Wetlands Ecology and Management **11:** 109–119, 2003.

Peatland restoration: A brief assessment with special reference to *Sphagnum* bogs

Eville Gorham[1] & Line Rochefort[2]
[1]*Department of Ecology, Evolution and Behavior, University of Minnesota, St. Paul, MN 55108 U.S.A., Tel: 1-612-625-5708, Fax: 1-612-624-6777;* [2]*Département de Phytologie, FSAA, Université Laval, Québec, QC G1K 7P4 Canada, E-mail: line.rochefort@plg.ulaval.ca*

Received 28 January 2002; accepted in revised form 28 June 2002

Key words: bog, fen, mire, paleoecology, peatland, restoration, *Sphagnum*

Abstract

Recent literature on peatland restoration indicates as a general goal repairing or rebuilding ecosystems by restoring ecosystem structure, trophic organization, biodiversity, and functions to those characteristic of the type of peatland to which the damaged ecosystem belonged, or at least to an earlier successional stage. Attainment requires provision of an appropriate hydrological regime, manipulating surface topography, improving microclimate, adding appropriate diaspores, manipulating base status where necessary, fertilizing in some cases, excluding inappropriate invaders, adaptively managing through at least one flood/drought cycle to ensure sustainability, and monitoring on a scale of decades. Several matching conditions favoring or opposing restoration are suggested.

In the restoration of peatlands, successes have generally been those of short-term repair. Periods of restoration have been much too short to ensure progression to, or even well toward, a fully functional peatland reasonably compatible with the pristine state of similar peatlands elsewhere, although with altered surface patterns.

Long-term monitoring of peatland-restoration projects is essential for a better understanding of how to carry out such restoration successfully. Paleoecology is suggested as an underutilized tool in peatland restoration.

Introduction

Peatlands, which are important in the global carbon cycle (Gorham, 1991, 1995; Roulet, 2000), have been exploited over many centuries, chiefly (in decreasing order of impact) for fuel, agriculture and forestry. In recent years, restoration has received considerable attention (Wheeler et al., 1995; Malterer et al., 1998), as interest in conservation has grown (Parkyn et al., 1997) and as the peat industry has become concerned with the problem and supported research on it (Hood, 2000). This paper attempts to (1) summarize the major goals of peatland restoration and the means for their attainment, (2) identify conditions favoring or opposing it, and (3) assess its successes and failures. In addition, greater utilization of paleoecology in restoration efforts is recommended. A general conceptual framework for restoration ecology has been outlined by Hobbs and Norton (1996); see also Ehrenfeld (2000) and Zedler (2000) for discussions of the limits to restoration. For another review of critical questions concerning bog restoration, see Money and Wheeler (1999).

This paper deals only with restoration to a reasonable approximation of a peatland's original condition (the 'biodiversity strategy' of Joosten, 2000), and not with restoration for practical human ends such as flood mitigation, storage of nutrients or toxins (the 'regulation strategy'), or production of food, forest products, industrial raw materials, etc. (the 'production strategy'), all of which would be better characterized as management. Restoration of *Sphagnum* cover in peatlands managed for repeated shallow harvesting of moss for horticultural uses may also be regarded as a 'production strategy', and is favored by leaving behind 30% of the original *Sphagnum* cover (Whinam et al., this issue).

Major goals and their attainment

For a degraded peatland the primary goal is to repair the ecosystem, if the damage is not too severe, or to rebuild it if there has been considerable loss of peat. This will involve re-establishing more or less normal peatland hydrology, biogeochemical cycling, and energy capture that will allow autogenic plant succession (Glaser and Janssens, 1986; Foster and Wright, 1990) and the renewal of peat accumulation. It is important to act as soon as possible after exploitation has ceased, in order to minimize degradation of the surface peat by decomposition and compaction (Schouwenaars, 1993) and further losses by wind or water erosion, frost-heaving and ice formation (Quinty and Rochefort, 2000). These authors point to the paradox that rewetting, as the fundamental basis for restoration, may exacerbate erosion by water and by frost-heaving, so that water management should be programmed to counter them. The restoration processes must be preceded by an accurate spatial evaluation of current hydrology, involving also a study of peat structure, hydrologic conductivity and vertical seepage.

According to Price and Whitehead (2001), hydrologic conditions where *Sphagnum* has recolonized block-cut trenches on a cutover peatland suggest three threshold conditions for its re-establishment: high water-table (mean -29 ± 14 cm), soil moisture $> 50\%$, and soil water-pressure -100 cm for the whole season, allowing the moss to extract water from the decomposed and compacted cutover peat. Wheeler et al. (1998) discuss the following site features influencing water management: site drainage, surrounding drainage, rainfall, boundary shape, loss to aquifer, edge/area ratio, landscape situation, and surface topography.

Once the hydrological assessment is done, internal hydrology can be improved by rewetting to the point of water surplus and by creating a large water-storage capacity at the peat surface (Heathwaite, 1995), which may involve filling in drains, dam construction, and alteration of the topography to allow partial flooding of the peat surface (Bugnon et al., 1997; LaRose et al., 1997; Farrell and Doyle, this issue). Rewetting is, however, much more difficult in vacuumed than in block-cut *Sphagnum* bogs (Lavoie et al., this issue), where restoring the water table during the growing season to less than 40 cm beneath the peat surface seems to permit the reestablishment of *Sphagnum* species (Schouwenaars, 1988; see also Price and Whitehead, 2001). Optimal rewetting would involve restoration of the full range of hydrological variability, which is, however, usually unknown. (For a long-term study of such variability in a small undisturbed peatland, see Verry, 1984.) Buffer zones may also need to be established around certain peatlands to protect the external hydrological regime (Eggelsmann, 1980; Schouwenaars, 1993), particularly where vertical seepage is strong (Schouwenaars, 1993, 1995). Hydrological processes in both abandoned and restored peatlands, subjected to both block-cut and vacuum extraction as well as to different methods of restoration, have been reviewed by Price et al. (this issue). They also deal with the consequences of drainage for oxidation, compression, and subsidence of the peat. Methods used to restore peatland hydrology following extraction are summarized in Table 1.

The hydrological regime should be considered from a broader catchment perspective if catchment hydrology beyond the peatland has been altered significantly (Vasander et al., this issue). This is particularly true of large, patterned peatlands where upwelling of groundwater from distant sources is important (Siegel, 1983, 1988). Water quality is also of great importance in the rewetting process, given the very substantial variation in water chemistry among bogs and the various categories of poor, rich, and calcareous (extreme) rich fens (Mullen et al., 2000). For example, Lamers et al. (1999) describe a mechanism by which groundwater or sulfate pollution can influence the buoyancy of living *Sphagnum* and its die-off by affecting the alkalinity of bog water. The difficulties of rewetting degraded fens in the relatively dry climate of north-eastern Germany have been outlined by Reichert et al. (2000).

Restoration also involves stabilization of the peat surface, done naturally by the use of species known to be effective, or artificially by the use, for instance, of coarsely woven, biodegradable matting (Grosvernier et al., 1995). In the case of bogs, straw mulch is very useful in improving the microclimate for *Sphagnum* growth (Price et al., 1998). Certain 'companion' species may also be employed (Ferland and Rochefort, 1997; Tuittila et al., 2000). Fertilization with phosphorus can have a positive effect (Ferland and Rochefort, 1997).

Where drainage has converted open communities into forest, as in many drained peatlands, it will be necessary to remove the trees, at least partially (Vasander et al., this issue). This is an especially important consideration in northern and midcontinental bogs.

Table 1. Methods used to restore hydrological regimes in peatlands after extraction has ceased[1].

Technique	*Purpose*
Block ditches	Raise water table
Create terraces by building bunds	Retain water and distribute it more evenly
Provide open-water reservoirs	Increase lateral seepage
Pump water	"
Alter microtopography	Provide variety of habitats for colonization
Provide shade	Lower temperature and increase relative humidity near the peat surface
Mulch with straw	"
Provide companion species	"
Establish buffer zones	Prevent adjacent land use from affecting restored hydrology

[1] Summarized from Price et al. (2001).

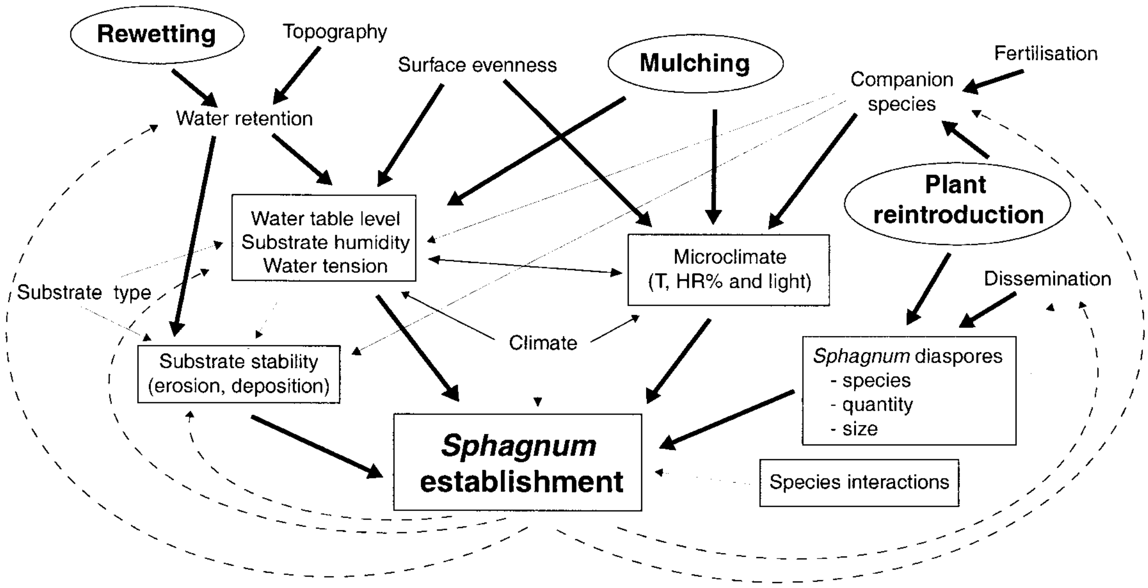

Figure 1. The interaction of restoration techniques in the re-establishment of *Sphagnum* mosses on mined raised bogs. Reproduced with permission from The Bryologist.

Where the seed bank has been removed, appropriate diaspores – representing major elements of the original flora – must be provided, from local remnants or nearby sources wherever possible in order to minimize ecotypic differences within species. Fertilization may be useful to assist their establishment (Rochefort et al., this issue), with particular attention to the balance between phosphorus and nitrogen (Verhoeven et al., 1996). At the same time potential invaders must be excluded as far as possible, whether exotic, or native species not normally found in the type of peatland being restored. Recent North American studies of *Sphagnum* re-establishment on mined raised bogs by Line Rochefort and her colleagues (Rochefort, 2000, 2001; Rochefort et al., this issue) exemplify the interactions of restoration techniques (Figure 1). Their paper in this issue describes in detail the steps that characterize the methods of restoration employed on North American *Sphagnum* bogs, and discusses eight controlled experiments to investigate each step. They also point out that given the variability of local conditions, field preparation to restore suitable hydrologic conditions must be site-specific.

Successful restoration must meet the goal stated by the U.S. National Research Council (NRC, 1992): 'to emulate a natural, functioning, self-regulating system that is integrated with the ecological landscape in which it occurs'. It will encompass returning the ecosystem to the structure, function, trophic organization, and biodiversity characteristic of its type (Rochefort, 2000), for instance an acid, forested *Sphagnum* bog or a circumneutral, open sedge fen. In the absence of direct measurement of these ecosystem properties, restoration of the characteristic floristic assemblages (including typical dominants and biodiversity) can provide a useful first step. Over the longer term, peat accumulation must recommence. (Unfortunately the surface pattern of the peat may seldom be capable of restoration, owing to severe alteration by the processes of exploitation.) It must inevitably be a long-term process, involving monitoring over several decades (Bakker et al., 2000). It also requires adaptive management – including the ability to manipulate hydrology – through at least one flood/drought cycle to establish the appropriateness and sustainability of the restored hydrological regime. It would be helpful if a set of 'indicator species' could be identified as useful in showing the re-establishment of various ecosystem functions (Zedler and Weller, 1989; Bakker et al., 2000). For a checklist of 28 questions appropriate to planning, carrying out, and assessing the success of restoration programs, see NRC (1992).

Peatlands can recover from certain degrees and types of disturbances through autogenic processes once a *Sphagnum* carpet is established (van Breemen, 1995; Hilbert et al., 2000; Belyea and Clymo, 2001). However, once disturbed severely, certain types of peatland will be difficult, if not impossible, to restore to their former state. Examples include peatlands underlain by permafrost (Zoltai et al., 1988), and the hydrologically complex, patterned peatlands of Canada and northern Minnesota (Glaser, 1989; Wright et al., 1992). Sites subject to anthropogenically enhanced acid and nitrogen deposition from the atmosphere will also be difficult to restore (but see Beltman et al., 1995). Poor-fen sites with pH values close to 5.7 will be especially vulnerable to acid deposition, being at the point of rapid natural transformation from circumneutral rich fen to strongly acid bog (Gorham and Janssens, 1992a, b). Even without acid stress, the normal processes of succession in such sites make pH difficult to maintain, which may be important because they can harbor rare species (Gorham et al., 1987).

The process of restoration becomes even more protracted if it is necessary to rebuild the ecosystem in cases where mining activity has been substantial, peat and water chemistry have been altered significantly (Wind-Mulder and Vitt, 2000), and the peat remaining is that of an earlier stage of development (White, 1930). In such a situation conditions must be established that allow the natural autogenic processes involved in peat accumulation, which gradually cause a decline in minerotrophic inputs from around or beneath the peat deposit, to induce plant succession to a reasonable approximation of the former stage of development. Paleoecological studies are likely to be helpful, and will be discussed below. Pfadenhauer and Klötzli (1996) state that for Central European bogs – drained and overgrown with heather – to be restored to the stage of peat accumulation, it may be necessary to interpose a tall-sedge community with minerotrophic *Sphagnum* species instead of allowing a dense stand of *Eriophorum vaginatum* to develop without an acrotelm being formed. They also examine the problems of rewetting, reducing nutrient inputs, and recolonizing damaged fen sites. Some poor fens are characterized by the presence of a few 'fen-indicator' species, rooted in fen peat beneath a shallow layer of acid *Sphagnum* peat and surviving by a process of 'biological inertia' (Gorham, 1957) under conditions in which they could not establish. Once damaged, they may require rebuilding from an earlier fen stage if those indicator species are to be restored.

Buckland et al. (2000) point out that where damage has been severe, as in many lowland English mires, restoration to the original state may be impossible because the *Sphagnum* species that were the predominant peat formers are now rare or extinct in the region, and in any case developed under climatic conditions different from those now prevailing. They also remark that there is a great need to consider the very diverse invertebrate fauna in peatland conservation and restoration.

Recent modeling studies may be helpful in thinking about the restoration of peat accumulation. Hilbert et al. (2000) devised a general model of peatland dynamics that describes the role of non-linear interaction between water-table depth, which reflects the water balance of the system, and peat production. In this way they add allogenic factors – climate and local hydrology – to the controlling autogenic factors of acrotelm/catotelm dynamics described by Clymo et al.

(1998). They point out that, at intermediate water-table depth, two equilibrium states are possible, in which a slight change in water balance could lead to a rapid shift in equilibrium. This in turn could, for example, shift the peatland from a current sink to a source of carbon to the atmosphere.

Belyea and Clymo (2001) modeled microtopographic adjustments of the peat surface based on a hump-backed relationship between rates of peat formation and the thickness of the aerobic surface layer (acrotelm). Their model provides a feedback mechanism that links hydrology and carbon sequestration to dynamic changes in peatland microforms (lawns, hummocks, hollows and pools).

Eight influences upon the natural recolonization of mined peatlands following abandonment are outlined in Table 2. They include spatial, temporal, physical and biological factors as well as the type of exploitation. The role of spontaneous vegetation succession in ecosystem restoration has been advocated as integral to the process (Prach et al., 2001). It is illustrated in the case of peatland ecosystems by Lavoie et al. in this issue.

Parameters for measuring the success of restoration

In the short term it is most important to manipulate hydrology so as to re-establish key mosses, such as *Sphagnum* species, in the case of acid bogs and a variety of rich-fen herbs, such as *Carex* species, in the case of circumneutral fens. *Sphagnum* re-establishment has often been partially successful in exploited acid peatlands, particularly in block-cut as opposed to vacuumed raised bogs, which require intensive drainage to support heavy machinery. Such drainage increases compaction and oxidation of the peat, considered by Price (1996) to be irreversible. In vacuumed bogs, cotton grass (*Eriophorum vaginatum)* is often the most successful colonizer, and seems to improve the microclimate for other bog species (Tuittila et al., 2000; Lavoie et al., this issue).

Over the longer term it is important to re-establish, as far as possible, (1) full biodiversity, taking into account its different levels (genetically different ecotypes, species, ecosystems and landscapes), (2) trophic organization of plants and animals into food webs resembling those present before disturbance, and (3) productivity, decomposition, and biogeochemical cycles characteristic of the original type of ecosystem and balanced so that peat accumulates. In this connection, Waddington et al. (this issue) describe methods for measuring *Sphagnum* productivity and decomposition in peatlands undergoing restoration. In the case of *Sphagnum* bogs, the re-establishment of normal *acrotelm/catotelm* dynamics is vital (Clymo, 1991). In evaluating long-term success it will be necessary to take into account all of the ecosystem properties listed above, and to pay attention to multiple limiting gradients of hydrology, alkalinity/acidity, and nutrients (Bridgham et al., 1996; see also Wheeler, 2000).

In general, periods of restoration have been too short to determine whether the appropriate ecosystem structure, function, trophic organization and biodiversity will ultimately be restored acceptably, or if a rebuilt ecosystem will follow, to a reasonable degree, the successional pathway of the original one. Rochefort et al. (this issue) estimate that a significant number of characteristic bog species can be established in 3–5 years, a stable high water-table in about a decade, and a functional ecosystem that accumulates peat in perhaps 30 years. As far as we are aware, no peatland restorations, most of which are very young, have met the criteria discussed in the paragraph above, including restoration of characteristic biodiversity. In this context it is fortunate that vascular-species richness of individual *Sphagnum* bogs appears not to be dependent on the extent of their area (Glaser, 1992).

It is instructive to consider here the possibility of natural peatland restoration over the long term without human intervention. For example, in what might be considered rather favorable conditions for restoration, Soro et al. (1999) compared plots from the ombrotrophic surface of Ryggmossen, one of the few pristine bogs left in east-central Sweden, with plots in a number of shallow, hand-dug peat trenches, mostly 0.5–1.0 m deep, from 11 similar bogs nearby where mining had been abandoned for 36–60 years (mean 50 years). Table 3 indicates that even though surface wetness was greater in the trenches than at Ryggmossen, the *Sphagnum* cover was much less, despite the presence, on average, of five more species. Most of the additional species that had invaded the bare peat were characteristic of fens, despite the strong acidity of the trench waters. A feature of particular interest in this study is the authors' observation that the percentage of non-random species associations was much lower in the trenches. This suggests that random events were more important, and biological processes less important, than on the mature bog surface.

Table 2. Eight factors influencing the type of natural recolonization of exploited peatlands after abandonment[1].

Area and depth of mining activity
Type of exploitation (e.g., removal of surface moss, block-cut or vacuum mining, drainage for agriculture or forestry)
Depth and type of peat remaining
Degree of hydrological disturbance
Presence of remnant vegetation
Nature of former vegetation
Nature of surrounding vegetation (distance to sources of appropriate propagules)
Time from abandonment to attempted restoration

[1] Modified from White (1930).

Table 3. A comparison of plots in mined peat trenches from eleven bog sites with plots from the ombrotrophic plane of the Ryggmossen bog.

	Ryggmossen bog plane	*Mined peat trenches*
Water-table depth (cm)	19.1	7.4
Bare peat (mean %)	2	17
Sphagnum cover	74	54
Number of *Sphagnum* species	9 (all bog)	11–21 (many fen)
Carex rostrata	absent	present (8 sites)
Carex lasiocarpa	absent	present (4 sites)
Total number of species per plot[1]	4.9	2.3
Number of *Sphagnum* species per plot[1]	1.5	0.75
Percentage of significantly non-random species associations[1]	52	24

[1] 25 × 25 cm plots, n = 800 (Ryggmossen) and 600 (trenches).

In most cases of disturbance there has been little or no prior measurement of ecosystem properties, so that the goal becomes more generalized: to restore the ecosystem in a way that reestablishes it as a more or less normal member of the type to which it belonged originally, such as an open bog, or a wooded rich fen. In central Europe, millennia of human disturbance have often made it difficult, if not impossible, to ascertain the original state of the ecosystem. In such a case, restoration end-points are difficult to base on original status and choices must involve other criteria, unless paleoecological studies provide adequate guidance. These choices will require societal decisions based, for example, on the desirability and ease of re-establishing rare species or types of ecosystems (Beltman et al., 1995), or providing habitat for certain kinds of wildlife such as birds (Bölscher, 1995; Desrochers et al., 1998) or butterflies (Duffey and Mason, 1970).

A further problem, especially for European peatlands, is the unprecedented anthropogenic enhancement of atmospheric nitrogen and sulfur deposition upon them, which appears to be having significant impacts upon their vegetation (Lee et al., 1993; Beltman et al., 1995; Grootjans and van Diggelen, 1995; Koerselman and Verhoeven, 1995; Tomassen et al., 2000), with important consequences for ecosystem structure, function and biodiversity. According to Grootjans and van Diggelen (1995), this means that most fens in the central European lowlands will require a mowing regime to control tall graminoids and preserve their current vegetation, even with optimal hydrology. Effects of nitrogen enrichment upon *Sphagnum* species appear mixed (Money and Wheeler, 1999). Climate warming is also likely to have profound effects upon peatlands (Gorham, 1991, 1995; Schouten et al., 1992; Heathwaite, 1993), and will interact with the above-mentioned impacts of acid and

Table 4. Landscape, ecosystem and social/industrial factors favoring and opposing peatland restoration.

Type of Factor	*Factor*	*Favoring*	*Opposing*
Ecosystem	Information on prior condition	Much	Little or none
	Time since abandonment	Short	Long
	Structure	Simple, single main community	Complex, zoned or patterned with many communities
	Substrate stability	(a) Flat topography (b) No frost-heaving (c) Freshly disturbed surface	Sloping topography Frost-heaving severe Aged and hydrophobic surface crust
	Remnant vegetation	Present	Absent
	Seed bank	Present	Absent
	Biodiversity	Low	High
	Rare/endangered species	Absent	Present
Landscape	Climate	Relatively stable and wet	Drier, strongly cyclical between flood and drought
	Hydrology	Simple (e.g., topogenous)	Complex (e.g., soligenous)
	Permafrost	Absent	Present
	Connections to other peatlands	Present	Absent
	Distance to sources of appropriate propagules	Near	Far
	Chemical inputs (nutrients, toxins)	Little altered by human activities	Greatly increased by human activities
	Invasive species	None or few	Many
Social/Industrial	Advance planning	2–5 years	1 year or less
	Environmental laws	Strong	Weak
	Environmental groups	Strong	Weak
	Research funding by industry and government	Adequate	Little or none
	Concern within peat industry	Strong	Weak

nitrogen deposition (van Dam and Beltman, 1992; Berendse et al., 2001).

Prioritizing peatlands for restoration

In prioritizing sites for restoration, an assessment must be made of conditions favoring and opposing restoration, assuming appropriate personnel and resources are available. Several of these, related to physical as well as biological and societal attributes, are listed in Table 4. They will aid in answering questions such as: (1) is success likely; (2) was the site ecologically unique or uncommon in the region; (3) did it, or can it, sustain rare species; (4) did it have important functional linkages to other peatlands, or to other types of ecosystem? Wheeler et al. (1998) list several attributes to be considered in setting priorities, three under the heading *Need and Urgency*, ten under *Feasibility and Requirements*, and four under *Practical Constraints*. They employ these to develop a 'restoration potential score' for assessing the eligibility of a given bog for restoration.

Paleoecology as an aid to peatland restoration

Although paleoecology is an important tool for understanding and monitoring peatland and other ecosystems (Gorham et al., 2001), stratigraphic studies of peatland development are only occasionally considered (e.g., Joosten, 1995; Wichtman and Koppisch, 1998) in peatland repair or rebuilding. They should, if possible, be undertaken before the ecosystem is exploited, although peatland remnants can be useful if not too marginal (Lavoie et al., 2001). Such studies can answer a variety of questions, beginning with whether the present system has been relatively stable or is on a trajectory of change, and how it developed to its present state. It is well known that peatland succession can follow many different pathways (Walker, 1970; Tallis, 1983), and in rebuilding peatlands in which the peat surface has been lowered to an earlier stage of development it can be particularly helpful to know the pattern of prior succession. It is also possible to infer, from a study of moss fossils in peat cores, depth profiles of past water levels and acidity (Janssens, 1983; Janssens et al., 1992) that can assist in explaining the successional sequence. Studies across recurrence surfaces in bogs can also yield valuable insights into natural recovery from surface drying (Schouwenaars, 1995), as might examination of the recolonization of naturally dried-out bog pools, and of post-fire vegetation succession (Lavoie et al., this issue).

Conclusion

Peatland restoration will not be placed on a firm footing until we understand a lot more about fundamental peatland science. We need to know much more about how climate, topography, soil parent material, hydrology and the biota have interacted to control ecosystem form and function over time (Gorham, 1957, 1994). For this to come about, we also need to know much more about the autecology of major peat-forming species, such as Sphagna (Clymo and Hayward, 1982) and Carices (Bernard 1988, 1990), as well as of rarities, for instance *Carex exilis* in Minnesota (Santelmann, 1991). In particular, we require more information on competitive abilities of peatland plants under different environmental conditions, and especially their capacities for dispersal and establishment (Campbell et al., in press). Wherever possible, restoration projects should attempt to incorporate an investigation of fundamental peatland science as an important component of the program, and peatland researchers and managers should be encouraged to keep in close touch with one another.

Acknowledgements

Dale Vitt and an anonymous referee provided helpful suggestions. Much of the Canadian research cited here has been generously funded through the Canadian Sphagnum Peat Moss Association (CSMPA), which sponsored the International Peat Society's symposium 'Restoration of *Sphagnum*-dominated Peatlands' at the International Peat Congress in Quebec City, August 2000 (see Rochefort and Daigle, 2000).

References

Bakker, J.P., Grootjans, A.P., Hermy, M. and Poschlod, P. 2000. How to define targets for ecological restoration? Appl. Veg. Sci. 3: 3–6.

Beltman, B., van den Broek, T. and Bloeman, S. 1995. Restoration of acidified rich-fen ecosystems in the Vechtplassen area: successes and failures. *In:* Wheeler, B.D., Shaw, S.C., Fojt, W.J and Robertson, R.A. (eds.), Restoration of Temperate Wetlands. pp. 273–286. Wiley, Chichester, UK.

Belyea, L.R. and Clymo, R.S. 2001. Feedback control of the rate of peat formation. Proc. Royal Soc. London, B 268: 1315–1321.

Berendse, F., Rydin, H., van Breemen, N., Buttler, A., Heijmans, M., Hoosbeek, M., Lee, J., Mitchell, E., Saarnio, S., Vasander, H. and Wallen, B. 2001. C sequestration is influenced by competitive shifts among plant species in Sphagnum bogs at elevated atmospheric CO_2 and N deposition. Gl. Change Biol. 7: 591–598.

Bernard, J.M. 1988. Studies in wetland carices of the temperate zone – an introduction. Aquat. Botany 30: 1–3.

Bernard, J.M. 1990. Life history and vegetative reproduction in *Carex*. Can. J. Botany 68: 1441–1448.

Bölscher, B. 1995. Niche requirements of birds in raised bogs: habitat attributes in relation to bog restoration. *In:* Wheeler, B.D., Shaw, S.C., Fojt, W.J. and Robertson, R.A. (eds.), Restoration of Temperate Wetlands. pp. 359–378. Wiley, Chichester, UK.

Bridgham, S.D, Pastor, J., Janssens, J.A., Chapin, C. and Malterer, T.J. 1996. Multiple limiting gradients in peatlands: a call for a new paradigm. Wetlands 16: 45–65.

Buckland, P.C., Eversham, B. and Warburton, S. 2000. Peatlands, invertebrates and paleoecology: a case study from the Humberhead Levels, U.K. *In:* Rochefort, L. and Daigle, J.Y. (eds.), Sustaining Our Peatlands. Proc. 11th Int. Peat Congresss, Quebec City, Canada, Vol. 2. pp. 1017–1026. Canadian Society of Peat and Peatlands & International Peat Society, Edmonton, Alberta, Canada.

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

Campbell, D.R., Rochefort, L. and Lavoie, C. (in press). Determining the immigration potential of plants colonizing disturbed environments: the case of milled peatlands, Québec. J. Appl. Ecol.

Clymo, R.S. 1991. Peat growth. *In*: Shane, L.C.K. and Cushing, E.J. (eds.), Quaternary Landscapes. pp. 76–112. University of Minnesota Press, Minneapolis, Minnesota, USA.

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

Clymo, R.S., Turunen, J. and Tolonen, K. 1998. Carbon accumulation in peatland. Oikos 81: 368–388.

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

Duffey, E. and Mason, G. 1970. Some effects of summer floods on Woodwalton Fen in 1968/69. Entomol. Gaz. 21: 23–26.

Eggelsmann, R. 1980. Hydrological aspects of peatland utilization and conservation in northwestern Germany. *In:* Proc. 6th Int. Peat Congress, Duluth, Minnesota, USA. pp. 28–30. International Peat Society, Helsinki, Finland.

Ehrenfeld, J.G. 2000. Defining the limits of restoration: the need for realistic goals. Rest. Ecol. 8: 2–9.

Farrell, C.A. and Doyle, G.J. 2001. (this issue) Rehabilitation of industrial cutaway Atlantic blanket bog in County Mayo, northwest Ireland. Wetlands Ecology and Management.

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

Foster, D.R. and Writght, H.E.Jr. 1990. Role of ecosystem development and climate change in bog formation in Central Sweden. Ecology 71: 450–463.

Glaser, P.H. 1989. Detecting biotic and hydrogeochemical processes in large peat basins with Landsat TM imagery. Remote Sens. Envir. 28: 109–119.

Glaser, P.H. 1992. Raised bogs in eastern North America – Regional controls for species richness and floristic assemblages. J. Ecology 80: 535–554.

Glaser, P.H. and Janssens, J.A. 1986. Raised bogs in eastern North America: transitions in landtroms and gross stratigraphy. Can. J. Botany 64: 395–415.

Gorham, E. 1957. The development of peatlands. Quart. Rev. Biol. 32: 145–166.

Gorham, E. 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecol. Appl. 1: 182–195.

Gorham, E. 1994. The future of research in Canadian peatlands: a brief survey with particular reference to global change. Wetlands 14: 206–215.

Gorham, E. 1995. The biogeochemistry of northern peatlands and its possible responses to global warming. *In:* Woodwell, G.M. and Mackenzie, F.T. (eds.), Biotic Feedbacks in the Global Climate System: Will the Warming Feed the Warming? pp. 169–186. Oxford University Press, Oxford, UK.

Gorham, E. and Janssens, J.A. 1992a. The paleorecord of geochemistry and hydrology in northern peatlands and its relation to global change. Suo 43: 117–126.

Gorham, E. and Janssens, J.A. 1992b. Concepts of fen and bog reexamined in relation to bryophyte cover and the acidity of surface waters. Acta Societatis Botanicorum Poloniae 61: 7–20.

Gorham, E., Janssens, J.A., Wheeler, G.A. and Glaser, P.H. 1987. The natural and anthropogenic acidification of peatlands. *In:* Hutchinson, T.C. and Meema, K. (eds.), Effects of Atmospheric Pollutants on Forests, Wetlands and Agricultural Ecosystems. pp. 493–512. Springer, New York, USA.

Gorham, E., Brush, G.S., Graumlich, L.J., Rosenzweig, M.L. and Johnson, A.H. 2001. The value of paleoecology as an aid to monitoring ecosystems and landscapes, chiefly with reference to North America. Envir. Rev. 9: 99–126.

Grootjans, A. and van Diggelen, R. 1995. Assessing the restoration prospects of degraded fens. *In:* Wheeler, B.D., Shaw, S.C., Fojt, W.J. and Robertson, R.A., (eds.), Restoration of Temperate Wetlands. pp. 73–90. Wiley, Chichester, UK.

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. Wiley, Chichester, UK.

Heathwaite, A.L. 1993. Disappearing peat – Regenerating peat? The impact of climate change on British peatlands. Geogr. J. 159: 203–208.

Heathwaite, A.L. 1995. Problems in the hydrological management of cutover raised mires, with special reference to Thorne Moors, Yorkshire. *In:* Wheeler, B.D., Shaw, S.C., Fojt, W.J. and Robertson, R.A. (eds.), Restoration of Temperate Wetlands. pp. 315–329. Wiley, Chichester, UK.

Hilbert, D.W., Roulet, N. and Moore, T. 2000. Modelling and analysis of peatlands as dynamical ecosystems. J. Ecology 88: 230–242.

Hobbs, R.J. and Norton, D.A. 1996. Toward a conceptual framework for restoration ecology. Rest. Ecol. 4: 93–110.

Hood, G. 2000. Canadian peat producers adopt new policy. Peatlands Int. 1: 1–2.

Janssens, J.A. 1983. A quantitative method for stratigraphical analysis of bryophytes in Holocene peat. J. Ecology 71: 189–196.

Janssens, J.A., Hansen, B.C.S., Glaser, P.H. and Whitlock, C. 1992. Development of a raised-bog complex in Northern Minnesota. *In:* Wright, H.E., Jr., Coffin, B. and Aaseng, N. (eds.), The Patterned Peatlands of Northern Minnesota. pp. 189–221. University of Minnesota Press, Minneapolis, Minnesota, USA.

Joosten, J.H.J. 1995. Time to regenerate: long term perspectives of raised-bog regeneration with special emphasis on palaeoecological studies: *In:* Wheeler, B.D., Shaw, S.C., Fojt, W.J. and Robertson, R.A. Restoration of Temperate Wetlands. pp. 379–404. Wiley, Chichester, UK.

Joosten, H. 2000. Peatland conservation in central and southern Europe. *In:* Rochefort, L. and Daigle, J.Y. (eds.), Sustaining our peatlands. Proc. 11th Int. Peat Congress, Quebec City, Canada, August 6–12, 2000. Vol. 2. pp. 1044–1049. Canadian Society of Peat and Peatlands & International Peat Society, Edmonton, Alberta, Canada.

Koerselman, W. and Verhoeven, J.T.A., 1995. Eutrophication of fen ecosystems: external and internal nutrient sources and restoration strategies. *In:* Wheeler, B.D., Shaw, S.C., Fojt, W.J. and Robertson, R.A., (eds.), Restoration of Temperate Wetlands. pp. 91–112. Wiley, Chichester, UK.

Lamers, L.P.M., Farhoush, C., van Groenendael, J.M. and Roelofs, J. 1999. Calcareous groundwater raises bogs: the concept of ombrotrophy revisited. J. Ecology 87: 639–648.

LaRose, S., Price, J. and Rochefort, L. 1997. Rewetting of a cutover peatland: Hydrological assessment. Wetlands 17: 416–423.

Lavoie, C., Zimmerman, C. and Pellerin, S. 2001. Peatland restoration: A paleoecological perspective. Ecoscience 8: 247–258.

Lavoie, C., Grosvernier, P., Girard, M. and Marcoux, K. (this issue) Spontaneous revegetation of mined peatlands:a useful restoration tool? Wetlands Ecology and Management.

Lee, J.A., Parsons, A.N. and Baxter, R. 1993. *Sphagnum* species and polluted environments, past and future. Adv. Bryology 5: 297–313.

Malterer, T., Johnson, K. and Stewart, J. (eds.) 1998. Peatland Restoration and Reclamation, Proc. 1998 Int. Peat Symposium, Duluth, Minnesota, USA.

Money, R.P. and Wheeler, B.D. 1999. Some critical questions concerning the restorability of damaged raised bogs. Appl. Veg. Sci. 2: 107–116.

Mullen, S.F., Janssens, J.A. and Gorham, E. 2000. Acidity of and the concentrations of major and minor metals in the surface of bryophyte assemblages from 20 North American bogs and fens. Can. J. Botany 78: 718–727.

National Research Council (NRC). 1992. Restoration of Aquatic Ecosystems. National Academy Press, Washington, DC, USA.
Parkyn, L., Stoneman, R.E. and Ingram, H.A.P. (eds.) 1997. Conserving Peatlands. CAB international, Wallingford, UK. 500 pp.
Pfadenhauer, J. and Klötzli, F. 1996. Restoration experiments in middle European wet terrestrial ecosystems: An overview. Vegetatio 126: 101–115.
Prach, K., Sandor, B., Joyce, C.B., Pysek, P., van Diggelen, R. and Wiegleb, G. 2001. The role of spontaneous vegetation succession in ecosystem restoration: A perspective. Appl. Veg. Sci. 4: 111–114.
Price, J.S. 1996. Hydrology and microclimate of a partly restored cutover bog, Quebec. Hydrol. Proc. 10: 1263–1272.
Price, J.S, Heathwaite, A.L. and Baird, A. (this issue) Hydrological processes in abandoned and restored peatlands: An overview of management approaches. Wetlands Ecology and Management.
Price, J., 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.), Sustaining our peatlands: Proc. 11th Int. Peat Congress, Quebec City, Canada, August 6–12, 2000. Vol. 2. pp. 751–756. Canadian Society of Peat and Peatlands & International Peat Society, Edmonton, Alberta, Canada.
Reichert, M., Dietrich, O., Koppisch, D. and Roth, S. 2000. The influence of rewetting on vegetation development and decomposition in a degraded fen. Rest. Ecol. 8: 186–195.
Rochefort, L. 2000. *Sphagnum* – A keystone genus in habitat restoration. The Bryologist 103: 503–508.
Rochefort, L. 2001. Restauration écologique. *In*: Payette, S. and Rochefort, L. (eds.), Écologie des tourbières du Québec-Labrador. pp. 449–504. Presses de l'Université Laval, Québec, Canada.
Rochefort, L. and Daigle, J.Y. (eds.) 2000. Sustaining our Peatlands. Proc. 11th Int. Peat Congress, Quebec City, Canada, August 6–12, 2000. Vol. I and II. Canadian Society of Peat and Peatlands & International Peat Society, Edmonton, Alberta, Canada. 1121 pp.
Rochefort, L., Quinty, F., Campeau, S., Johnson, K.W. and Malterer, T.J. (this issue) North American approach to the restoration of *Sphagnum* dominated peatlands. Wetlands Ecology and Management.
Roulet, N.T. 2000. Peatlands, carbon storage, greenhouse gases, and the Kyoto Protocol: prospects and significance for Canada. Wetlands 20: 605–615.
Santelmann, M.V. 1991. Influences on the distribution of *Carex exilis*: an experimental approach. Ecology 72: 2025–2037.
Schouten, M.G.C., Streefkerk, J.G. and van der Molen, P.C. 1992. Impact of climatic change on bog ecosystems, with special reference to sub-oceanic raised bogs. Wetl. Ecol. Manag. 2: 55–61.
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.
Schouwenaars, J.M. 1995. The selection of internal and external water management options for bog restoration. *In:* Wheeler, B.D., Shaw, S.C., Fojt, W.J. and Robertson, R.A. (eds.), Restoration of Temperate Wetlands. pp. 331–346. Wiley, Chichester, UK.
Siegel, D.I. 1983. Groundwater and the evolution of patterned mires, Glacial Lake Agassiz Peatlands, northern Minnesota. J. Ecology 71: 913–921.
Siegel, D.I. 1988. Evaluating cumulative effects of disturbances on the hydrologic function of bogs, fens, and mires. Envir. Manag. 12: 621–626.
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.
Tallis, J. 1983. Changes in wetland communities. *In:* Gore A.J.P. (ed.), Ecosystems of the World 4A. Mires: Swamp, Bog, Fen and Moor, General Studies. pp. 331–347. Elsevier, Amsterdam, The Netherlands.
Tomassen, H.B.M., Smolders, A.J.P., Lamers, L.P.M. and Roelofs, J.G.M. 2000. Conservation of ombrotrophic bog vegetations: The effects of high atmospheric nitrogen deposition. *In*: Rochefort, L. and Daigle, J.Y. (eds.), Sustaining our peatlands: Proc. 11th Int. Peat Congress, Quebec City, Canada, August 6–12, 2000. Vol. 1. pp. 253–261. Canadian Society of Peat and Peatlands & International Peat Society, Edmonton, Alberta, Canada.
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 Breemen, N. 1995. How *Sphagnum* bogs down other plants. Trends Ecol. & Evol. 10: 270–275.
van Dam, H. and Beltman, B. 1992. Effects of climatic change on chemistry and vegetation of peatlands, with special reference to interaction with atmospheric deposition. Wetl. Ecol. Manag. 2: 63–68.
Vasander, H., Tuittila, E.-S., Lode, E., Lundin, L., Ilomets, M., Sallantaus, T., Heikkilä, R., Pitkänen, M.-L. and Laine, J. (this issue). Status and restoration of peatlands in Northern Europe. Wetlands Ecology & Management.
Verhoeven, J.T.A., Koerselman, W. and Meuleman, A.F.M. 1996. Nitrogen-or-phosphorus-limited growth in herbaceous, wet vegetation: relations with atmospheric inputs and management regimes. Trends Ecol. & Evol. 11: 494–499.
Verry, E.S. 1984. Microtopography and water table fluctuation in a sphagnum mire. *In:* Proc. 7th International Peat Congress, Dublin, Eire. pp. 11–31. Irish National Peat Committee, Dublin, Ireland.
Waddington, J.M., Rochefort, L. and Campeau, S. (this issue). *Sphagnum* production and decomposition in a restored cutover peatland. Wetlands Ecology & Management.
Walker, D.A. 1970. Direction and rate in some British post-glacial hydroseres. *In:* Walker D. and West, R.G. (eds.), Studies in the Vegetation History of the British Isles. pp. 117–139. Cambridge University Press, London, UK.
Wheeler, B.D. 2000. Ecological gradients, subdivisions and terminology of north-western European mires. J. Ecology 88: 187–203.
Wheeler, G.D., Shaw, S.C., Fojt, W.J. and Robertson, R.A. (eds.), 1995. Restoration of Temperate Wetlands. Wiley, Chichester, UK.
Wheeler, B.D., Money, R.P., Shaw, S.C. and Meade, R. 1998. Assessing priorities and approaches to the restoration of damaged lowland bogs in northwestern Europe. *In:* Malterer, T., Johnson, K. and Stewart, J. (eds.), Peatland Restoration and Reclamation, Proc. 1998 Int. Peat Symposium, Duluth, Minnesota, USA, pp. 23–31.

Whinam, J., Hope, G.S., Clarkson, B.R., Buxton, R.P., Alspach, P.A. and Adam, P. (this issue). *Sphagnum* in peatlands of Australasia: Their distribution, utilisation and management. Wetlands Ecology and Management.

White, J.M. 1930. Re-colonization after peat-cutting. Proc. Royal Irish Acad., B 39: 453–476.

Wichtmann, W. and Koppisch, D. 1998. Degraded fens in northeastern Germany: goals for cultivation and restoration. *In:* Malterer, T., Johnson, K. and Stewart, J. (eds.), Peatland Restoration and Reclamation, Proc. 1998 Int. Peat Symp., Duluth, Minnesota, USA, pp. 32–36. International Peat Society, Jyväskylä, Finland.

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

Wright, H.E., Jr., Coffin, B. and Aaseng, N. (eds.). 1992. The Patterned Peatlands of Northern Minnesota. University of Minnesota Press, Minneapolis, Minnesota, USA.

Zedler, J.B. and Weller, M.W. 1989. Overview and future directions. *In:* Kusler, J.A. and Kentula, M.E. (eds.), Wetland Creation and Restoration: The Status of the Science, Vol. 1, Regional Reviews. pp. 465–473. U.S. EPA 600/3-89/038A. Environmental Research Laboratory, Corvallis, Oregon, USA.

Zedler, J.B. 2000. Progress in wetland restoration ecology. Trends Ecol. & Evol. 15: 402–407.

Zoltai, S.C., Tarnocai, C., Mills, G.F. and Veldhuis, H. 1988. Wetlands of Subarctic Canada. *In:* National Wetlands Working Group. Wetlands of Canada. Ecological Land Classification Series, No. 24. pp. 55–96. Environment Canada and Polyscience Publishers, Montreal, Quebec, Canada.