Energy and moisture considerations on cutover peatlands: surface microtopography, mulch cover and *Sphagnum* regeneration

Jonathan Price [a,*], Line Rochefort [b], Francois Quinty [b]

[a] *Department of Geography and Wetland Research Centre, University of Waterloo, Waterloo, Ont. N2L 3G1, Canada*
[b] *Department of Phytologie and Centre d'Etudes Nordiques, Pavillon Paul-Comtois, Universite Laval, Ste-Foy, Que. G1K 7P4, Canada*

Abstract

This study examined (i) the effect of artificially created microtopography and straw mulch on the soil moisture and (ii) energy balance and the establishment of a *Sphagnum* cover on a cutover peatland. Straw mulch caused rainfall interception approaching 2 mm per event. Although interception represented 44% of the total rainfall over the measurement period, water that evaporated from the mulch used energy that would otherwise have been used to evaporate soil water. Thus, the net effect of interception by mulch was negligible. The soil heat flux below the mulch was only 13% of the bare soil value and was decoupled from the daily net radiation. Net radiation over the bare soil was 15% greater than over the mulch. However, because of the greater heat flux into the bare peat, the energy available for sensible and latent heat fluxes was similar between the mulch covered and bare peat. Average evaporation from mulch and bare soil was estimated to be 2.6 and 3.1 mm d^{-1}, respectively. Soil water tension 1 cm below the surface remained above -100 cm (mb) all season (100% of the time) when a mulch was used, compared to only 30% of the time in the bare soil. Correspondingly, the water table was sustained above the 40 cm depth, 60% of time in the mulch covered site, compared to only 40% of the time in the bare peat site. Negative relief

* Corresponding author. Tel.: +1 519 8884567; fax: +1 519 7460658; e-mail: jsprice@watserv1.uwaterloo.ca

elements of the microtopography were wetter and cooler than positive relief elements. However, when under a mulch, the negative relief elements provided no additional benefit, in terms of temperature or soil moisture amelioration. The control site with a mulch cover was equivalent or better than negative relief elements with a mulch cover. Taking into account the poorer performance of positive relief elements, even when mulch covered, the creation of surface microtopography reduced the overall moisture content of the site. *Sphagnum* established and spread only when the diaspores were protected with a straw mulch. All microtopography types tested had no effect on the establishment of *Sphagnum* mosses when the microtopography treatments, including positive and negative relief elements, were treated as a whole, although being in a depression helped *Sphagnum* establishment. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Hydrology; Microtopography; Peatlands; Restoration; *Sphagnum*; Colonization

1. Introduction

Exploitation of peatlands for horticultural peat and peat fibre is an important industry in Canada and Europe (Lapalainen, 1996), but the process has a profound and long lasting impact on these sensitive wetland systems. The restoration of cutover bogs requires a return to the peat forming cycle, which relies largely on the development of a *Sphagnum* carpet on the cutover peat surface. However, *Sphagnum* will not readily regenerate on cutover peat, largely because of water limitations at the surface. Indeed, cutover bogs experience more frequent and larger variations in water table because of the low specific yield of the substrate, compared to natural bogs (Schouwenaars, 1993; Price, 1996). Schouwenaars (1988) indicated that for successful regeneration of European bogs, the water table depth should be within 40 cm of the surface during the growing season. However, Price (1997) demonstrated that water table was not a good indicator of the surface condition in Canadian peatlands. Spatially variable soil characteristics (i.e. state of decomposition), control local capillary effects, hence soil moisture distribution in the vertical profile and ultimately, water availability for plants. Price (1996, 1997) suggested that the capillary forces within the residual peat soil bound the soil water beyond the reach of *Sphagnum* diaspores which were introduced to the surface. Consequently, *Sphagnum* diaspores become desiccated and die (Sagot and Rochefort, 1996).

Various strategies employed to ameliorate the surface conditions include blocking ditches (Eggelsmann, 1988; Price, 1997), providing open water reservoirs to increase lateral seepage (LaRose et al., 1997), altering the surface microtopography (Ferland and Rochefort, 1997; Quinty and Rochefort, 1997), using shading devices (Rochefort and Bastien, 1998), straw mulches (Price, 1997; Quinty and Rochefort, 1997; Rochefort et al., 1997) and companion species (Ferland and Rochefort, 1997). These experiments suggest that *Sphagnum* recolonization is possible, even when the water table depth is > 40 cm. However, many of these studies focus on demonstrating the (un)suitability of the substrate for *Sphagnum* recolonization by field

experimental techniques. There remains a dearth of knowledge about the physical processes.

Bare peat surfaces are prone to cracking and crust formation, frost heaving and erosion by wind or water, restricting the establishment of plant propagules (Salonen, 1987). Wheeler and Shaw (1995) proposed the use of mulches to assist the development of a vegetation cover and stabilize the peat surface. The use of mulch over soils has been shown to ameliorate soil moisture and temperature conditions through its effect on the energy balance. Hares and Novak (1992) reported lower net radiation and evaporation from a mulch covered surface. In addition to the presence of the shading surface, the mulch decreased the airflow, thereby increasing the resistance to vapour and heat. Mulch covered soil remains cool during the day, although heat is retained at night (McDonald and Helgerson, 1990). Price (1997) showed that the use of mulch during a dry summer kept the soil water potential between 0 and -100 mb; suctions inadequate to extract water from intercellular structures of live *Sphagnum* plants (Hayward and Clymo, 1982). Wetter conditions (i.e. lower soil water suction) significantly increased the probability of survival and growth of *Sphagnum* diaspores (Campeau and Rochefort, 1996).

The creation of surface microtopography is a technique often used in restoration. For example: (1) it can improve the physical structure of wasteland soils (Bradshaw, 1995); (2) increase the floristic diversity of freshwater wetlands (Wheeler and Shaw, 1995; Vivian-Smith, 1997); or (3) may help to increase water storage or function in lieu of the acrotelm in peatlands (Heathwaite et al., 1993). The effect of surface preparations and reprofiling on microclimate, soil moisture and plant diversity in cutover peatlands is poorly understood. Bugnon et al. (1997) found that reprofiling of vacuum harvested peat fields to reverse the surface convexity between ditches, decreased the average depth to the water table by 0.2 m and increased the average volumetric soil moisture content by 7%, between May and September. Smaller scale modifications, such as ploughing and harrowing, have little mention in peat literature. In the case of harrowing, breaking the soil capillary connection can be expected to result in drying of the surface. This is supported by O'Kane (1992), who modeled evaporation from harrowed peat and demonstrated that the initially high evaporation rate drops quickly, as the surface layers dry. In a peatland restoration study, Salonen and Laaksonen (1994) observed a positive effect of tillage of bare peat on vascular plant seedling establishment.

It is apparent, that in peat soils the energy balance and moisture characteristics, as influenced by mulches and surface microtopography, are poorly understood. The objective of this study is to determine the role of a straw mulch, in combination with various surface preparations, on the energy balance and soil water in peat soils and on the establishment of *Sphagnum* mosses. Specifically, the objectives are:

1. to evaluate the energy and moisture regime of peat soil under a mulch cover;
2. to evaluate the energy and moisture regime of peat soil after surface preparation, including ploughing, harrowing and trenching of peat soils, with and without mulch cover; and

3. to determine if mulch or surface preparations enhance the re-establishment of *Sphagnum* carpet.

2. Study area

The study area (Fig. 1) is in the Lac-Saint-Jean area of Quebec, Canada (48°47′ N; 72°10′ W). The average annual temperature is 1.7°C, with average January and July temperatures of −17.1 and 17.3°C, respectively (Environment Canada, 1982). Mean annual total precipitation is 906 mm (32% falling as snow). Mean annual runoff in the nearby Mistassini River, which is indicative of the difference between precipitation and evaporation, is 623 mm (Environment Canada, 1992).

The peatland is located over a terrace of deltaic sands in the Lac-Saint-Jean lowland (Morin, 1981) and is part of a 4315 ha bog-poor fen complex which has been classified as Plateau Bog (National Wetland Working Group, 1987). The peat deposit has developed over permeable sands because the presence of a well developed iron pan limits seepage losses (Price, 1996). Residual peat thickness ranges from 1.2 to 1.8 m and has suffered oxidation and compression due to drainage and mining activities. This study examined a cutover portion of the peatland. Drainage operations began in 1990. The upper 0.35–0.6 m was removed by block-cutting with heavy machinery in 1991, then the ditches were blocked with peat dams in the fall of 1992. The cutover surface is generally flat.

3. Methods

3.1. Experimental design

The experiment compares various hydrological and microclimatic variables and *Sphagnum* recovery data on four microtopographic surface types on a cutover peat surface, both with and without a straw mulch cover. The experiment was designed as a split-plot experiment in a completely randomized block design (Fig. 1). Three blocks of four main experimental units (15 × 30 m) were delimited in the field. Four microtopographic treatments were randomized to the mainplot units of each block. These include surfaces that were: (i) untreated; (ii) harrowed; (iii) ploughed; and (iv) rendered into shallow track-and-ridge microtopography made by the tracks of a bulldozer (≈1 m wide and trenches 0.2 m deep and ≈1 m apart). Each main plot unit was further divided into two subplots (15 × 15 m), one of which was covered with a straw mulch at a rate of 2250 kg ha^{-1} and the other left bare, treatments that were also assigned randomly. The untreated plots are referred to as control (bare) and control (mulch), respectively.

3.2. Hydrological and microclimatic variables

The intensive hydrological and microclimatic measurements were made between

May and September, 1995. Rainfall data were also collected in 1996. Meteorological data were collected both at the experimental site and at a meteorological station 200 m away (control (bare)). A comparison of the energy balance, soil moisture and soil water tension was made between the control (bare) and control (mulch) sites (control (mulch) is the untreated peat covered by mulch). A comparison of the soil temperatures and moisture was also made between all combinations of sites, including control (bare), control (mulch), harrowed, plough ridges and furrows and track hollows and ridges.

Rain was measured with a tipping bucket rain gauge 0.5 m above the surface at the meteorological station and experimental site. In 1996, straw mulch was laid across the screen of a tipping bucket rain gauge to determine interception. Daily evapotranspiration was estimated with the combination model of Priestley and Taylor (1972), where

$$E = \alpha \frac{(s/(s+q))(Q^* - Q_{\mathrm{G}})}{L\rho} \tag{1}$$

where E is the evapotranspiration rate (mm d^{-1}), L is the latent heat of vaporization (J kg^{-1}), ρ is the density of water (kg m^{-3}), s is the slope of the saturation vapour pressure–temperature curve (Pa °C^{-1}), q is the psychometric constant (0.0662 kPa °C^{-1} at 20°C), Q^* is the net radiation flux (J d^{-1}) and Q_{G} is the ground heat flux (J d^{-1}). When $\alpha = 1$, Eq. (1) represents equilibrium evaporation,
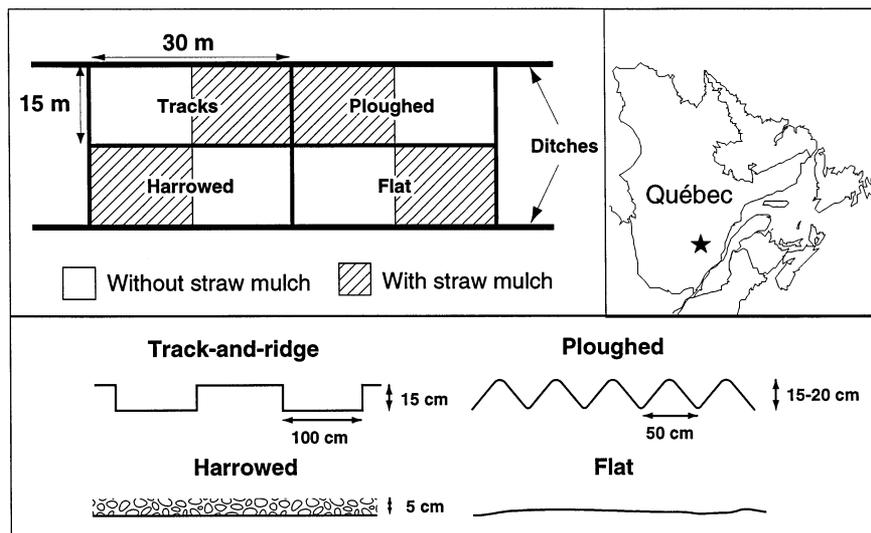

Fig. 1. Study area and experimental design of one block. Treatments at the main and subplot levels were assigned randomly in the field.

which is the condition when there is no vapour pressure deficit in the near surface atmosphere. The ratio of actual and equilibrium evapotranspiration provides an empirical coefficient (α) which can be used in Eq. (1) to estimate evapotranspiration when direct measurements are unavailable and when net radiation, ground heat flux and air temperature are available. The coefficient α was determined from Bowen ratio–energy balance measurements at this site in 1993 (Price, 1996). The average ($\pm$ S.D.) α for the site between 06:30 and 18:00 h was 1.25 ± 0.16. Net radiation was recorded with a radiometer 3.0 m over the bare peat surface and 1.0 m over the straw mulch surface. The ground heat flux was measured with two soil heat flux plates at each site, 0.5 cm below the peat surface. The air temperature was measured with a shielded thermistor at 0.01 and 1.0 m above the peat surface, at the bare and mulch control sites. Heat storage (S) in the mulch layer was calculated as

$$S = \frac{dT}{dt} C_m z \tag{2}$$

where dT/dt is the change in temperature over time in the mulch layer, C_m is the heat capacity of the mulch layer and z is its thickness (5 cm). C_m was determined as $0.9\, C_{air} + 0.1\, C_{veg}$, where C_{air} and C_{veg} are the heat capacity of air and vegetation. The heat capacity of vegetation is ≈ 0.7 that of water (Miller 1981). The coefficients 0.9 and 0.1 represent the minimum expected distribution of air-filled porosity in the mulch layer, which according to Hares and Novak (1992) is > 0.9.

Relative humidity was measured with a hand-held Vaisala™ temperature–humidity probe at a height of ≈ 0.01 m in both bare and mulch sites, on ten different occasions over the 1995 season. On each site, ten measurements were made on each measurement date. Soil temperature was measured continuously in 1995, at depths of 0.5 and 5 cm beneath the surface at all experimental microtopographic sites. Water level was measured daily using wells which were constructed of 50 mm ABS, slotted along their entire length, each located about 10 m from the nearest (blocked) ditch, at both the control (bare) and control (mulch) experimental sites.

Soil moisture and bulk density were determined gravimetrically on samples retrieved with a cutter which sampled the upper 3 cm of soil. Three samples were taken daily at all sites and returned to the laboratory for analysis. Matric tension was also measured at both sites. Tension was measured at -1, -3 and -7 cm with a 1 cm o.d. porous ceramic cup inserted horizontally into a pit wall, connected to a partially water filled L-shaped tube protruding above the peat surface. The pit was backfilled with peat. Pressure was measured with a Tensimeter™ pressure transducer, accurate to 1 mb and adjusted to account for the height of the water column above the ceramic cup. Values herein are expressed in cm of water (l cm = mb).

3.3. Sphagnum reintroduction and performance

Before applying the mulch on the surface preparation treatments, a mixture of *Sphagnum* fragments (diaspores) was spread on the bare peat surface. The *Sphag-*

num material was collected from two zones: a *S. fuscum* dominated zone and a *S. angustifolium* zone. Voucher specimens from the collection sites are deposited at QFA (collection numbers 1012 and 1013). The *Sphagnum* material was collected mechanically with the aid of a rototiller, shredding the top surface (5–10 cm) of the moss layer. This operation was done early in the spring so that the ground frost could support the heavy machinery while protecting the below-ground structure of the remaining plants, hence favouring a rapid recovery of the site (Rochefort et al., 1997). The shredded bog plant material was packaged in plastic bags, then transported to the experimental site. The *Sphagnum* diaspores were spread by hand in early May on the experimental plots, each plot receiving a mix of one-third of *S. angustifolium* dominated material and two-thirds of *S. fuscum* dominated material. The material was spread at a density of 1:15 surface collected:surface covered density ratio (i.e. 1 m^2 collected from the natural areas was used to seed 15 m^2 of bare peat surface). Because of the limited amount of material available and the time-consuming task involved with manually spreading diaspores—machinery would destroy the microtopography—diaspores were only applied to one-third of the surface of the subplots without straw mulch and to two-thirds of the surface of plots with mulch. Less material was spread on subplots without straw mulch, as we know from previous experimental trials that few *Sphagnum* mosses will survive (Quinty and Rochefort, 1997; Rochefort et al., 1997). Accordingly, vegetation data reported here refer only to areas that were seeded with *Sphagnum*.

At the end of September of 1995 and 1996 and in June 1996, vegetation re-establishment was assessed by estimating the percent cover of *Sphagnum* mosses, other mosses, herbaceous plants and ericaceous shrubs from a series of 25×25 cm quadrats (36–72) that were systematically located along transects within each subplot, for a density of 1 quadrat per 2 m^2 in areas of introduced plant material. As the 1995 hydrological and microclimatic data suggested that important differences in microconditions may exist between the shallow tracks and ridges, the sampling was adjusted to evaluate the micro relief impact on *Sphagnum* re-establishment there. Therefore, for each quadrat located in the track-and-ridge plots, we recorded its position as being part of the track or of the ridge (so more or less, half of the quadrats fell into each of the categories).

3.4. Statistical analysis of vegetation data

For the general experiment, data were analysed using a split-plot ANOVA with repeated measures in a completely randomized block design. The percent cover data noted in fall 1995 were not included in the analysis as to many quadrats had zero percentages rendering the variance quite heterogeneous. Mainplots are the four levels of the topography factor (harrowed, ploughed, track-and-ridge and untreated (control)) and the subplots are the presence or absence of mulch. Data were transformed using the rank procedure because they did not pass Leveneis test for homogeneity of group variance. All analyses were performed with SAS software systems (SAS Institute, Cary, NC).
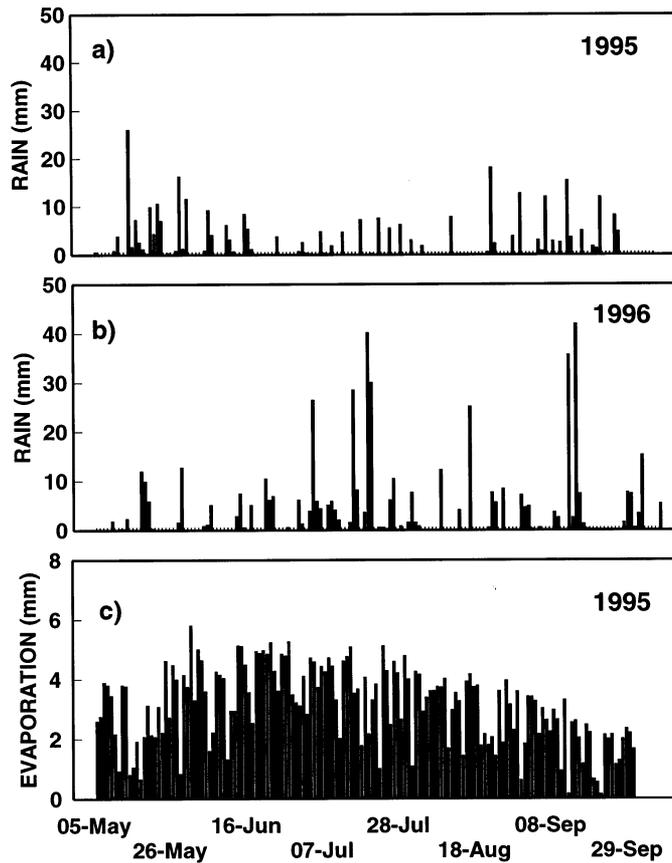
Fig. 2. Precipitation in 1995 (top), 1996 (middle) and evaporation from the bare peat surface in 1995 (bottom).

4. Results and discussion

4.1. Hydrology and microclimate

The relatively warm and dry summer of 1995 provided severe conditions to test the effectiveness of straw mulch and surface microtopography on *Sphagnum* recolonization. Monthly temperature and total precipitation at nearby Peribonca, for May–September, 1995 deviated from the long term normals (1951–1980) by $+0.7$, $+1.3$, $+2.7$, $+3.3$ and $-0.3°C$ and $+36.5$, -46.0, -56.7, -47.6 and -23.2 mm, respectively (Environment Canada, 1982). The 1996 season was notably wetter than 1995 (Fig. 2), providing conditions more amenable to re-establishing *Sphagnum*. In 1996 the corresponding values were $+0.4$, $+1.2$, $+0.2$, $+1.2$ and $+2.3°C$ and -13.3, -11.8, $+79.9$, -7.0 and $+13.2$ mm of rain, respectively (Sommaire Climatologique du Quebec, 1995. Unpublished data from

May to September 1995 for Peribonca, Quebec, Ministre de l'Environment, Direction des reseaux atmospheriques, Quebec City, Que.).

4.2. Energy and moisture regime under a mulch cover

In 1995 the effect of the mulch on interception of precipitation was not considered. However, we realized that this was potentially important, so measurements were made between July 5 and October 7, 1996 at the experimental plots. During this period, interception represented 44% of the total precipitation. The clustering of points (Fig. 3) representing small rainstorms indicates that the relative importance of interception was greater during small events (i.e. points fall below 1:1 line). Low intensity rainfalls account for the series of rain events where the effective rainfall below the mulch (i.e. y-axis values) was zero. The dashed line in Fig. 3 is an envelope curve for mid-to-higher interception events and represents a difference of ≈ 2 mm (i.e. interception loss is ≤ 2 mm). This compares to 2.8 mm, for example, intercepted on a sugar cane mulch (Bussière and Cellier, 1993). Thus interception by mulch decreased the water supply to the soil. However, because mulch application is non-uniform, the spatial variability of interception at this site is unknown.

Mulch changed the surface energy balance (Fig. 4). Both net radiation and the soil heat flux were greater over bare peat. Visual observations suggest the mulch had a significantly higher albedo than the bare peat surface, resulting in less incident shortwave energy. This may have been partly offset by lower daytime longwave emittance from the mulch, since the temperature within the straw was lower than over bare peat ($T_{\text{air (0.01 m)}}$ in Table 1). The energy flux to the soil under
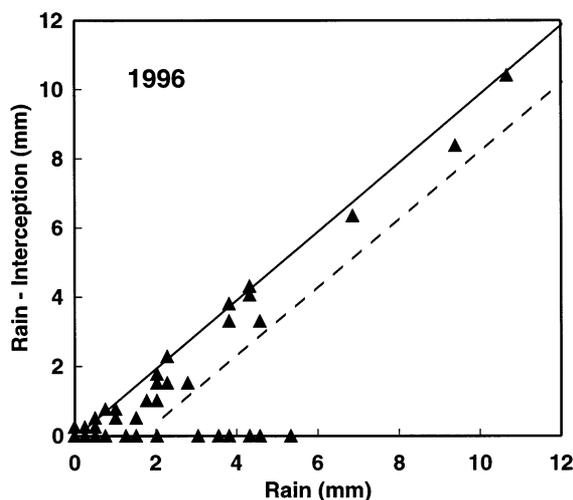

Fig. 3. Effects of interception by the mulch compared to rainfall over bare peat. The y-axis represents the effective rainfall penetrating the mulch layer.
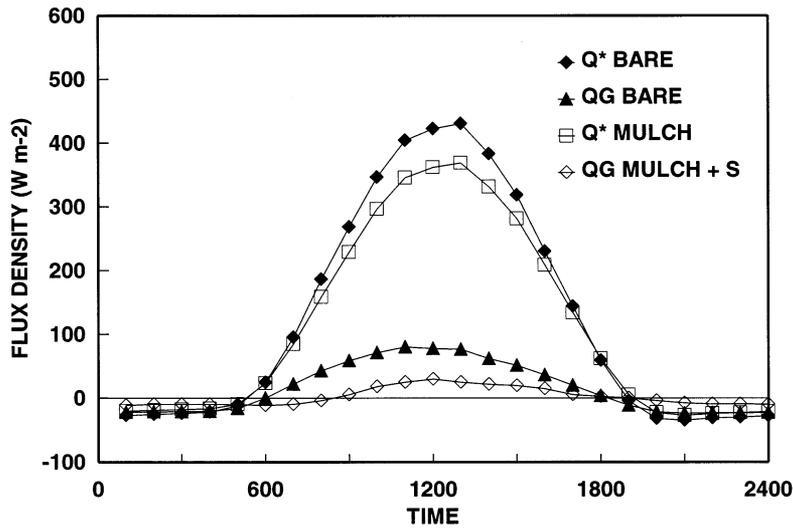
Fig. 4. The surface energy balance over a bare peat and mulch covered peat surface, including net radiation (Q^*), soil heat flux (Q_G) and heat storage in the mulch layer (S).

the mulch (Q_G) was also much less, only 13% of the seasonal flux into the bare peat (Table 2). Energy storage (S), however, represented a relatively small component of the budget, since the mass of straw was small. While the net daily and seasonal changes in heat storage were negligible, it represented an average of 4% of the noon soil heat flux in the mulch site. Therefore, the available energy at the mulch site ($Q^* - Q_G - S$), was only slightly affected by the heat storage in the mulch layer. During days of low to moderate energy fluxes, there appears to be slightly more

Table 1

Mean ($\bar{X}$) and S.D. (s) of net radiation (Q^*) and soil heat flux (Q_G) (W m^{-2}), air temperature (T_{air}) and ground temperature (T_g)

Time	$\bar{X}_{05:00}$		$s_{05:00}$		$\bar{X}_{12:00}$		$s_{12:00}$	
Location	Bare	Straw	Bare	Straw	Bare	Straw	Bare	Straw
Q^*	−12.0	−16.1	16.0	11.8	422.6	361.8	166.4	143.0
Q_G	−16.1	−10.2	12.1	11.3	77.9	28.5	54.2	38.0
Q_G harrowed	—	−22.1	—	17.3	—	75.2	—	42.1
T_{air} +0.01 m	8.2	9.8	5.9	5.1	23.6	23.3	7.5	6.1
T_g control (bare)	8.8	10.6	5.4	4.6	28.3	21.4	10.1	5.7
T_g harrowed	8.7	10.4	5.4	4.8	26.1	23.4	8.9	6.0
T_g ploughed-ridge	8.1	8.4	5.9	5.8	29.9	25.8	10.0	7.9
T_g ploughed-furrow	9.7	9.1	4.7	5.1	25.5	25.7	8.3	9.1
T_g track-ridge	9.2	10.0	5.4	5.0	28.0	24.0	8.5	9.6
T_g track-hollow	8.9	10.4	5.4	4.7	26.1	24.9	7.7	6.7

At locations stated (°C) from June 3 to October 13 1995, at 05:00 and 12:00 h.

Table 2
Net radiation (Q^*), soil heat flux (Q_G), heat storage in the mulch (S), latent heat flux (Q_E) (W m^{-2}) and evaporation (E) in mm from June 3 to October 13, 1995

	Q^*	Q_G	s	$Q^* - Q_G - s$	Q_E	E
Control	128.2	16.4	0	111.8	88.3	3.1
Mulch	112.0	2.2	−0.07	109.9	74.2	2.6

energy available over the bare peat surface (Fig. 5a). On days with greater energy fluxes, the available energy over the bare peat was slightly less than over the mulch covered surface. This is because the soil heat flux becomes strongly coupled to net radiation at higher flux densities (Fig. 5b) and proportionally more heat is lost to the soil. In contrast, the soil heat flux below the mulch appears to be completely decoupled from net radiation (Fig. 5c).

In general, the mulch kept the air above the cutover peat surface (0.01 m) warmer than the bare peat at night (9.8 vs 8.2°C, respectively) and a little cooler during the day (23.6 vs 23.3°C, respectively) (Table 1). The seasonal average daytime temperature difference shown in Table 1 does not fairly represent the temperature differences during the summer, since in September the trend reversed and daytime temperatures were warmer under the mulch. The actual noon-time temperature was as much as 9.2°C higher over the bare peat.

Evaporation was controlled by the available energy for the sensible and latent heat flux and air and soil temperature. The amount of evaporation from the bare peat surface was estimated (Fig. 2) using the Priestley and Taylor (1972) combination model Eq. (1). Evaporation from the unprotected cutover surface averaged 3.1 mm d^{-1} between May 6 and October 1, 1995 (Table 2) and ranged from 0.1 to 5.8 mm d^{-1}. Evaporation cannot be estimated from the mulch covered surface in the same way, without *a priori* knowledge of the α parameter Eq. (1). Evaporation from the mulch surface was estimated on the basis of a relationship derived from data by Hares and Novak (1992), which suggests the mulch application rate used here (2250 kg ha^{-1}) limited evaporation to 84% of the bare surface (non-soil limited) evaporation. Thus the evaporation from the mulch was estimated at 2.6 mm d^{-1}. The consequence of greater water loss from the bare peat site was lower soil moisture content. The seasonal trend indicates soil moisture at the surface was distinctly higher under the mulch than in the bare peat and the difference increased over the summer (Fig. 6a). Values early in May (data obscured in Fig. 6 by the moving average), were similar at both sites, but quickly registered a difference as evaporation increased.

The lower evaporation rate from the mulch covered surface is attributable to poor atmospheric mixing within the mulch (Hares and Novak, 1992). This is evident here by the relative humidity beneath the straw, which at noon was 10–15% higher than above the bare peat during drier periods (Fig. 7a). Not only does this reflect and explain the lower evaporation from the mulch surface, it has positive implications for the *Sphagnum* diaspores it is supposed to be protecting. It should
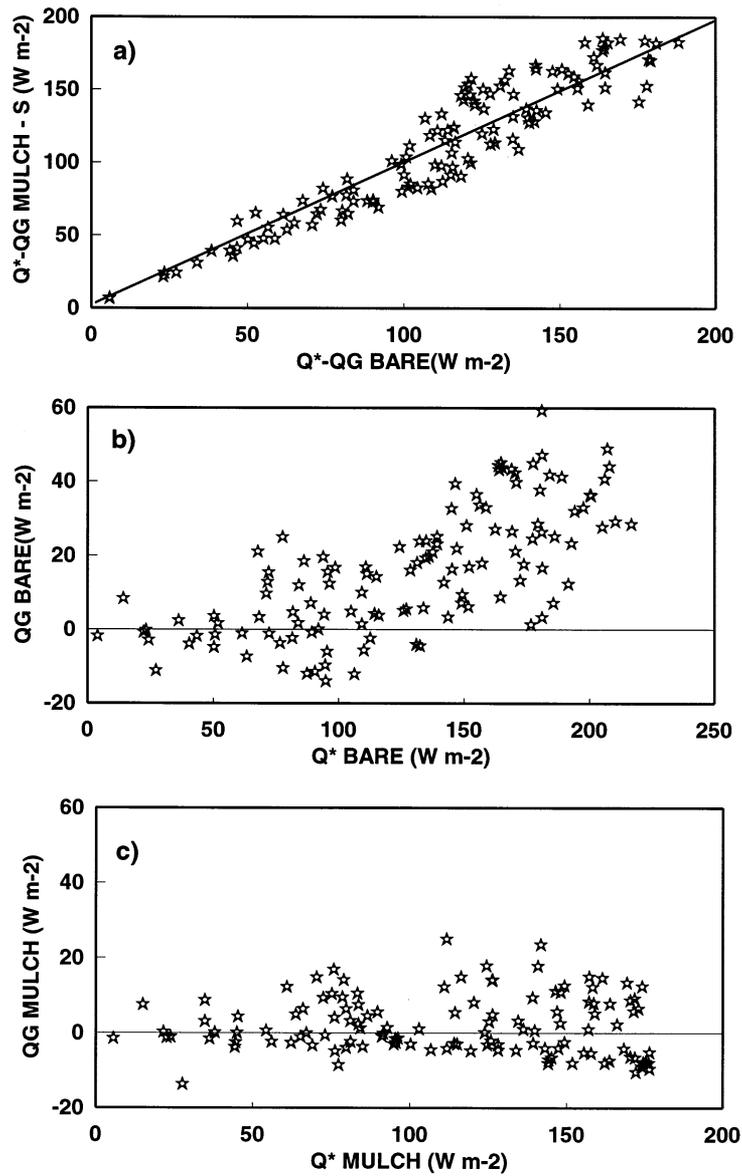
Fig. 5. (a) Average daily available energy over bare peat ($Q^* - Q_G$) and over mulch ($Q^* - Q_G - S$), (b) and (c) average daily net radiation vs soil heat flux at the control (bare) and mulch covered sites, respectively. Note the relationship between Q^* and Q_G at the control (bare) site is only evident at higher flux densities. At the mulch site there is no relationship. The r^2 for (a), (b) and (c) are 0.89, 0.50 and 0, respectively.
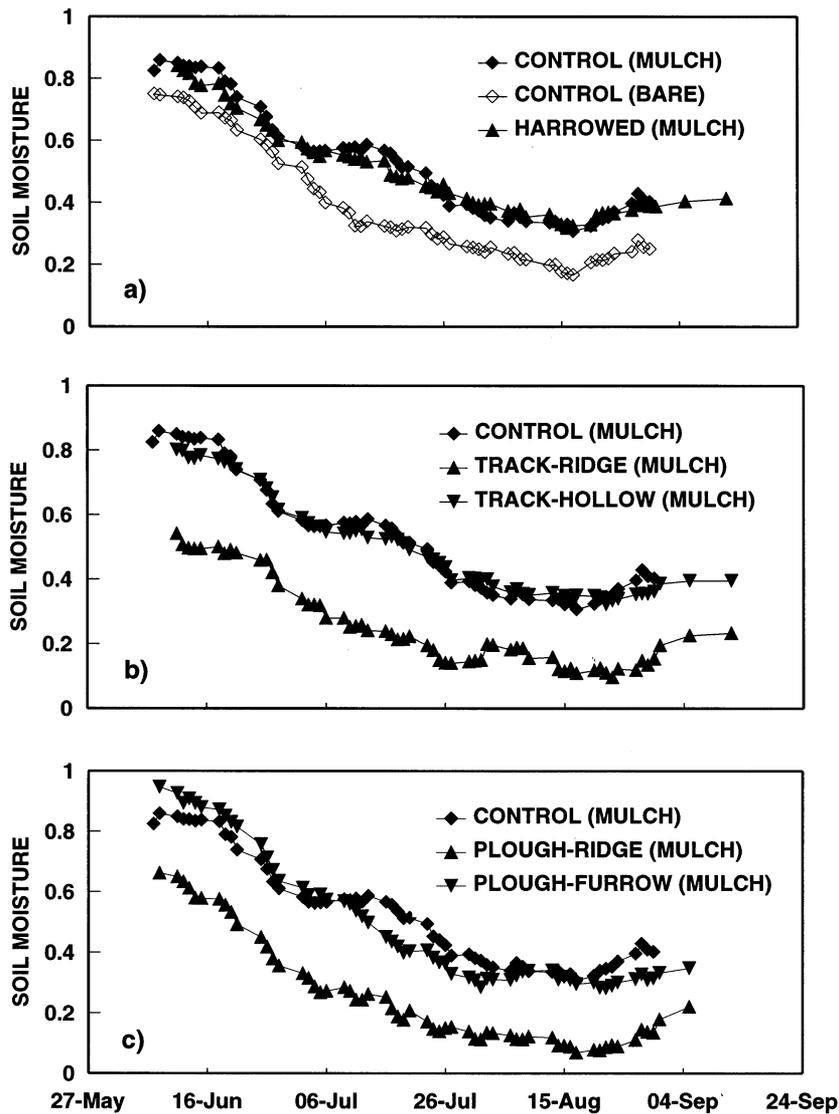
Fig. 6. Seven-day moving average of volumetric soil moisture at mulch covered locations and at the control (bare) sites.

be noted, that evaporation from the mulch included water that was intercepted. This is significant because it essentially cancelled the negative influence of the interception loss on the soil water deficit. Water evaporated from the mulch used energy that would otherwise have been used to evaporate water from the peat surface. Consequently, the water table position, soil moisture condition and soil water tension were lower at the bare peat site (Fig. 7b–d). It can be seen that the

water table remained below the 40 cm level identified as important by Schouwe-naars (1988), for 60 and 40% of the season, in the bare and mulched sites, respectively. In spite of the relatively low water table position, soil moisture and soil water pressure were sustained at higher levels in the presence of mulch. Note also that water tension near the peat surface under the mulch was above −100 cm,
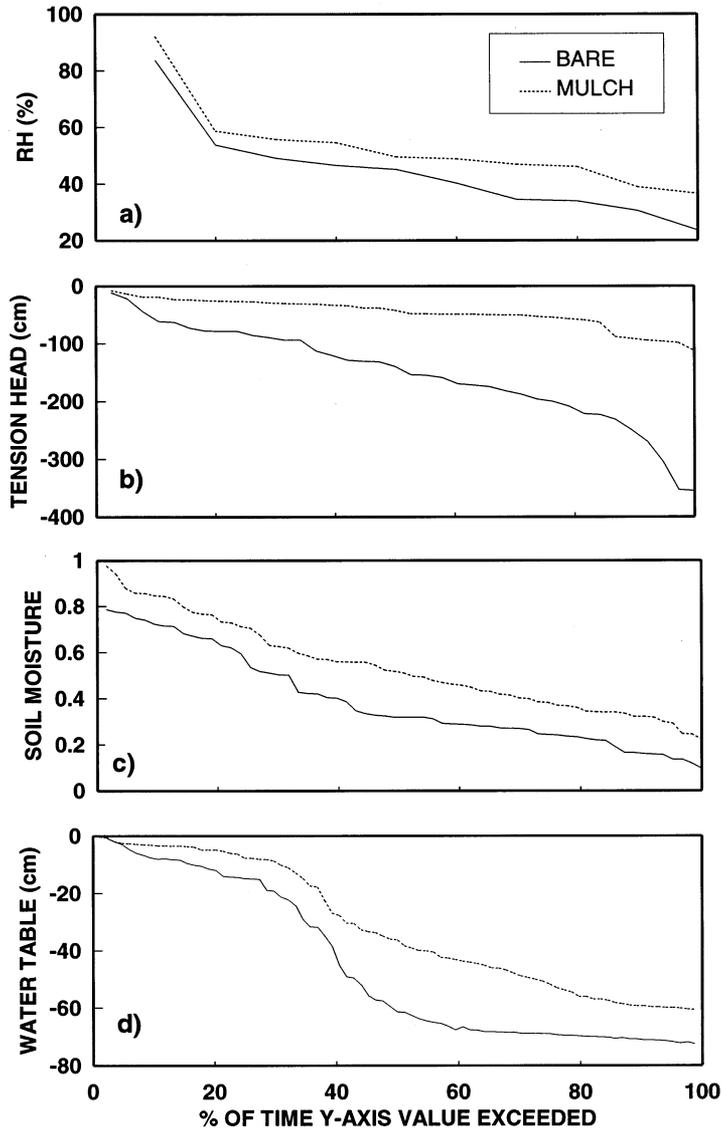

Fig. 7. Duration curves for (a) relative humidity, (b) water table depth below the surface, (c) volumetric soil moisture and (d) soil water tension. Data are from 4 June to 27 September, 1995.

below which, capillary draw into the water holding hyaline cells of *Sphagnum* plants cannot occur (Hayward and Clymo, 1982).

4.3. Energy and moisture regime of peat soil with surface microtopography

Energy balance measurements are unavailable at the scale of the microtopographic surfaces created for this study. However, inferences can be made by examining the soil temperature at each location. As described previously, the mulch kept the air immediately above the soil slightly cooler during the day and warmer at night. A similar situation occurred with the soil temperature (at -5 mm) at each of the various microtopographic surfaces (Table 1). This was exacerbated in the positive relief elements of the ploughed and track-and-ridge microtopography. At these locations, lower soil moisture (see below) reduced the heat capacity of the soil, resulting in higher soil temperatures. The mulch tended to minimize temperature variations, as indicated by the lower S.D. (Table 1).

Bare peat soil moisture at all microtopographic positions was significantly lower than similar sites covered with mulch. Only the data from the mulch covered microtopographic surfaces are shown in Fig. 6, except for the control (bare) site. Soil moisture at the harrowed site and in negative relief elements were similar, or slightly lower than at the control (mulch) site. Positive relief elements (ploughed ridges and ridges between tracks) were sometimes at a soil moisture more than 20% lower than the negative elements or the control (mulch) site. From a soil moisture standpoint, conditions were significantly poorer in raised microtopographic surfaces and in none of the treatments were better than on the untreated cutover peat surface simply covered with mulch.

5. *Sphagnum* colonization

5.1. Plant material recovery

The rapid success of bog plant colonization is now known to be dependent on the climatic conditions prevailing in the first 2–3 months of reintroduction (Rochefort et al., 1997; Rochefort and Bastien, 1998). The spring and summer of 1995 was relatively dry and the plant material reintroduced for this experiment did not establish readily ($<1\%$ in cover), whereas in a wetter season (such as 1996) *Sphagnum* cover reached 5–7% after only one growing season (Ferland and Rochefort, 1997). As the plant cover for other mosses and vascular plants were still $<1.5\%$ after two growing seasons, the results concerning these two groups of plants will be not be discussed further.

5.2. Straw mulch

The *Sphagnum* recovery data presented in Fig. 8 show the favorable effect of using a straw mulch to protect the *Sphagnum* diaspores during the establishing
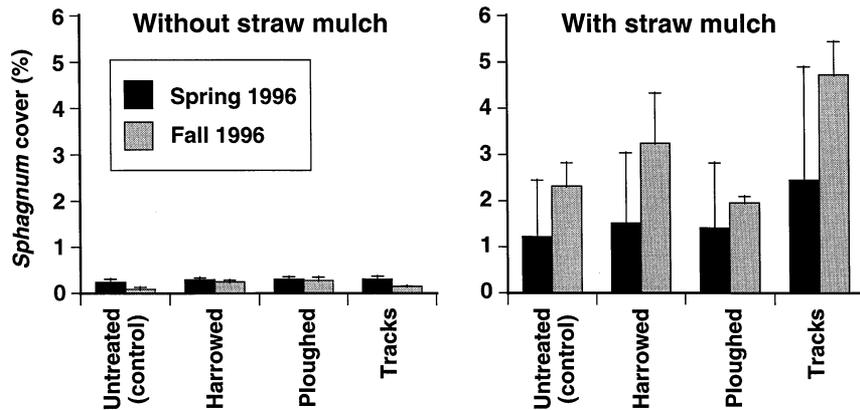
Fig. 8. *Sphagnum* establishment on bare and mulch plots for each microtopography treatments. ANOVAs for repeated measures: topography ($F_{3,6} = 1.93$, $P = 0.23$), mulch ($F_{1,8} = 130.7$, $P < 0.0001$), interaction ($F_{3,8} = 2.44$, $P = 0.14$).

phase (Quinty and Rochefort, 1997; Rochefort et al., 1997). Wheeler and Shaw (1995) advocated the use of a surface mulch or artificial stabilants in peatland restoration as a surrogate for the loss of a *Sphagnum* carpet, which was reported to reduce evapotranspiration losses by forming a mulch in its upper layers (Ingram, 1983). However, Wheeler and Shaw (1995) cautioned that the use of mulch was untested. This study shows that the presence of the mulch indeed reduced evaporation from the covered peat surface and improved the moisture and hydrological conditions of the peat substrate for the establishment of *Sphagnum* mosses. Hence, it is with greater confidence that the use of a surface mulch can be recommended as a technique to facilitate *Sphagnum* establishment over the cutover peat surface.

5.3. Microtopography

Wetness is of utmost importance for *Sphagnum* diaspore survival (Sagot and Rochefort, 1996). The surface preparations tested in this experiment were aimed at creating wetter and sheltered microsites to ensure better establishment of *Sphagnum* mosses. As the soil moisture conditions of the different surface preparations were more or less similar (Fig. 6), the different types of artificial microtopography did not improve overall *Sphagnum* colonization success ($P > 0.23$; Fig. 8). Therefore, the idea of simulating the pattern of hummocks and hollows of undisturbed bogs as a restoration technique (Heathwaite et al., 1993) did not improve colonization by *Sphagnum* mosses, at least for the microtopography created in this experiment (Fig. 1). For the direct goal of restoring an accumulating peat moss layer, the creation of microtopography appears to be an unnecessary action, although the creation of microsites might prove advantageous with respect to increasing the floristic diversity of the newly restored habitat (Harper et al., 1965; Vivian-Smith 1997), an aspect not measured in this study. It is noted, however, that on small-scale scrapes
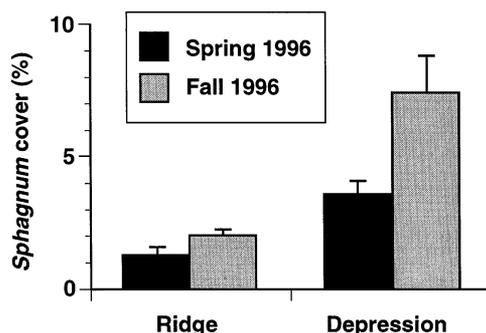
Fig. 9. Average percentage cover of *Sphagnum* for different microhabitats within the treatment track-and-ridge microtopography, in the presence of a straw mulch. Mean ± S.E. ANOVAs for repeated measures: block ($F_{2,2} = 0.76$), microhabitat ($F_{1,2} = 112.52$, $P = 0.0.0088$), error ($F = 0.17$).

created on a cutover peatland in Westhay Moor, UK (Wheeler and Shaw, 1995), where *Molinia* and birch had already established, *Sphagnum* colonization did occur.

5.4. Track-and-ridge

Heretofore, comparisons between the different surface preparations were done by averaging the sampling data of the depressions and ridges within the track-and-ridge experimental units. Analyzing the data by making a distinction between these two microhabitats for the track-and-ridge treatment covered with the mulch, it becomes evident that the *Sphagnum* diaspores had a greater success of colonization in the depressions (tracks) than on the ridges (Fig. 9). Ferland and Rochefort (1997) suggested remodelling abandoned flat surfaces into a series of narrow ridges (≈ 50 cm wide) and larger tracks or small trenches (1–5 m) to create a more advantageous ratio of sheltered and wetter microhabitat to promote *Sphagnum* establishment.

6. Conclusions

Straw mulch caused considerable rainfall interception, which approached 2 mm per event. This represented 44% of the rain over the measurement period. The importance of this was minimized, however, since water evaporated from the mulch used energy that would otherwise have been used to evaporate soil water.

Heat storage in the mulch was minor. The soil heat flux below the mulch was only 13% of the bare soil value and was decoupled from the daily net radiation. Net radiation over the bare soil was 15% greater than over the mulch. However, because of the greater heat flux into the bare peat, the energy available for turbulent fluxes was similar at both sites. Since the mulch dried more readily that the underlying peat, it can be concluded that sensible heat dominated more often than over the bare soil site (McDonald and Helgerson (1990) noted this, but there

is no data here to confirm it). Consequently, evaporation from the mulch covered soil was less than from the bare soil— ≈ 2.6 mm d^{-1} compared to bare soil evaporation of 3.1 mm d^{-1}.

The increased resistance to vapour transfer (upwards) and heat penetration (downwards) through the mulch, resulted in a cooler, wetter soil. In turn, this reduced the soil water tension. Tension was sustained below -100 cm all season (i.e. smaller negative values) when a mulch was used, compared to only 30% of the time in the bare soil. Correspondingly, the water table was sustained above the 40 cm depth, 60% of time in the mulch covered site, compared to only 40% of the time in the bare peat site.

The creation of microtopography by various surface preparation techniques cause localized amelioration of the soil moisture and temperature. Negative relief elements were wetter and cooler than positive relief elements. However, when under a mulch, the negative relief elements provided no additional benefit, in terms of temperature or soil moisture amelioration. The control site with a mulch cover was equivalent or better than negative relief elements with a mulch cover. Taking into account the poorer performance of positive relief elements, even when mulch covered, the creation of surface microtopography reduced the overall moisture content of the site.

Sphagnum colonization data reflect hydro-climatic conditions observed for the treatments. Establishment of a moss carpet was enhanced by the presence of a straw mulch, which reduced soil water tension and soil temperature and increased soil moisture. *Sphagnum* species typically compose much of the moss carpet and they depend essentially on water availability for their survival and growth. As shown by these interactions, they are very sensitive to desiccation (Sagot and Rochefort, 1996).

All microtopography types tested had no effect on the establishment of the three types of plants. Although being in a depression helped *Sphagnum* establishment, this positive effect was limited to the trenches (compared to the ridges) and did not result in a better establishment of *Sphagnum* over the entire track-and-ridge plot experiments.

References

Bradshaw, A.D., 1995. Alternative endpoints for reclamation. In: Cairns, J. (Ed.), Rehabilitating Damaged Ecosystems. CRC Press, Boca Raton, FL, pp. 165–186.

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

Bussière, F., Cellier, P., 1993. Interception de la pluie par un mulch de feuilles de canne a sucre *(Saccacharum officinarum):* Utilisation d'un dispositif de mesure automatique pour le test d'un modèle. Agronomie 13, 35–43.

Campeau, S., Rochefort, L., 1996. *Sphagnum* regeneration on bare peat surfaces: Field and greenhouse results. J. Appl. Ecol. 33 (3), 599–608.

Eggelsmann, R.F., 1988. Rewetting for protection and renaturation/regeneration of peatland after or without peat winning. Proceedings of the Eighth International Peat Congress, Lenningrad 3, 251–260.

Environment Canada, 1982. Canadian Climatic Normals 1951–1980: Temperature and Precipitation, Quebec. Atmospheric Environment Service, Downsview, Ontario.

Environment Canada, 1992. Historical Streamflow Summary, Quebec. Water Survey of Canada, Ottawa, Ontario.

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

Hares, M.A., Novak, M.D., 1992. Simulation of surface energy balance and soil temperature under strip tillage: II. Field test. Soil Sci. Soc. Am. J. 56, 29–36.

Harper, J.L., Williams, J.T., Sagar, G.R., 1965. The behaviour of seeds in the soil. I. The heterogeneity of soil surfaces and its role in determining the establishment of plants from seed. J. Ecol. 53, 273–286.

Hayward, P.M., Clymo, R.S., 1982. Profiles of water content and pore size in *Sphagnum* and peat and their relation to peat bog ecology. Proc. Roy. Soc. Lond. B. 215, 299–325.

Heathwaite, A.L., Eggelsmann, R., Gottlich, Kh., 1993. Ecohydrology, mire drainage and mire conservation. In: Heathwaite, A.L., Gottlich, Kh. (Eds.), Mires: Process, Exploitation and Conservation. Wiley, Chichester, pp. 417–484.

Ingram, H.A.P., 1983. Hydrology. In: Gore, A.J.P. (Ed.), Ecosystems of the World 4A–Mires: Swamp, Bog, Fen and Moor. Elsevier, Amsterdam, pp. 67–159.

Lapalainen, E. (Ed.), 1996. Global Peat Resources. International Peat Society, Jyska, Finland.

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

McDonald, P.M., Helgerson, O.T., 1990. Mulches aid in regenerating California and Oregon forests: Past present and future. Gen. Tech. Rep. PSW-123, Berkley, CA, Pacific Southwest Research Station, Forest Service, USDA.

Miller, D.H., 1981. Energy at the Surface of the Earth: An Introduction to the Energetics of Ecosystems. Academic Press, New York.

Morin, G. 1981. Atlas Règional du Saguenay-Lac-Saint-Jean. Les Laboratoires de Gèographie de l'Universitè du Quebec Chicoutimi, Chicoutimi, Quebec.

National Wetland Working Group 1987. The Canadian Wetland Classification System. Ecological Land Classification Series, Inland Waters/Land Directorate, Environment Canada, Ottawa, Ontario.

O'Kane, J.P., 1992. The hydrology of milled peat production. In: O'Kane, J.P. (Ed.), Advances in Theoretical Hydrology, European Geophysical Society Series in Hydrological Science 1, pp. 27–46.

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

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

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Mon. Weather Rev. 100, 81–92.

Quinty, F., Rochefort, L., 1997. Plant re-introduction on a harvested peat bog. In: Trettin, C.C., Jurgensen, M.F., Grigal, D.F., Gale, M.R., Jeglum, J.K. (Eds.), Northern Forested Wetlands: Ecology and Management. CRC Press, Boca Raton, FL, pp. 133–145.

Rochefort, L., Bastien, D.F., 1998. Rèintroduction de phaignes dans une tourbiËre exploitèe et abandonnèe: Èvaluation de divers moyens de protection contre la dessication. Ecoscience 5, 117–127.

Rochefort, L., Quinty, F., Campeau, S., 1997. Restoration of peatland vegetation: the case of damaged or completely removed acrotelm. Int. Peat J. 7, 20–28.

Sagot, C., Rochefort, L., 1996. Tolerance des sphaignes ‡ la dessiccation. Cryptogamie Bryol. Lichenol. 17, 171–183.

Salonen, V., 1987. Relationship between the seed-rain and the establishment of vegetation in 2 areas abandoned after peat harvesting. Holarctic Ecol. 10, 171–174.

Salonen, V., Laaksonen, M., 1994. Effects of fertilization, liming, watering and tillage on plant colonization of bare peat surfaces. Ann. Bot. Fennici 31, 29–36.

Schouwenaars, J.M., 1988. Hydrological research in disturbed bogs and its role in decisions on water management in the Netherlands. Proceedings of the International Symposium on the Hydrology of Wetlands in Temperate and Cold Regions. Joensuu, Finland, 6–8 June 1988, pp. 170–177.

Schouwenaars, J.M., 1993. Hydrological differences between bogs and bog-relicts and consequences for bog restoration. Hydrobiologia 265, 217–224.

Vivian-Smith, G., 1997. Microtopographic heterogeneity and floristic diversity in experimental wetland communities. J. Ecol. 85, 71–82.

Wheeler, B.D., Shaw, S.C., 1995. Restoration of Damaged Peatlands. HMSO, London.