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Spontaneous revegetation of mined peatlands: An useful restoration tool?

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Abstract

The recent development of peatland restoration activities indicates that modern peat mining techniques seriously hamper the natural capacity of bog ecosystems to regenerate after a disturbance. However, some plants have the ability to colonize dry peat deposits, and seem to help stabilize the soil surface and facilitate the establishment of other plant species. In this paper, we review studies regarding the spontaneous regeneration of ombrotrophic peatlands. There are numerous examples throughout North America and Europe showing that spontaneous revegetation of mined peatlands by typical bog plants, and particularly by *Sphagnum* species, is possible. However, this phenomenon is much more common in block-cut peatlands than in vacuum-mined sites. The slow recovery of vacuum-mined peatlands compared to block-cut sites is probably related to intense drainage necessary for the use of tractor-drawn vacuum machines. There are some cases, however, where the spontaneous revegetation of vacuum-mined sites is successful, particularly for vascular plants. These sites are mainly dominated by cotton-grass (*Eriophorum vaginatum* L.). It seems that the microclimatic conditions created by cotton-grass tussocks improve establishment conditions for other vascular and non-vascular plants. Restoration activities should be minimal in mined peatlands already invaded by cotton-grass, and spontaneous revegetation processes could and should be integrated into peatland restoration programs.

Introduction

Peatland mining for the production of horticultural peat is a major anthropogenic disturbance – bogs are drained, vegetation is removed, and a thick layer of soil is harvested – and usually occurs over a period of several decades. A post-mined peatland is a harsh environment for plants. The surface of the residual peat deposit is dry and devoid of viable seeds (Salonen, 1987; Price, 1996). Eolian peat erosion and frost heaving prevent the successful establishment of seedlings (Le Quéré and Samson, 2000; Quinty & Rochefort, 2000). Such processes may remain effective for decades (Figure 1). The recent development of peatland restoration activities (Wheeler et al., 1995) indicates that modern peat mining techniques (the use of tractor-drawn vacuum machines) seriously hamper the natural capacity of bog ecosystems to regenerate after a disturbance; dry peat soils are required to support tractors and only very dry peat can be harvested by vacuum machines. However, numerous cases of successful post-mining bog regeneration, including restoration of the *Sphagnum* cover, are reported in the literature (e.g., Lavoie and Rochefort, 1996; Soro et al., 1999; Rochefort et al., this issue). Some plants have the ability to colonize dry peat deposits, and seem to help stabilize the soil surface and facilitate the establishment of other plant species (Grosvernier et al., 1995; Tuittila et al., 2000). Understanding the processes that favor the spontaneous regeneration of ombrotrophic peatlands is an essential step in any restoration program. It then becomes possible to rapidly identify

a)

b)

Figure 1.


c)

Figure 1. Three different revegetation patterns in mined peatlands of southern Québec: a) block-cut mined peatland, Cacouna Bog, Bas-Saint-Laurent region (abandoned in 1975; photograph taken in 1994): mined trenches are covered by *Sphagnum* spp., *Eriophorum vaginatum* L., and ericaceous shrubs; b) vacuum-mined peatland, Bois-des-Bel Bog, Bas-Saint-Laurent region (abandoned in 1980, photograph taken in 1996): the spontaneous revegetation process is very slow, and numerous tree logs and roots buried in the peat surfaced because of peat oxidation and erosion processes; c) vacuum-mined peatland, Saint-Henri Bog, south of Québec City (abandoned in 1993, photograph taken in 2000): this site has been rapidly and massively invaded by *E. vaginatum*.

sites with a high potential for spontaneous recovery, keeping restoration activities to a minimum and consequently reducing restoration costs. Moreover, in sites with poor potential for spontaneous regeneration, it helps ecological engineers to initiate revegetation processes, thus improving overall restoration success.

In this paper, we review North American and European studies on spontaneous revegetation of ombrotrophic peatlands, i.e., without active (man-made) reintroduction of plant diaspores. Our aim is to identify which factors seem to favour the rapid re-establishment of typical bog species on abandoned mined surfaces. These species are in turn expected to act as keystone species facilitating the restoration of *Sphagnum* communities and initiating a long-term succession leading towards more typical bog vegetation communities.

Spontaneous regeneration of mined peatlands: North America

Few studies have been conducted on the revegetation patterns of mined peatlands in North America (Famous et al., 1991). The horticultural peat industry is relatively recent (older sites have been mined since 1930–1940), and most sites are still being harvested (Lavoie and Saint-Louis, 1999). Furthermore, only 11 000 ha of peatlands have been mined in Québec and New Brunswick (Canada), the two main peat harvesting regions in North America. This represents only 0.003% of the total peatland area of these two provinces (Desrochers et al., 2000). Nevertheless, some mined bogs have been abandoned for a long period of time (>30 years) in Canada and the United States.

The first study on the spontaneous regeneration of mined bogs was conducted in the vacuum-mined peatlands of northern Minnesota, USA (Green, 1983).

These bogs were abandoned for 4–17 years. Nutrient-poor and acidic mined sites with a water table at or near (<12 cm) the soil surface supported open bog vegetation with a *Sphagnum* cover of 22%. Acidic sites characterized by a water table far below (>31 cm) the soil surface had sparse vegetation cover (<20% of the total peat surface) dominated by trees and shrubs. Similar revegetation patterns were observed in the vacuum-mined Wainfleet Bog in southern Ontario (Canada), where four sampling sites representing one to 24 years of unassisted revegetation were studied in 1986 (Jonsson-Ninniss and Middleton, 1991). The water table level was 20–40 cm below the soil surface. At the oldest abandoned site, more than 86% of the peat surface was covered by typical bog plant species (ericaceous shrubs, *Sphagnum* spp.) or trees (birch, aspen). However, at the youngest site, only 3% of the soil surface was covered by vegetation, and mainly by an exotic birch species (*Betula pendula* Roth).

The largest concentration of abandoned mined bogs in North America is located in the Bas-Saint-Laurent region, in eastern Québec (Desrochers et al., 1998; Lavoie and Saint-Louis, 1999). Lavoie and Rochefort (1996) studied the spontaneous revegetation of block-cut (harvested by hand using shovels) and vacuum-mined sites in the Cacouna Bog. Dendroecological data indicated that most block-cut sections of the bog were rapidly (less than five years) revegetated (>90% plant cover) by typical peatland species (Figure 1). The re-establishment of *Sphagnum* and ericaceous shrub species was initiated directly on the residual peat deposit (Robert et al., 1999). However, *Sphagnum* species were much more common in natural conditions than in the Cacouna Bog where they were restricted to a small portion of the peatland with a water level <14 cm below the soil surface. In 1994, after four years of abandonment, the plant cover of the vacuumed sections was only 48%, and mainly dominated by gray birch (*Betula populifolia* Marsh.). Between 1994 and 1998, there was a significant increase in the total plant cover of the vacuumed sections (from 48 to 62%), and particularly that of ericaceous shrub species (Bérubé and Lavoie, 2000). The low water table level in the vacuumed peat fields (65 cm below the soil surface) still prevents the massive establishment of *Sphagnum* species, although some small colonies have recently (2000) been discovered (C. Lavoie, unpublished data).

Spontaneous regeneration of mined peatlands: Europe

Although peatlands have been mined in Europe for several centuries (Smart et al., 1989; Meade, 1992; Lode, 2001), few studies have been devoted to the spontaneous regeneration of bogs. Most of these studies are related to the description of secondary succession in ancient peat cuttings that have been reflooded. In Ireland, White (1930) was probably the first to study such hydrosere systems. Royer et al. (1978) and Giller and Wheeler (1988) published a synthesis of studies conducted on the revegetation of abandoned peat cuttings in France and the United Kingdom, respectively. Bertram (1988) and Lütt (1992) presented detailed results on the physico-chemical conditions influencing the growth of *Sphagnum* species in peat cuttings.

In Europe, spontaneous re-establishment of *Sphagnum* colonies in mined bogs is not frequent (Money, 1995; Rowlands and Feehan, 2000). This phenomenon has been reported in Sweden in block-cut peatlands abandoned between 1940 and 1964 (Soro et al., 1999). Mined trenches in these bogs had a water table just below (7 cm) the soil surface, and a high (54%) *Sphagnum* cover, although lower than in unmined bogs in the study area (74%). However, at most mined sites in Europe, some hydrological work is needed to accelerate the revegetation process. In England, two well-documented studies concerning the revegetation of peat excavations were conducted in a block-cut section of Thorne Waste (Smart et al., 1989), and in a flat area dissected by shallow drains in Danes Moss (Meade, 1992). Thorne Waste was mined between 1870 and 1920, and has been reflooded since that time. Macrofossil analyses indicated that ericaceous shrubs were the primary colonists of most mined trenches. *Sphagnum* species typical of ombrotrophic peatlands colonized the trenches later, i.e., after the artificial raising of the water table above (10 cm) the soil surface for most of the year. In Danes Moss, peat cutting activities ceased around 1960. In 1974, the water level in the study area was raised by 0.5 m by obstructing the outfall. This resulted (1987) in a net increase of the *Sphagnum* cover and a 10–50% decrease of the invading grass *Molinia caerulea* (L.) Moench cover. It is noteworthy that cotton-grass (*Eriophorum vaginatum* L.) was the dominant vascular plant species in Thorne Waste, and was broadly distributed over the waterlogged surface amongst *Sphagnum* species in Danes Moss.

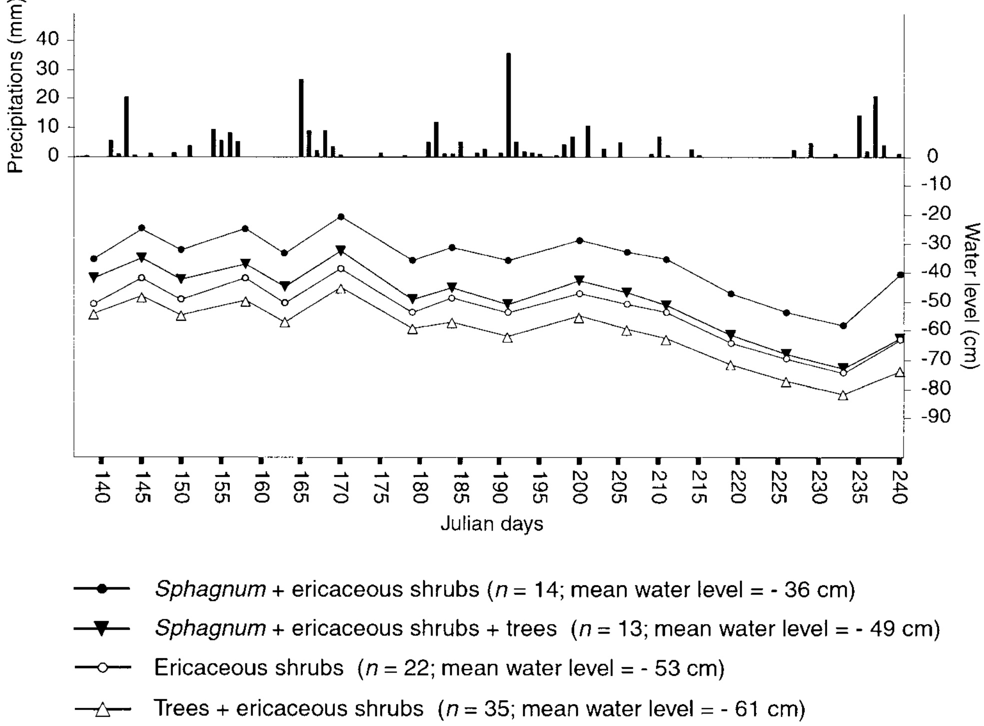

Figure 2. Monitoring of atmospheric precipitation and water levels under four different types of vegetation cover in the Cacouna Bog, Bas-Saint-Laurent region, southern Québec (summer 1998). Four vegetation types were described in the bog: 1) dominated by *Sphagnum* spp. and ericaceous shrubs (both groups having a cover >25%); 2) dominated by *Sphagnum* spp., ericaceous shrubs and trees (all groups having a cover >25%); 3) dominated by ericaceous shrubs only (>25% cover); and 4) dominated by trees and ericaceous shrubs (both groups having a cover >25%). The number of wells used in this study and corresponding to a particular vegetation type is indicated (Girard, 2000; Van Seters and Price, 2001).

In Finland, Veikko Salonen and collaborators conducted a very elaborate study of the plant colonization processes operating in 17 vacuum-mined peatlands that have recently (less than 14 years) been abandoned. Many biophysical aspects were studied, including seed rain and soil seed banks (Salonen, 1987; Salonen and Setälä, 1992), substrate quality for plant establishment (Salonen, 1994), and early plant succession (Salonen, 1990; Salonen et al., 1992). Seeds of *Eriophorum vaginatum* and birches formed the vast majority of the pool of viable diaspores in abandoned mined sites. However, only *E. vaginatum* succeeded in producing seedlings and in covering large areas of bare peat surfaces, probably because of its ability to colonize oligotrophic peat soils, and to recycle nutrients within individual tussocks. Salonen (1990) also suggested that smaller particle size in the uppermost soil layer may have contributed to enhance the water retention potential of the peat and to reduce soil aeration, resulting in a higher ammonium nitrogen instead of nitrate nitrogen content in the peat. Such conditions would hamper the establishment of more nutrient demanding species and, by contrast, favor *E. vaginatum*, which is well adapted to oligotrophic and poor aeration conditions (Gebauer et al., 1995).

Finally, the spontaneous regeneration of bogs in Switzerland has been studied by Philippe Grosvernier, Yvan Matthey and Alexandre Buttler (Buttler et al., 1996; Grosvernier, 1996; Matthey, 1996). In old block-cut peatlands (abandoned between 1925 and 1936), they observed several types of vegetation succession leading to complete *Sphagnum* dominance. Cotton-grass (*Eriophorum vaginatum*) or *Polytrichum strictum* Brid. were often early colonizers on the cutover surfaces, initiating different developmental series favoring the establishment of *Sphagnum* colonies. Grosvernier et al. (1995) proposed that cotton-grass tussocks would provide particular microclimatic conditions triggering the growth of *Sphagnum* plants under their cover. Buttler et al. (1998) further experimentally showed that optimal peat properties (particularly small size of pores), combined with microclimatic conditions under cotton-grass tussocks, enable *Sphagnum* mosses to grow, even with a water table at 40 cm depth, as well as in natural waterlogged conditions. On the other hand, *P. strictum* carpets would prevent the formation of dry peat crusts near the soil surface, which has been shown to hamper the establishment of plants (Salonen and Laaksonen, 1994).

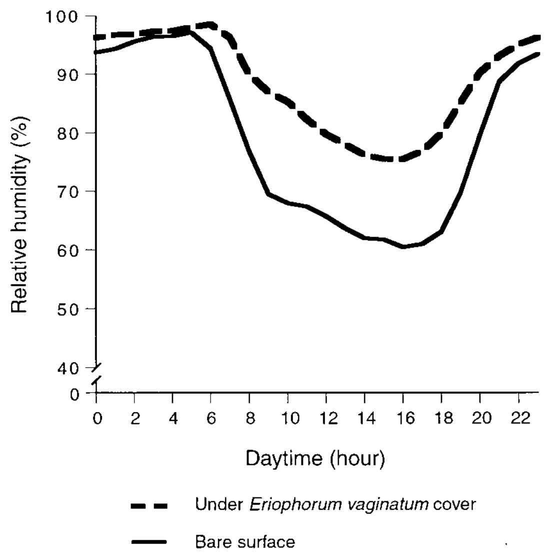

Figure 3. Monitoring of relative humidity under *Eriophorum vaginatum* L. tussocks and above bare peat in the Saint-Henri Bog south of Québec City, southern Québec. Data were recorded every hour during a 90-day period in summer 1999, using six dataloggers installed near (5 cm) the soil surface, i.e., three under tussocks and three above bare peat (Marcoux, 2000).

Recent studies concerning spontaneous regeneration of mined peatlands

In 1997, the first author of this paper initiated a research project concerning the spontaneous regeneration of mined peatlands in southern Québec, in collaboration with the members of the Peatland Ecology Research Group (Université Laval, University of Waterloo, McMaster University). The aims of this project were to describe all revegetation patterns observed in the Bas-Saint-Laurent region, to understand why the plant recolonization of block-cut peatlands was much more rapid than that of vacuum-mined sites, and to study the impact of some invasive plants in mined bogs.

Our team went back to the Cacouna Bog for a detailed study of the history, vegetation, and hydrological characteristics of the site. Girard (2000) reconstructed the history of the bog (back to 1839), and used canonical and correspondence analyses to link revegetation patterns to 24 physical (water level, pH, residual peat thickness, etc.) or historical (time elapsed since abandonment, climate characteristics at the time of abandonment, etc.) variables. The water level of mined trenches was by far the main factor related to revegetation patterns. There was a strong positive correlation between water level and typical bog vegetation type in the canonical and correspondence analysis models; such relationship between water level and vegetation is illustrated in Figure 2. This is consistent with the experimental results obtained by Grosvernier et al. (1997) on the growth of various *Sphagnum* species in different conditions of waterlogging and physico-chemical properties of the peat substrate. Large sections of the Cacouna Bog were still devoid of *Sphagnum* colonies even after more than 30 years of abandonment because of a loss of 26% of precipitation inputs from drainage ditches that were still functioning (Van Seters and Price, 2001). A more detailed study of the relationship between *Sphagnum* cover and the hydrological characteristics of mined trenches in the Cacouna Bog (Price and Whitehead, 2001) revealed that the majority of *Sphagnum* colonies were located where volumetric soil moisture and soil-water pressure of the surface peat remained above 50% and –100 cm, respectively, throughout the summer. Likewise, all *Sphagnum*-regenerated sites described in the Swiss Jura mountains by Matthey (1996) had water pressure values above –50 cm, with some lower values at –60 cm and –80 cm during severe drought periods. Water pressure values below –100 cm prevent *Sphagnum* branches and stems from extracting water from the peat, leading to the desiccation and death of *Sphagnum* colonies (Hayward and Clymo, 1982).

In several European and North American studies (Schouwenaars, 1993; Grosvernier et al., 1995; Boudreau and Rochefort, 1999; Robert et al., 1999; Soro et al., 1999; Tuittila et al., 2000), cotton-grass (*Eriophorum vaginatum*) tussocks, one of the most common plant structures in abandoned mined peatlands, are presumed to have created microclimatic

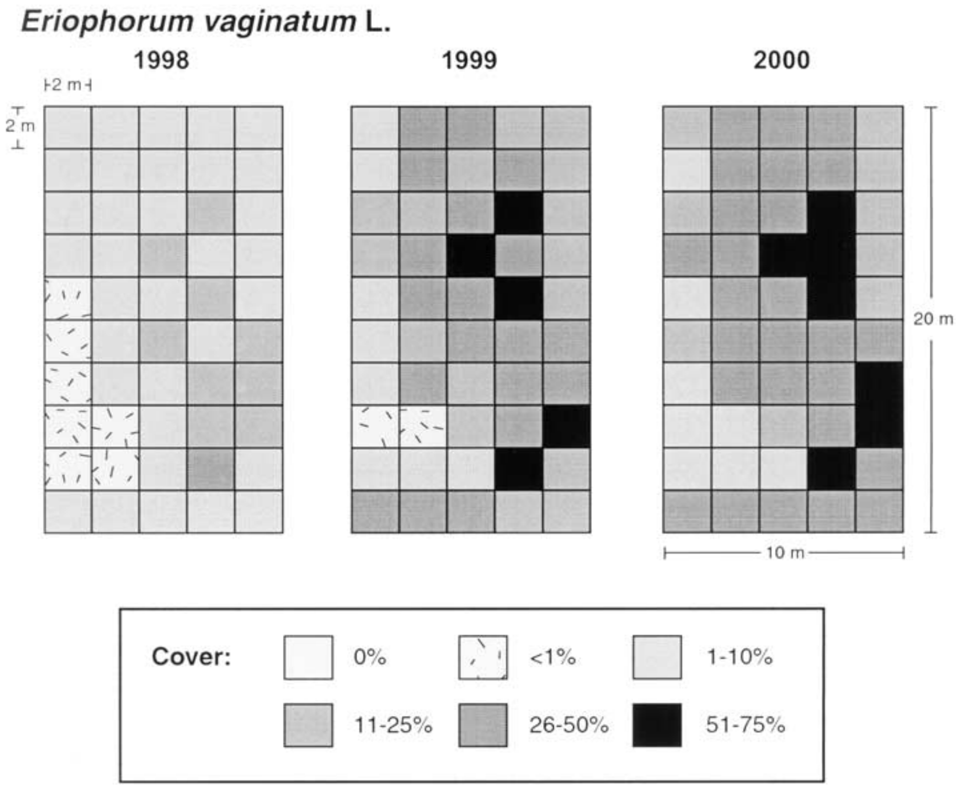

Figure 4. Monitoring of the cover of *Eriophorum vaginatum* L. in a 10 × 20 m quadrat installed in a vacuum-mined section (abandoned in 1993) of the Saint-Henri Bog south of Québec City, southern Québec. The quadrat was subdivided into fifty 2 × 2 m quadrats in which the cover of living *E. vaginatum* individuals was evaluated in June 1998, 1999 and 2000. Cover classes are indicated in the legend (C. Lavoie, unpublished data).

conditions suitable for the establishment and growth of other plants, particularly *Sphagnum* species. However, few data were used to support this hypothesis. Matthey (1996) measured evaporative losses of 0.65 mL/h during the daytime over cotton-grass tussocks, whereas these losses were reduced to 0.40 mL/h between the tussocks, and 0.16 mL/h underneath the shelter of the tussocks where pioneer *Sphagnum* mosses were found. Similarly, Marcoux (2000) compared climatic characteristics under cotton-grass tussocks and above the surface of bare peat fields. The most striking result was significantly higher levels of relative humidity under cotton-grass tussocks than above bare peat, particularly between 07:00 and 20:00 (Figure 3). This may explain why some plant species (e.g., *Polytrichum strictum*) seem to be associated with cotton-grass tussocks in vacuum-mined peatlands (Tuittila et al., 2000).

If *Eriophorum vaginatum* improves the microclimatic conditions in abandoned peat surfaces, do massive cotton-grass invasions, as observed in many southern Québec peatlands (Figure 1), accelerate the revegetation of mined sites by typical bog plant species? Since 1998, we monitored the vegetation succession in five vacuum-mined sites that have been invaded (to various degrees) by cotton-grass since 1985–1993. Preliminary results suggest that a rapid expansion of the cotton-grass cover (Figure 4) is followed by a decline in the population (death of tussocks) accompanied by an increase in the cover of ericaceous shrubs and mosses (Figure 5). It is too early to confirm whether cotton-grass facilitates the establishment of other plant species, but recent studies concerning *E. vaginatum* strongly suggest that cotton-grass could be used as a companion plant for moss and *Sphagnum* species in bog restoration programs.

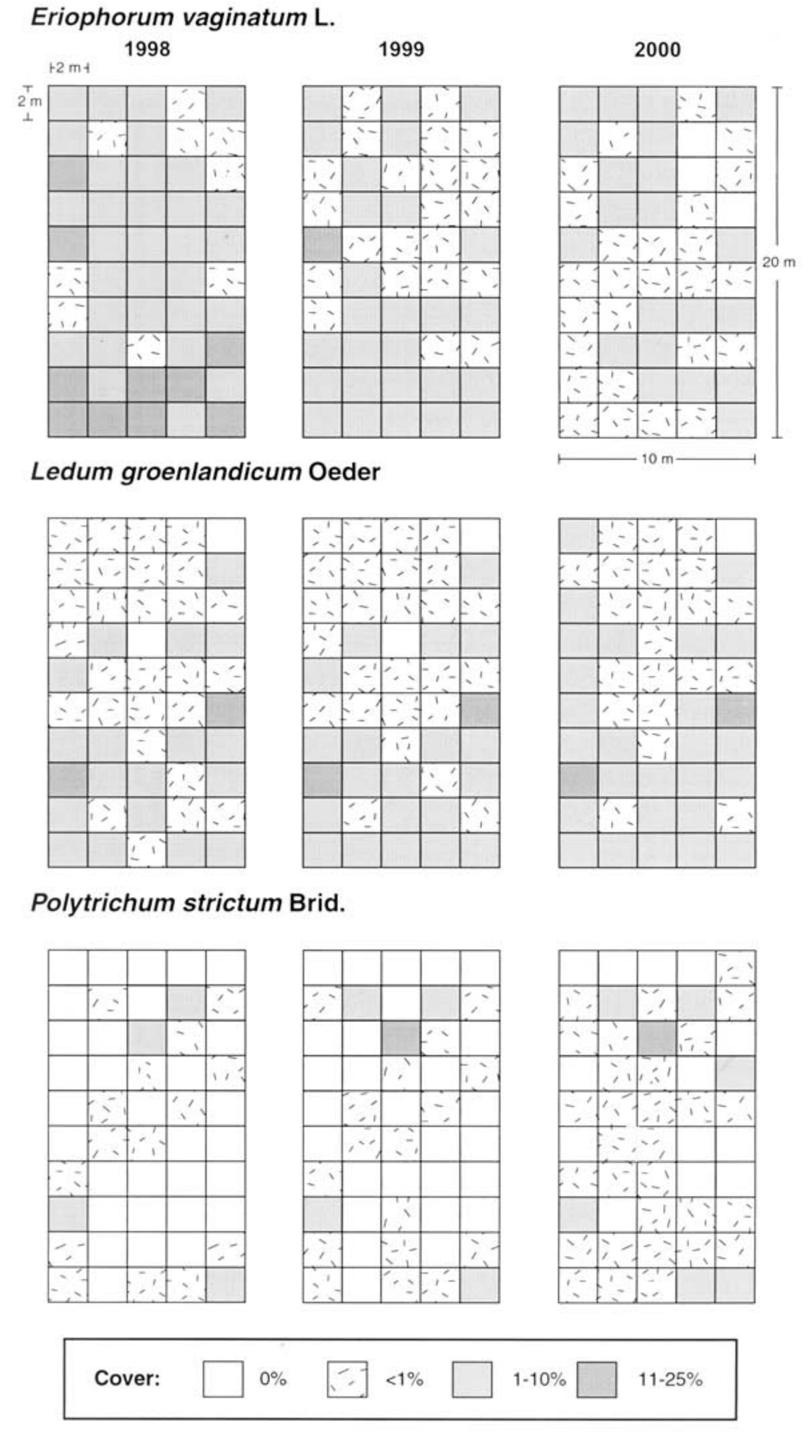

Figure 5. Monitoring of the cover of *Eriophorum vaginatum* L., *Ledum groenlandicum* Oeder, and *Polytrichum strictum* Brid. in a 10 × 20 m quadrat installed in a vacuum-mined section (abandoned in 1985) of the Rivière-du-Loup Bog, Bas-Saint-Laurent region, southern Québec. The quadrat was subdivided into fifty 2 × 2 m quadrats in which the cover of living individuals was evaluated in June 1998, 1999 and 2000. Cover classes are indicated in the legend (C. Lavoie, unpublished data).

Conclusion

There are numerous examples throughout North America and Europe showing that spontaneous revegetation of mined peatlands by typical bog plants, and particularly by *Sphagnum* species, is possible. However, this phenomenon is much more common in block-cut peatlands than in vacuum-mined sites, especially after the blocking of drainage ditches leading to the waterlogging of abandoned mined trenches. In block-cut peatlands, a water level just below the soil surface (<40 cm) seems to be sufficient to allow the rapid re-establishment of *Sphagnum* colonies, as previously suggested by Schouwenaars (1988). The slow recovery of vacuum-mined peatlands compared to block-cut sites is probably related to the improvement of drainage techniques due to the use of heavy tractor-drawn vacuum machines (Lavoie and Rochefort, 1996; Price, 1996; Girard, 2000). Furthermore, drainage of vacuum-mined peatlands increases soil oxidation and compression, and such changes are considered irreversible (Price, 1996). Consequently, it is much more difficult to rewet a vacuum-mined peatland, i.e., to obtain a water level close to the soil surface (<40 cm) over most of the summer, even after blocking drainage ditches (Price, 1996; Bugnon et al., 1997; Ferland and Rochefort, 1997; Price et al., 1998). Blocking drains may certainly help spontaneous revegetation of vacuum-mined sites, but it is doubtful that this measure alone would be enough to rapidly restore typical bog vegetation (Price et al., 1998; Rochefort, 2000). There are also several other factors seriously limitating revegetation processes: frost heaving, low dispersal abilities of bog plants, and wind erosion (Campbell, 2002; Cambpell et al., 2002).

There are some cases, however, where the spontaneous revegetation of vacuum-mined sites is successful, particularly for vascular plants. These sites are mainly dominated by *Eriophorum vaginatum.* The recovery of these bogs is much slower than that of block-cut mined peatlands, but it seems that the microclimatic conditions created by cotton-grass tussocks improve establishment conditions for other vascular and non-vascular plants. The conditions favoring a rapid invasion of cotton-grass in some natural conditions are known (Wein and MacLean, 1973), and have been successfully recreated by means of numerous and expensive restoration works (Weber, 1993). Such ambitious restoration programs also favor the rapid re-establishment of *Sphagnum* species, which have strict hydrological requirements (Campeau and Rochefort, 1996). They are however not applicable to very extended areas due to excessive costs.

In conclusion, restoration activities should be minimal in mined peatlands already invaded by cotton-grass, and further research is required to understand how the massive establishment of this species can be promoted, while keeping restoration costs as low as possible. Furthermore, restoration activities resulting in a high percent cover of cotton-grass (e.g., LeQuéré and Samson, 1998) should not be considered as failures, but rather as alternatives to promoting the establishment of other bog plants. The spontaneous re-establishment of cotton-grass in vacuum-mined peatlands should already be considered as a success, because a successionnal process is being initiated by a typical bog species. We should however keep in mind that any spontaneous revegetation process is slow, and it can take decades or even centuries before a more typical bog vegetation community is being restored.

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References

Bertram, R. 1988. Pflanzengesellschaften der Torfstiche Nordniedersächsischer Moore und die Abhängigkeit dieser Vegetationseinheiten von der Wasserqualität. Dissertationes Botanicae 126: 1–192.

Bérubé, M.-È. and Lavoie, C. 2000. The natural revegetation of a vacuum-mined peatland: eight years of monitoring. Can. Field-Nat. 114: 279–286.

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

Bugnon, J.-L., Rochefort, L. and Price, J.S. 1997. Field experiment of *Sphagnum* reintroduction on a dry abandoned peatland in eastern Canada. Wetlands 17: 513–517.

Buttler, A., Grosvernier, P. and Matthey, Y. 1998. Development of *Sphagnum fallax* diaspores on bare peat with implications for the restoration of cut-over bogs. J. Appl. Ecol. 35: 800–810.

Buttler, A., Warner, B.G., Grosvernier, P. and 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.R. 2002. Comprendre la mécanique du processus de recolonisation végétale des tourbières exploitées. Ph.D. Dissertation, Université Laval, Sainte-Foy, Canada.

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

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

Desrochers, A., Lavoie, C., Pellerin, S. and Poulin, M. 2000. Bog conservation: A Canadian perspective. *In:* Rochefort, L. and Daigle, J.-Y. (eds.), Proc. 11th Int. Peat Congress. pp. 1027–1033. Canadian Society of Peat and Peatlands and International Peat Society, Québec City, Québec, Canada.

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

Famous, N.C., Spencer, M. and Nilsson, H. 1991. Revegetation patterns in harvested peatlands in central and eastern North America. *In:* Grubich, D.N. and Malterer, T.J. (eds), Proc. Int. Peat Symp. pp. 48–66. International Peat Society, Duluth, Minnesota, USA.

Ferland, C. and Rochefort, L. 1997. Restoration techniques for *Sphagnum*-dominated peatlands. Can. J. Botany 75: 1110–1118.

Gebauer, R.L.E., Reynolds, J.F. and Tenhunen, J.D. 1995. Growth and allocation of the arctic sedges *Eriophorum angustifolium* and *E. vaginatum*: effects of variable soil oxygen and nutrient availability. Oecologia 104: 330–339.

Giller, K.E. and Wheeler, B.D. 1988. Acidification and succession in a flood-plain mire in the Norfolk Broadland, U.K. J. Ecology 76: 849–866.

Girard, M. 2000. La régénération naturelle d'écosystèmes fortement perturbés: le cas d'une tourbière exploitée du Bas-Saint-Laurent (Québec). M.A. Thesis, Université Laval, Sainte-Foy, Québec, Canada.

Green, P.E. 1983. Natural Revegetation of Mined Peatlands in Northern Minnesota. M.Sc. Thesis, University of Minnesota, St. Paul, Minnesota, USA.

Grosvernier, P. 1996. Stratégie et génie écologique des sphaignes (*Sphagnum* sp.) dans la restauration spontanée des marais jurassiens suisses. Une approche expérimentale. Ph.D. Dissertation, Université de Neuchâtel, Neuchâtel, Switzerland.

Grosvernier, P., Matthey, Y. and Buttler, A. 1995. Microclimate and physical properties of peat: new clues to the understanding of bog restoration processes. *In:* Wheeler, B.D., Shaw, S.C., Fojt, W.J. and Robertson, R.A. (eds.), Restoration of Temperate Wetlands. pp. 435–450. John Wiley & Sons, Chichester, UK.

Grosvernier, P., Matthey, Y. and Buttler, A. 1997. Growth potential of three *Sphagnum* species in relation to water table level and peat properties with implications for their restoration in cut-over bogs. J. Appl. Ecol. 34: 471–483.

Hayward, P.M. and Clymo, R.S. 1982. Profiles of water content and pore size in *Sphagnum* and peat, and their relation to peat bog ecology. Proc. Royal Soc. London B215: 299–325.

Jonsson-Ninniss, S. and Middleton, J. 1991. Effect of peat extraction on the vegetation in Wainfleet Bog, Ontario. Can. Field-Nat. 105: 505–511.

Lavoie, C. and Rochefort, L. 1996. The natural revegetation of a harvested peatland in southern Québec: a spatial and dendroecological analysis. Écoscience 3: 101–111.

Lavoie, C. and Saint-Louis, A. 1999. The spread of gray birch (*Betula populifolia*) in eastern Quebec: landscape and historical considerations. Can. J. Botany 77: 859–868.

LeQuéré, D. and Samson, C. 1998. Peat bog restoration: industrial scale application. *In:* Malterer, T., Johnson, K. and Stewart, J. (eds.), Proc. 1998 Int. Peat Symp. pp. 69–72. International Peat Society, Duluth, Minnesota, USA.

Le Quéré, D. and Samson, C. 2000. Peat bog restoration challenges at the industrial scale in Canada. *In:* Rochefort, L. and Daigle, J.-Y. (eds.), Proc. 11th Int. Peat Congress. pp. 705–709. Canadian Society of Peat and Peatlands and International Peat Society, Québec City, Québec, Canada.

Lode, E. 2001. Natural mire hydrology in restoration of peatland functions. Acta Universitatis Agriculturae Sueciae, Silvestria 234. Uppsala, Sweden.

Lütt, S. 1992. Produktionsbiologische Untersuchungen zur Sukzession der Torfstichvegetation in Schleswig-Holstein. Mitteilungen der Arbeitsgemeinschaft Geobotanik in Schleswig-Holstein und Hamburg, Heft 46, Kiel, Germany.

Marcoux, K. 2000. Les invasions de linaigrette (*Eriophorum vaginatum* L.): aide ou frein à la restauration des tourbières? M.ATDR Thesis, Université Laval, Sainte-Foy, Québec, Canada.

Matthey, Y. 1996. Conditions écologiques de la régénération spontanée du *Sphagnion magellanici* dans le Jura suisse. Typologie, pédologie, hydrodynamique et micrométéorologie. Ph.D. Dissertation, Université de Neuchâtel, Neuchâtel, Switzerland.

Meade, R. 1992. Some early changes following the rewetting of a vegetated cutover peatland surface at Danes Moss, Cheshire, UK, and their relevance to conservation management. Biol. Conserv. 61: 31–40.

Money, R.P. 1995. Re-establishment of a *Sphagnum* dominated flora on cut-over lowland raised bogs. *In:* Wheeler, B.D., Shaw, S.C., Fojt, W.J. and Robertson, R.A. (eds.), Restoration of Temperate Wetlands. pp. 405–422. John Wiley & Sons, Chichester, UK.

Price, J.S. 1996. Hydrology and microclimate of a partly restored cutover bog, Québec. Hydrol. Proc. 10: 1263–1272.

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

Price, J.S. and Whitehead, G.S. 2001. Developing hydrologic thresholds for *Sphagnum* recolonization on an abandoned cutover bog. Wetlands 21: 32–40.

Quinty, F. and Rochefort, L. 2000. Bare peat substrate instability in peatland restoration: problems and solutions. *In:* Rochefort, L. and Daigle, J.-Y. (eds.), Proc. 11th Int. Peat Congress. pp. 751–756. Canadian Society of Peat and Peatlands and International Peat Society, Québec City, Québec, Canada.

Robert, E.C., Rochefort, L. and Garneau, M. 1999. Natural revegetation of two block-cut mined peatlands in eastern Canada. Can. J. Botany 77: 447–459.

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

Rochefort, L., Quinty, F., Campeau, S., Vitt, D.H., Johnson, K.W. and Malterer, T.J. (this issue) North American approach to peatland restoration. Wetlands Ecology and Management.

Rowlands, R.G. and Feehan, J. 2000. The ecological future of industrially milled cutaway peatlands in Ireland. Aspects Appl. Biol. 58: 263–270.

Royer, J.M., Vadam, J.C., Gillet, F. and Aumonier, M.F. 1978. Étude phytosociologique des tourbières acides et alcalines du Haut-

Doubs. Réflexions sur leur régénération et leur genèse. Centre universitaire d'études régionales Besançon 2: 109–185.
Salonen, V. 1987. Relationship between the seed rain and the establishment of vegetation in two areas abandoned after peat harvesting. Holarctic Ecol. 10: 171–174.
Salonen, V. 1990. Early plant succession in two abandoned cut-over peatland areas. Holarctic Ecol. 13: 217–223.
Salonen, V. 1994. Revegetation of harvested peat surfaces in relation to substrate quality. J. Veg. Sci. 5: 403–408.
Salonen, V. and Laaksonen, M. 1994. Effects of fertilization, liming, watering and tillage on plant colonization of bare peat surfaces. Annales Botanici Fennici 31: 29–36.
Salonen, V., Penttinen, A. and Särkkä, A. 1992. Plant colonization of a bare peat surface: population changes and spatial patterns. J. Veg. Sci. 3: 113–118.
Salonen, V. and Setälä, H. 1992. Plant colonization of bare peat surface: relative importance of seed availability and soil. Ecography 15: 199–204.
Schouwenaars, J.M. 1988. The impact of water management upon groundwater fluctuations in a disturbed bog relict. Agric. Water Manag. 14: 439–449.
Schouwenaars, J.M. 1993. Hydrological differences between bogs and bog-relicts and consequences for bog restoration. Hydrobiologia 265: 217–224.
Smart, P.J., Wheeler, B.D. and Willis, A.J. 1989. Revegetation of peat excavations in a derelict raised bog. New Phytol. 111: 733–748.
Soro, A., Sundberg, S. and Rydin, H. 1999. Species diversity, niche metrics and species associations in harvested and undisturbed bogs. J. Veg. Sci. 10: 549–560.
Tuittila, E.-S., Rita, H., Vasander, H. and Laine, J. 2000. Vegetation patterns around *Eriophorum vaginatum* L. tussocks in a cut-away peatland in southern Finland. Can. J. Botany 78: 47–58.
Van Seters, T.E. and Price, J.S. 2001. The impact of peat harvesting and natural regeneration on the water balance of an abandoned cutover bog, Quebec. Hydrol. Proc. 15: 233–248.
Weber, H.E. 1993. Steuerung und Beobachtung der Vegetation: Leegmoorprojekt. Naturschutz und Landschaftspflege Niedersachsens 29: 49–78.
Wein, R.W. and MacLean, D.A. 1973. Cotton grass (*Eriophorum vaginatum*) germination requirements and colonizing potential in the Arctic. Can. J. Botany 51: 2509–2513.
Wheeler, B.D., Shaw, S.C., Fojt, W.J. and Robertson, R.A. (eds.). 1995. Restoration of Temperate Wetlands. John Wiley & Sons, Chichester, UK.
White, J.M. 1930. Re-colonisation after peat cutting. Royal Irish Acad. Proc. 39B: 453–476.