 96:200–207

Noguchi A, Muraoka S (1959) Sporelings and regenerants in some mosses, 4. Kumamoto J Sci Ser B Sect 2 4:118–149

Oehlmann V (1898) Vegetative Fortpflanzung der Sphagnaceen nebst ihrem Verhalten gegen Kalk. Inaugural-Dissertation. Der Mathematisch-Naturwissenschaftlichen Fakultät der Universität Freiburg in der Schweiz

Pellerin S, Lavoie C (2000) Peatland fragments of southern Quebec: recent evolution of their vegetation structure. Can J Bot 78:255–265

Pfadenhauer J, Schneekloth H, Schneider R, Schneider S (1993) Mire distribution. In: Heathwaite AL, Göttlich K (eds) Mires. Process, exploitation and conservation. Wiley, Chichester, pp 77–121

Poschlod P, Pfadenhauer J (1989) Regeneration of vegetative parts of peat mosses – a comparative study of nine *Sphagnum* species. Telma 19:77–88

Poulin M, Rochefort L, Desrochers A (1999) Conservation of bog plant species assemblages: assessing the role of natural remnants in mined sites. Appl Veg Sci 2:169–180

Ecological Studies Vol 188, page proofs as of 04/21 by Kröner, HD

Poulin M, Rochefort L, Quinty F, Lavoie C (2005) Spontaneous revegetation of mined peatlands in eastern Canada. Can J Bot 83:539–557

Price J (1997) Soil moisture, water tension, and water table relationships in a managed cutover bog. J Hydrol 202:21–32

Price JS, Schlotzhauer SM (1999) Importance of shrinkage and compression in determining water storage changes in peat: the case of a mined peatland. Hydrol Process 13:2591–2601

Price JS, Whitehead GS (2001) Developing hydrologic thresholds for *Sphagnum* recolonization on an abandoned cutover bog. Wetlands 21:32–40

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

Price JS, Rochefort L, Campeau S (2002) Use of shallow basins to restore cutover peatlands: hydrology. Restor Ecol 10:259–266

Price JS, Heathwaite AL, Baird AJ (2003) Hydrological processes in abandoned and restored peatlands: an overview of management approaches. Wetlands Ecol Manage 11:65–83

Quinty F, Rochefort L (1997) Plant reintroduction on a harvested peat bog. In: Trettin CC, Jurgenses MF, Griga DF, Gale MR, Jeglum JK (eds) Northern forested wetlands: ecology and management. CRC, Boca Raton, pp 133–145

Quinty F, Rochefort L (2000) Bare peat substrate instability in peat land restoration: problems and solutions. In: Rochefort L, Daigle JY (eds) Sustaining our peatlands. Proceedings of the 11th international peat congress, vol II. Canadian Society of Peat and Peatlands and International Peat Society, Quebec City, pp 751–756

Quinty F, Rochefort L (2003) Peatland restoration guide, 2nd edn. Canadian Sphagnum Peat Moss Association, New Brunswick Department of Natural Resources and Energy, Quebec, Canada. http://www.peatmoss.com/pm-resre.html

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

Rochefort L (2001) Restauration écologique. In: Payette S, Rochefort L (eds) Écologie des tourbières du Québec-Labrador. Presses de l'Université Laval, Sainte-Foy, pp 449–504

Rochefort L, Campeau S (2002) Recovery of donor sites used for peatland restoration. In: Schmilewski G, Rochefort L (eds) Proceedings of the international peat symposium: peat in horticulture – quality and environmental challenges. A joint symposium of Commission II (industrial utilization of peat and peatlands) and Commission V (after-use of cut-over peatlands) of the International Peat Society, Pärnu, Estonia, 3–6 September 2002. International Peat Society, Jyväskylä, pp 244–250

Rochefort L, Price J (2003) Restoration of *Sphagnum* dominated peatlands. Wetlands Ecol Manage 11:1–2

Rochefort L, Gauthier R, LeQuéré D (1995) *Sphagnum* regeneration – toward an optimisation of bog restoration. In: Wheeler BD, Shaw SC, Fojt WJ, Robertson RA (eds) Restoration of temperate wetlands. Wiley, Chichester, pp 423–434

Rochefort L, Campeau S, Bugnon JL (2002) Does prolonged flooding prevent or enhance regeneration and growth of *Sphagnum*? Aquat Bot 74:327–341

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

Rosenberg NJ, Blad BL, Verma SB (1983) Microclimate: the biological environment, 2nd edn. Wiley, New York

Ecological Studies Vol 188, page proofs as of 04/21 by Kröner, HD

Rubec C (1996) The status of peatland resources in Canada. In: Lappalainen E (ed) Global peat resources. International Peat Society, Jyväskylä, pp 243–252

Sagot C, Rochefort L (1996) Tolérance des sphaignes à la dessication. Cryptogamie Bryol Lichénol 17:171–183

Salonen V (1987) Relationship between the seed rain and the establishment of vegetation in two areas abandoned after peat harvesting. Holarct Ecol 10:171–174

Schlotzhauer SM, Price JS (1999) Soil water flow dynamics in a managed cutover peat field, Quebec: field and laboratory investigations. Water Resour Res 35:3675–3683

Schothorst CJ (1997) Subsidence of low moor peat soil in the western Netherlands. Geoderma 17:265–291

Schouten MGC (ed) (2002) Conservation and restoration of raised bogs; geological, hydrological and ecological studies. Geological, hydrological and ecological studies. Department of the Environment and Local Government Ireland, Geological Survey of Ireland, Staatsbosbeheer, The Netherlands

Schouten MGC, Streefkerk JG, van der Schaaf S, Ryan JB (2002) General conclusions: implications for management and restoration. In: Schouten MGC (ed) Conservation and restoration of raised bogs; geological, hydrological and ecological studies. Geological, hydrological and ecological studies. Department of the Environment and Local Government Ireland, Geological Survey of Ireland, Staatsbosbeheer, The Netherlands, pp 210–217

Sliva J (1998) Regeneration of milled peat bog: a large scale approach in Kollerfilze (Bavaria, southern Germany). In: Malterer T, Johnson K, Stewart J (eds) Peatland restoration and reclamation: proceedings of the 1998 international peat symposium, Duluth, 14–18 July. International Peat Society, Duluth, pp 82–87

Sobotka D (1976) Regeneration and vegetative propagation of Sphagnum palustre as factor of population stability. Acta Soc Bot Pol 45:357–368

Society for Ecological Restoration Science, Policy Working Group (2004) The SER international primer on ecological restoration. Society for Ecological Restoration International, Tucson. http://www.ser.org/

Soro A, Sundberg S, Hakan R (1999) Species diversity, niche metrics and species associations in harvested and undisturbed bogs. J Veg Sci 10:549–560

Sottocornola M, Boudreau S, Rochefort L (2002) Fertilisation aspects in peatland restoration. In: Schmilewski G, Rocheford L (eds) Proceedings of the international peat symposium: peat in horticulture – quality and environmental challenges. A joint symposium of Commission II (industrial utilization of peat and peatlands) and Commission V (after-use of cut-over peatlands) of the International Peat Society, Pärnu, pp 256–261

Spieksma JFM, Moors EJ, Dolman AJ, Schouwenaars JM (1997) Modelling evaporation demand from a drained and rewetted peatland. J. Hydrol. 199:252–271

Standen V, Tallis JH, Meade R (eds)(1998) Patterned mires and mire pools. Origin and development; flora and fauna. British Ecological Society, London

Streefkerk JG, Casparie WA (1989) The hydrology of bog ecosystems. Guidelines for management. Staatsbosbeheer, The Netherlands

Sundberg S (2000) The ecological significance of sexual reproduction in peat mosses (*Sphagnum*). PhD thesis, Acta Universitatis Upsaliensis, Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 581, Uppsala

Tallis JH, Meade R, Hulme PD (eds) (1997) Blanket mire degradation – causes, consequences and challenges. Proceedings of the Mires Research Group meeting, Manchester, 9–11 April 1997. Macaulay Land Use Research Institute, Aberdeen

Ecological Studies Vol 188, page proofs as of 04/21 by Kröner, HD

Tuittila ES, Rita H, Vasander H, Laine J (2000) Vegetation patterns around *Eriophorum vaginatum* L. tussocks in a cut-away peatland in southern Finland. Can J Bot 78:47–58

Tuittila ES, Vasander H, Laine L (2003) Success of re-introduced *Sphagnum* in a cut-away peatland. Boreal Envir Res 8:245–250

Tuittila ES, Vasander H, Laine J (2004) Sensitivity of C sequestration in reintroduced *Sphagnum* to water-level variation in a cutaway peatland. Restor Ecol 12:483–493

van Breemen N (1995) How *Sphagnum* bogs down other plants. Tree 10:270–275

van Seters TE, Price JS (2001) The impact of peat harvesting and natural regenaration on the water balance of an abandoned cutover bog, Quebec. Hydrol Process 15:233–248

van Seters TE, Price J (2002) Towards a conceptual model of hydrological change on an abandoned cutover bog, Quebec. Hydrol Process 16:1965–1981

Vasander H, Tuittila ES, Lode E, Lundin L, Ilomets M, Sallantaus T, Heikkilä R, Pitkänen ML, Laine J (2003) Status and restoration of peatlands in northern Europe. Wetlands Ecol Manage 11:51–63

Waddington JM, McNeil P (2002) Peat oxidation in an abandoned cutover peatland. Can J Soil Sci 82:279–286

Waddington JM, Greenwood MJ, Petrone RM, Price JS (2003) Mulch decomposition impedes recovery of net carbon sink function in a restored peatlands. Ecol Eng 20:199–210

Wheeler BD (1995) Introduction: Restoration and wetlands. In: Wheeler BD, Shaw SC, Fojt WJ, Robertson RA (eds) Restoration of temperate wetlands. Wiley, Chichester, pp 1–18

Wheeler BD (1999) Water and plants in freshwater wetlands. In: Baird AJ, Wiby RL (eds) Eco-hydrology. Plants and water in terrestrial and aquatic environments. Routledge, London, pp 127–180

Wheeler BD, Shaw SC 1995. Restoration of damaged peatlands. HMSO, London

Wheeler BD, Shaw SC, Fojt WJ, Robertson RA (eds) (1995) Restoration of temperate wetlands. Wiley, Chichester

Woesler A (1934) Beitrag zur Kenntnis der vegetativen Vermehrung von Sphagnum cymbifolium Ehrh. Beitr Biol Pflanzen 22:13-24

Ecological Studies Vol 188, page proofs as of 04/21 by Kröner, HD