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EFFECT OF PEATLAND DRAINAGE, HARVESTING, AND RESTORATION ON ATMOSPHERIC WATER AND CARBON EXCHANGE

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Abstract: There is a limited understanding of the hydrological and microclimatic processes from drained, harvested, or restored peatlands, and by extension the nature of the carbon balance is uncertain. However, understanding the symbiotic processes governing water and gas exchange is essential to the development of appropriate management plans for peatland restoration. In this paper, we highlight and contrast the suite of processes governing the atmospheric exchange of water and carbon on natural, harvested, and restored peatlands. Evapotranspiration from harvested sites is important throughout the spring and summer, and is not greatly different from the adjacent natural bog. On cutover peatlands, strong capillary water movement compensates for the lack of vascular plants, which on the natural bog become increasingly important as the capillary water movement within drying *Sphagnum* decreases. Methane emissions from cutover bogs are an order of magnitude lower than in natural sites, however, carbon dioxide (CO_2) emissions are approximately three times greater. Peatland restoration enhances CO_2 sequestration, although restoration (at least in the short term) does not restore the net carbon sink function to that in natural bogs. A conceptual model highlighting these changes in the atmospheric exchange of water and carbon from a natural bog through drainage, harvesting, abandonment, and restoration is presented. [Key words: peatlands, restoration, hydrology, climatology, evaporation, carbon dioxide, methane, harvested peatlands.]

INTRODUCTION

The drainage and harvesting of peatlands has increased greatly over the last 50 years, particularly in response to the demand for horticultural and specialty peat products (Keys, 1992). Land-use changes in peatlands, such as drainage for forestry, agriculture, or peat mining, alter the local hydroclimatology and affect greenhouse gas exchange (e.g., Armentano and Menges, 1986). Considering the growing concern of global warming and the Kyoto Protocol, countries with large peatland resources must consider the value of peatlands as a sink for atmospheric carbon dioxide (CO_2). Peatlands form one of the largest carbon pools in the terrestrial biosphere, representing approximately one-third of the world's soil carbon (Gorham,

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1991). Carbon storage in peatlands is determined by the balance between primary productivity and decomposition (Clymo, 1984). Anaerobic conditions decrease peat decomposition, leading to an accumulation of CO_2. Based on records of peat accumulation and profiles of peat density and carbon content, Gorham estimated a long-term accumulation of carbon of 29 g C m^{-2} yr^{-1}, with a slightly lower rate of 23 g m^{-2} yr^{-1} over the last few centuries. Therefore, natural peatland ecosystems reduce the amount of atmospheric CO_2, but at the same time increase the amount of methane (CH_4) in the atmosphere. CH_4 is produced under anaerobic conditions and because peatlands are usually saturated they are a significant CH_4 source (Bartlett et al., 1992; Waddington and Roulet, 1996). However, during dry conditions or following drainage, peat may act as a net sink for CH_4 (Harriss et al., 1982), but release CO_2 (e.g., Glenn et al., 1993; Warner, 1999). In the drained or rewetted state, the soil conditions critical to the carbon exchange are dominated by the evaporative water loss over the summer (e.g., Price, 1996; Van Seters and Price, in press). Consequently, the atmospheric exchanges of carbon and water are closely related.

There is a paucity of information regarding hydrological and microclimatic processes from actively harvested or abandoned cutover peatlands, and by extension the nature of the carbon balance is uncertain. Peatlands that have been drained and harvested do not readily recover their original ecological function (Lavoie and Rochefort, 1996). Severe hydrological disruption causes water limitations to the nonvascular *Sphagnum* mosses (Price, 1997), the dominant peat forming species that cannot survive prolonged desiccation (Sagot and Rochefort, 1996). Consequently, the long-term peat accumulation (carbon sequestration) role of bogs is lost and, moreover, accelerated oxidation of the residual peat enhances carbon release to the atmosphere (Nykänen et al., 1997). Restoration of these systems requires appropriate water management to optimize the revegetation of appropriate species, such that carbon sequestration occurs. Understanding the symbiotic processes governing water and gas exchange is important to the development of appropriate management plans for restoration. Therefore, the goal of this paper is to highlight and contrast the suite of processes governing microclimatic and gas exchange processes on natural and abandoned peatlands. Specifically, the objective of this paper is to determine the effects of peatland mining, abandonment, natural regeneration, and restoration on evapotranspiration, ground heat flux, net ecosystem CO_2 exchange, and the atmosphere-peatland exchange of CH_4. In this paper, we review some of our previous research and present new findings, followed by a conceptual model on bog restoration, hydroclimatology, and greenhouse gas exchange (CO_2 and CH_4).

REVIEW

Natural Peatland Ecosystems

Peatlands have an interdependent ecological and hydrological function. The accumulation of organic matter imposes a gradually changing set of hydrological relationships governing the flow direction and chemical characteristics of water, which in turn control the rate and type of plant growth. Bogs are peatlands that have reached a stage of ecological and hydromorphic succession such that *Sphagnum* mosses are the dominant peat-forming vegetation. The actively growing *Sphagnum* carpet, and the dead and decaying plant matter beneath it, form a diplotelmic soil characterized by an acrotelm, which has a variable water content and permeability (high near the surface) and a catotelm that is permanently waterlogged with a relatively constant and low permeability (Ingram, 1983).

Evapotranspiration from natural peatlands occurs at the potential rate when there is a large proportion of open water (Price, 1994), dominance of emergent, or vascular vegetation (Lafleur and Rouse, 1988; Lafleur, 1990), or when the moss surface is damp from dew, fog or rain (Price, 1991). Since the dominant vegetation in bogs (i.e., *Sphagnum*) is nonvascular, water transport to the surface primarily relies on capillary flow between pendant branches and leaves of the moss (Hayward and Clymo, 1982). This process is inefficient, and the atmospheric demand commonly exceeds supply (e.g., Ingram, 1983; Price, 1991). Natural bogs have a self-regulatory mechanism, in which mosses turn white in color and reflect more incident radiation (Ingram, 1983). Consequently, evaporative water loss decreases as the water table declines (Schouwenaars, 1988).

Several studies have stated the importance of peatland hydroclimatology to the carbon balance of a peatland (e.g., Crill et al., 1988; Waddington and Roulet, 2000). Fringe areas of peatlands are influenced by groundwater and/or upland runoff with higher nutrient levels that enhance carbon mineralization, producing higher CH_4 fluxes (Crill et al., 1988; Waddington and Roulet, 1996). The position of the water table and capillary fringe determines the oxic-anoxic ratio within the peat profile. Furthermore, it strongly influences the thermal regime since water has a high heat capacity, thus affecting the amplitude of diurnal temperature variation. Methanogenesis occurs under anaerobic conditions, while CH_4 oxidation requires an oxic environment. In general, the exchange of CO_2 and CH_4 is best explained by water table position, rather than temperature, microsite variability (Billings et al., 1982), or atmospheric CO_2 concentration (Billings et al., 1983). However, temperature directly affects decomposition through its influence on microbial activity, and higher peat temperatures have been correlated to higher CO_2 respiration (e.g., Waddington et al., 1998).

The substrate composition of peat can result in differences in peat decomposition rates because this material is the energy source for microorganisms implicated in the gas exchange process. There is also evidence that vascular plant vegetation can influence CH_4 production by transporting CH_4 from the soil to the atmosphere (Chanton et al., 1993; Waddington et al., 1997) bypassing the surface layers of potential oxidation. CH_4 fluxes also are boosted by enhanced methanogenesis through root exudates (Whiting and Chanton, 1993; Waddington et al., 1996).

Mined Peatlands

Development of peatlands for peat extraction has resulted in the extensive drainage and mining of peatlands globally (Armentano and Menges, 1986). Generally only bog peatlands with a peat thickness of 2 m or greater, and an area of 50 hectares or greater, are of commercial value for horticultural peat production (Keys, 1992). Peat extraction typically is preceded by cutting drainage ditches, usually 30 m apart, to lower the moisture content, and increase bearing capacity for mechanized cutting. Mined peatlands are often abandoned when the botanical composition is no longer suitable, or when the mineral substrate is approached, typically after 20 to 30 years. Eggelsmann (1988) noted that a layer of peat sufficiently thick (<50 cm) should be left to minimize percolation losses during restoration.

Peat harvesting typically results in the destruction and removal of the acrotelm, and exposure of cutover peat formerly in the catotelm. The concept of the diplotelmic soil no longer applies in cutover peatlands, and the hydrological functions previously attributable to the acrotelm no longer apply. Surface runoff is abrupt, and because of the low storativity of the catotelmic peat (Schlotzhauer and Price, 1999), the water table is unstable (Price, 1996) and processes affecting gas exchanges become more temporally variable. In most continental peatlands, evapotranspiration typically dominates water losses (e.g., Lafleur and Rouse, 1988; Price and Maloney, 1994; Lafleur et al., 1998). Consequently, it is essential to consider its role in the water balance of bogs when restoration is being planned, and in the water table dynamics so closely linked to carbon gas exchanges.

Few studies have examined evaporation or greenhouse gas exchange from actively harvested or abandoned mined peatlands. Price (1996) compared a natural and reflooded cutover bog and showed that summer evaporation rates averaged 2.7 and 2.9 mm d^{-1}. In an abandoned revegetated bog, Van Seters (1999) noted that the average daily evapotranspiration rate was 2.9 mm d^{-1} in summer, and was 92% and 84% of total outputs in 1997 and 1998, respectively (Van Seters and Price, in press). Evapotranspiration from a nearby natural bog was similar, although less spatially variable. In contrast to the undecomposed living and dead mosses near the surface, the exposed cutover peat has a finer pore structure and higher bulk density (Okruszko, 1995). Consequently, the water retention capacity is higher (Schlotzhauer and Price, 1999), and capillary moisture transport can sustain soil moisture at a higher level than in *Sphagnum* hummocks (Price, 1996). Whitehead (1999) showed that the capillary fringe in moderately decomposed peat can be 30 cm above the water table. Sustained levels of saturation by this process can assist in maintaining the water supply to the evaporating surface. This, along with increased vascular plant growth and dereliction of drainage ditches, led Van Seters (1999) to suggest that evapotranspiration losses increase with time since abandonment. However, moisture content of the peat in early stages of abandonment may be enhanced by soil volume change (shrinkage), which keeps the water table higher than it otherwise would be (Price and Schlotzhauer, 1999). The water table falls in response to evaporation losses, but eventually the water table becomes disconnected from the surface-atmosphere exchange, and subsequent storage changes occur above the water table manifest as soil moisture change (Price, 1997). The degree of soil moisture change is important in terms of the gas exchange processes.

Several studies have shown a 100% to 400% increase in CO_2 emissions to the atmosphere in several drained peatlands owing to an increase in soil respiration and the destruction of carbon fixing vegetation, when the acrotelm is removed (e.g., Nykänen et al., 1995, 1997; Waddington and Warner, 2000). For example, in an undisturbed Finnish peatland, the net release of CO_2 was 2.4 to 3.6 g CO_2 m^{-2} d^{-1}, which increased to 7.2 to 9.6 g CO_2 m^{-2} d^{-1} when the water table was lowered from 0–10 cm to 40–60 cm (Silvola, 1986). Schotorst (1977) suggested that CO_2 losses decrease with time since abandonment, owing to a decrease in substrate quality. In contrast, Warner (1999) found that older abandoned sites lost more carbon than recently abandoned (and wetter) sites. Gorham (1991) estimated that oxidation of peat as a result of long-term drainage operations results in a net flux of CO_2 to the atmosphere of 8.5 Tg yr^{-1}. Despite this increase, Laine et al. (1996) suggested that drained peatlands have a lower overall radiative forcing than natural peatlands because of the large decrease in CH_4 emissions.

Peatland Restoration

Abandoned mined peatland reclamation (after-use of mined peatlands) and restoration (reestablishment of the site as a functioning natural peatland ecosystem) are important for the long-term sustainability of peatlands as a renewable resource. Reclamation options include transforming the peatland into a different wetland type, creation of a forestry plantation on site, or development of agricultural cropland. However, none of these new functions restore the natural peat accumulating function. Consequently, peatland restoration is necessary to return abandoned mined peatlands to a carbon accumulating system.

Restoration of cutover peatlands must begin with rewetting. Schouwenaars (1988) suggested that the water table depth should not exceed 40 cm over the growing season. However, Price (1997) argued that the water table depth is not as important as the water tension in the surface layer of the cutover peat, which should not exceed −100 mb for prolonged periods. To achieve either of these, the first step requires blocking the drainage ditches (Eggelsmann, 1988). This alone can restore the water balance to a state comparable to an undisturbed bog, although does not defend against a deep and variable water table (Price, 1996), or high values of water tension near the surface (Price, 1997).

More-direct remedial measures are required to reduce water tension near the surface. At Lac St.-Jean, Québec, LaRose et al. (1997) tested the effect of open water reservoirs on rewetting adjacent peat baulks. They found that wetter hydrological conditions favored better *Sphagnum* establishment (Schlotzhauer, 1998). Bugnon et al. (1997) addressed the problem of rewetting by reprofiling the surface to reverse the camber that originally enhanced lateral drainage. This, along with the addition of plastic sheets to direct rainfall into the concave peat field, improved *Sphagnum* recovery. Price et al. (1998) found microtopography created by ploughing, harrowing, and track-and-ridge topography created with bulldozer tracks, provided no net benefit to *Sphagnum*, because of enhanced dryness on the positive relief elements. However, conditions in the depressions were more favorable. Application of straw mulch (Quinty and Rochefort, 1997; Price et al., 1998) improved humidity conditions above the soil, reduced water tension in the surface layer, and increased soil moisture and the water table elevation. A combination of blocking ditches, broad trenches, coupled with the use of straw mulch, provide the highest water table and soil moisture conditions most favorable for restoration (Price et al., in press).

Few micrometeorological measurements of evapotranspiration or greenhouse gas exchange have been made in restored peatlands because of the limited size of typical restoration plots (10s of m^2). However, Van Seters and Price (in press) suggested that revegetated *Sphagnum* mats evaporate similarly to natural peatlands. Also, several enclosure measurements of net ecosystem CO_2 exchange (e.g., Komulainen et al., 1999; Warner, 1999) do exist. Komulainen et al. (1998) found that CH_4 emissions increased from 0.8 to 4.6 g m^{-2} yr^{-1} at a restored ombrotrophic bog in southern Finland. Komulainen et al. (1999) determined that a restored fen returned to a net carbon sink within two years post-restoration, however, much of the carbon was fixed by *Eriophorum vaginatum* and not *Sphagnum* spp. Warner (1999) found that restored *Sphagnum* plots did not return to a net carbon sink, primarily because of high soil respiration. This is consistent with the findings of Komulainen et al. (1999) that suggested that carbon accumulation is faster in restored fens than bogs.

STUDY AREAS

Data reported below were collected in two study areas—near Lac St.-Jean (48°47'N, 72°10'W); and near Rivière-du-Loup (47°53'N, 69°27'W), Québec. The average annual temperature is 1.7° and 3°C, respectively (Environment Canada, 1993). Mean annual total precipitation is 906 and 926 mm (32% and 27% falling as snow), respectively.

The Ste.-Marguerite-Marie peatland near Lac St.-Jean (LSJ) is part of a 4315 ha bog-poor fen complex, classified as "plateau bog" (National Wetland Working Group, 1997). The peat deposit has developed over permeable deltaic sands (Morin, 1981) where a well-developed iron pan limits seepage losses (Price, 1996). A natural site, two rewetted block-cut sites, an actively vacuum harvested site, and a partly restored block-cut peat field were studied. Drainage operations began in 1990. Block cutting and vacuum harvesting began in 1991. Residual peat thickness currently ranges from 1.2 to 1.8 m, and has suffered oxidation and compression as a result of drainage and mining activities. Block-cut areas reported here have been partially rewetted by ditch blocking. The vacuum harvested site comprised a 30 m wide peat field that was taken out of production for the year of the measurements. Adjacent peat fields, for at least 300 m in all directions, were actively harvested. The restored site was a field within the older block cut area, also drained in the fall of 1990 and cutover in 1991. The restored site was actively restored with *Sphagnum fuscum*, and some *S. capillifolium* in 1997 (Campeau and Rochefort, 1996). More detail on the other sites is reported by Price (1996, 1997) and Price et al. (1998).

The other study site was an abandoned mined bog at Cacouna Station, situated approximately 10 km northeast of Rivière-du-Loup (RDL), and a nearby natural bog. Both sites are raised bogs (National Wetland Working Group, 1997) underlain by thick deposits of Champlain Sea clay. Harvesting activities occurred from 1942 to 1975 using the traditional "block-cut" method, where up to 2 m of peat was removed. By 1998, more than half the drainage canals were either inactive or operating at only a fraction of their original capacity (Van Seters, 1999). Natural revegetation has occurred with typical bog species including ericaceae, black spruce, tamarack, and jack pine, although *Sphagnum* is absent from all but about 10% of the trenches (Lavoie and Rochefort, 1996).

METHODS

Hydroclimatology

Evaporation was measured at the Lac St.-Jean site with a four-level Bowen ratio-energy balance system, with sensors at 0.5, 1.0, 1.5, and 2.0 m above the surface. The 1993 data included the natural and rewetted cutover site only. More details on the site and instrumentation are given by Price (1996). In 1994, the vacuum harvested site also was monitored at this peatland. The Priestley and Taylor (1972) combination model of evaporation was used to determine equilibrium evaporation at LSJ, and also was used to determine actual evaporation at RDL in 1997 and 1998. Weighing-type soil lysimeters that allowed measurable drainage, and which were maintained daily at a similar soil moisture condition as surrounding soil (based on TDR measurements), were used to calibrate the model at RDL (Van Seters and Price, in press). Soil temperature was measured at LSJ with thermocouples at 0.001, 0.01, 0.05, 0.10, 0.25, 0.50, and 1.0 m beneath the surface.

Greenhouse Gas Exchange

Measurements of net ecosystem CO_2 exchange (NEE) were made several times a week at each of the sites from early May to late August in 1998, with a climate-controlled chamber and a PP systems EGM-1or EGM-2 infrared gas analyzer (IRGA) assembly placed and sealed over PVC collars set into the peat. Five collars were monitored at each of the natural, blocked, and restored sites. No measurements were made at the vacuum harvested site. Instantaneous measurements of soil temperature and water table position were taken to establish an empirical relationship between these variables and total ecosystem respiration (R_{TOT}). Gross ecosystem CO_2 production (GEP) was measured using a clear chamber, with a series of neutral density shrouds to measure GEP under low light conditions. A relationship between photosynthetically active radiation (PAR) and GEP was developed.

CH_4 flux was measured once a month with static enclosures equipped with air sampling ports. The headspace of the enclosure was sampled immediately after the enclosure was set into the peat, 15 minutes later and at the end of the measurement period (30 minutes) using a 10 ml syringe. Samples were transferred into vacutainers and returned to the lab for analysis on a Varian 3800 gas chromatograph equipped with a Porapaq Q column (80/120 mesh) and a flame ionization detector (FID). More details on greenhouse gas exchange instrumentation and measurements are given by Waddington and Warner (2000).

RESULTS AND DISCUSSION

Hydroclimatology

The surface energy balance and exchange of greenhouse gases in mined peatlands is dictated by changing seasonal characteristics of the bog surface. This includes frost depth, moisture content, and capillary characteristics of the soil, and presence or absence of vegetation. Following snowmelt there is considerable ponded and gently flowing water over frozen, generally saturated peat. In the natural peatlands, meltwater occupies only the depressions, with hummocks being freely drained. In the blocked block-cut peatland (LSJ), meltwater occupies all but the central ridges where peat was stockpiled previously, and directly adjacent to the drainage ditches, where low berms were created as part of the ditching process. More-elevated areas remain generally saturated, since the relatively well-decomposed peat does not drain rapidly. Vacuum harvested peatland has a cambered surface, so meltwater drains directly into the still-active drainage ditches and away from the site. The peat remains close to saturation until evaporation becomes significant. At the manually block-cut RDL peatland, snow accumulates in the deep vegetated trenches. Meltwater generally moves off the raised skag in the central axis of each trench, to the lateral tertiary ditches. These are partly overgrown, so drainage to secondary canals is inefficient. Some of these secondary ditches are collapsed or otherwise blocked (Van Seters, 1999), but large-scale flooding does not occur.

Thinner pre-melt snow cover at open cutover bog (LSJ) results from scouring of the open surface by wind, hence greater frost penetration occurs there than at natural sites. For example, at LSJ the post-melt ground-frost in 1994 was 50 to 70 cm in the harvested sites, compared to 0 to 30 cm at the natural bog. The cold ground (Fig. 1), and relatively high thermal conductivity of moist soils, results in a high ground heat flux (Q_G) at all locations following snowmelt (Table 1). When the surface thaws, and drainage and evaporation dry the soils (JD 222, Table 1), Q_G becomes insignificant at the natural site, as well as at the blocked block-cut site. The higher Q_G that persisted at the vacuum harvested site was unexpected. Its soil temperature profile later in the summer (Fig. 1) was nearly identical to the block-cut site, thus differences could be attributable to higher thermal conductivity at the vacuum site. Higher thermal conductivity is associated with moister soils, however, there are no data to confirm this. In fact, the lower water table at the drained vacuum site would suggest a lower moisture content. However, soil heat flux at the block-cut site was the average of two heat-flux plates, one of which was positioned on a raised ridge characteristic of the central portion of the peat field, where the peat was significantly drier than the flat part (Price, 1996). The surface of the vacuum harvested site was flat by comparison, and probably of similar moisture content (and Q_G) as the flat part of the block-cut site.

Early in the season, the latent heat flux dominates all sites because water is abundant near the surface. At LSJ, the dominance of latent heat persists through the summer, and increases as a portion of the available energy, as Q_G diminishes. Likewise, sensible heat flux (Q_H) increases as the soil dries, and is greatest at the natural site, since surface temperatures in the relatively drier hummocks (Price,

Table 1. Ratio of Ground, Latent, and Sensible Heat Flux to Net Radiation at Lac St.-Jean in 1994 and Rivière-du-Loup in 1997[a]

	Julian Day	Q_G/Q^*	Q_E/Q^*	Q_H/Q^*
Lac St.-Jean				
Natural peatland	125	0.17	0.69	0.10
	222	0.02	0.74	0.24
Abandoned peatland (seven-year post-mining)	125	0.43	0.67	-0.08
	222	0.02	0.86	0.12
Vacuum harvest peatland	125	0.38	0.50	0.11
	222	0.13	0.69	0.18
Rivière-du-Loup				
Sphagnum covered	152	0.05	0.64	0.31
	221	0.05	0.71	0.24
Bare peat	152	0.06	0.63	0.31
	222	0.08	0.69	0.23

[a]Q_G = ground heat flux; Q^* = net radiation; Q_E = latent heat flux; Q_H = sensible heat flux.

1996) are relatively high (e.g., Waddington and Roulet, 1996). The similarity in evaporation between natural and blocked block-cut sites was evident in July and August 1993, averaging 2.7 and 2.9 mm d^{-1}. The 1994 data in Table 1 also demonstrate a similarity. Evaporation from the vacuum site in on JD 125 and 222, 1994 (Table 1) was 72% and 93% of natural bog evaporation. The lower rates early in the season reflect the greater consumption of energy used for ground warming at the disturbed sites (Table 1).

Equilibrium evaporation is the rate that would occur into a fully saturated atmosphere, thus the relation between actual and equilibrium evaporation is indicative of the evaporative efficiency with which a particular system can operate. The ratio of actual to equilibrium evaporation determined at LSJ is shown in Figure 2A. Data for the natural and blocked block-cut site are from July and August 1993, and for the vacuum site from May to August 1994. The Bowen ratio could not be calculated regularly at the natural site in 1994 because of equipment malfunction. The slope of the latent heat flux (Q_E)/equilibrium latent heat flux (Q_{EQ}) relationship is similar at all sites at LSJ (Fig. 2), indicating they share a common evaporative efficiency. The greater scatter at the vacuum site may be caused by harvesting activity. Immediately following harrowing the exposed moist peat promotes evaporation, but after a day or so, the "fluffy" textured harrowed peat becomes dry, as its capillary contact is broken, suppressing the evaporation rate.

At Cacouna Station, trees and ericaceous shrubs that have revegetated the site protect the snow cover from wind redistribution. The ground frost is relatively shallow (Van Seters, 1999), and the ground heat flux is relatively small. For example, on

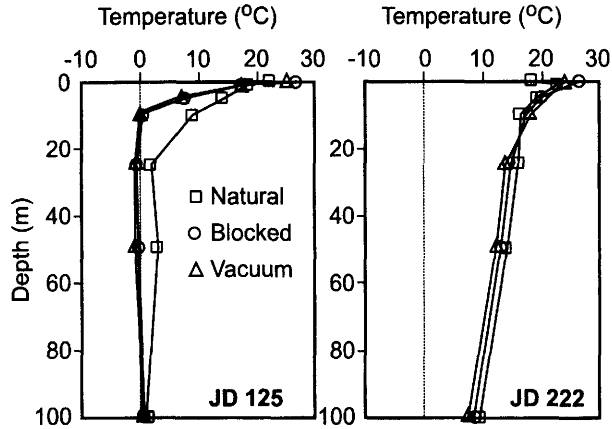

Fig. 1. Soil temperature profiles at Lac St.-Jean on natural, blocked block-cut, and vacuum sites on Julian days 125 and 222 (1994).

JD129 (1998) Q_G/Q^* (Q^* = net radiation) was only 0.04, and the latent heat flux dominated the nonradiative energy flux, with Q_E/Q^* at 0.59. Later in the spring (JD152) and summer (JD222), the Q_G was similarly low (Table 1). Therefore, the increase in Q_E/Q^* was not caused by diminished Q_G, but rather because of transpiration by plants (i.e., that are not present at LSJ). At RDL, there was a notable difference between evaporation within the peatland, depending on the type of surface. Moist surfaces supporting revegetated *Sphagnum* cover evaporated 3.6 mm d^{-1} on average, other parts of the peat diggings (trenches) without *Sphagnum* (i.e., dryer) averaged 2.9 mm d^{-1}, and raised baulks and roadways used for drying and transporting peat (driest) evaporated an average of 1.9 mm d^{-1}. The ratio of actual to equilibrium evaporation (Fig. 2B) show that there was more scatter in the data for dryer locations, but that the bare surfaces had a distinctly lower value.

The hydroclimatic conditions of peat soils relevant to the carbon flux can be summarized as follows. At LSJ, the deep frost at cutover sites (and consequent high Q_G) reduces the evaporative loss (Q_E) early in the season, thus soils remain relatively moist, and the ground cool. By midsummer, the soil temperatures approach that at the natural site, and the Q_E flux is more-or-less similar. The lower specific yield of cutover soils (Price, 1996) results in a more rapid water table drop, thus soil aeration occurs. At RDL, snow trapped by the vegetation insulates the ground in winter, and little ground frost develops. Therefore, spring Q_G consumes a relatively small proportion of the available energy, in favor of convective fluxes (Q_E and Q_H). This, along with partially active drainage ditches causes the soil to dry. Where *Sphagnum* is present, however, soils are moister, a function of site location (elevation) and restricted evaporation when the moss surface dries.

Greenhouse Gas Exchange

Prior to disturbance, an intact acrotelm with *Sphagnum* mosses ensures that the water table position remains relatively near the surface. As such, CH_4 flux to the

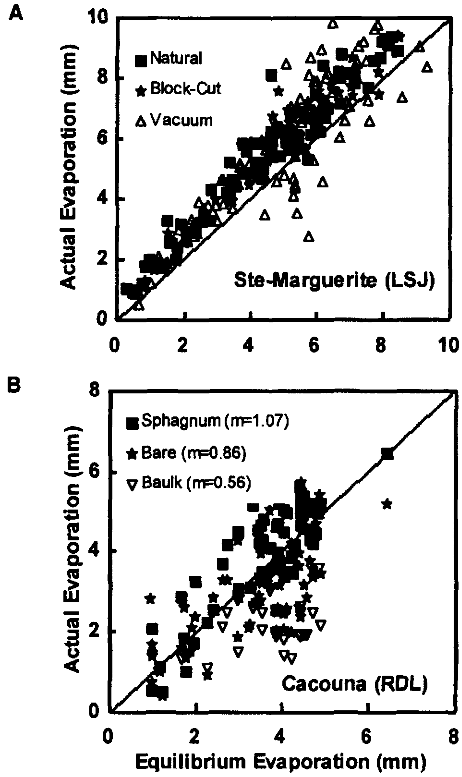

Fig. 2. Actual versus equilibrium evaporation at (A) Lac St.-Jean (upper graph), and (B) Rivière-du-Loup (lower graph). Diagonal line shows 1:1 relationship.

atmosphere is high and peat decomposition rates are retarded, leading to a net atmospheric CO_2 sink (Gorham, 1991). Table 2 summarizes the seasonal CH_4 flux at the natural and mined (two- and seven-year post-mined) sites for three different periods (early, mid, and late) during the summer months. The natural site was a relatively large source of CH_4 to the atmosphere (>35 mg CH_4 m^{-2} d^{-1}) for much of the summer period. Only during the late summer when the water table dropped more than 40 cm below the surface (Waddington and Warner, 2000) did the CH_4 flux decrease (approximately 8 mg CH_4 m^{-2} d^{-1}). Waddington and Warner noted that such a large drop in water table is uncommon in natural peatlands and that this was in response to abnormally dry conditions when sustained evapotranspiration caused a substantial water deficit. This dry period also decreased GEP and enhanced total respiration (Waddington and Warner, 2000). Consequently the natural site NEE represented a net source of atmospheric CO_2 in 1998 (138 g C m^{-2}, Table 3).

Sustained evaporation from the cutover peat soil, in association with the low specific yield of the peat, causes the mean water table position to drop from 0–10 cm to 40–60 cm below the surface. The loss of water also decreases the volumetric soil moisture of the peat, especially in the upper 5 cm. Compounding this is the loss

Table 2. Methane (CH_4) Flux (mg CH_4 m^{-2} d^{-1}) at Lac St.-Jean in 1998

Location	Early summer[a]	Midsummer	Late summer	Summer
Natural peatland	37.2 (35.4)	35.8 (34.6)	8.1 (3.1)	28.0 (25.7)
Abandoned peatland (two-year post-mining)	28.2 (17.7)	3.3 (3.3)	3.2 (3.9)	13.2 (9.3)
Abandoned peatland (seven-year post-mining)	3.4 (2.5)	3.4 (4.2)	2.2 (0.8)	3.0 (2.5)

[a]Parentheses represent standard deviation.

Table 3. Seasonal Carbon Balance and Carbon Dioxide Equivalents (CO_2-e) at Lac St.-Jean in 1998

Location	NEE (g C m^{-2})[a]	CH_4 (g C m^{-2})[b]	ΔC (g C m^{-2})	CO_2-e (g CO_2-e m^{-2})[c]
Natural peatland (Gorham, 1991)	–47	4.0	–23.0[d]	–60
Natural peatland (this study)	138	2.5	140.5	576
Abandoned peatland (two-year post-mining)	363	1.2	364.2	1,365
Abandoned peatland (seven-year post-mining)	397	0.3	397.3	1,464
Vacuum harvest peatland	n/a	n/a	n/a	n/a
Restored peatland	170	0.3	170.3	632

[a]NEE = net ecosystem CO_2 exchange. Negative numbers represent uptake by the peatland, while positive numbers represent a source to the atmosphere.
[b]Restored peatland methane (CH_4) flux was assumed to equal the adjacent abandoned plot with similar moisture and thermal conditions.
[c]CH_4 multiplier for CO_2 equivalents was 21.
[d]This estimate includes dissolved organic carbon (DOC) loss of 20 g C m^{-2}.

of water through evaporation. The lower water table position also results in a decrease in the thermal capacity of the peat layer as the volume of water, which has a high thermal capacity, is reduced. Warner (1999) found that modeled respiration increased with decreasing volumetric moisture content. Upon rewetting, respiration decreased substantially (sometimes to near zero). Natural peatland CO_2 and CH_4 flux modeling approaches (e.g., Roulet et al., 1992) that use water table position are, therefore, unsuitable for mined peatlands. The magnitude in the fluctuations of soil temperature also increases after drainage owing to the decreased thermal capacity. The temporal variation in soil temperatures at the mined sites was 55% greater than at the adjacent natural site (Waddington and Warner, 2000).

These hydroclimatological differences lead to changes in the carbon balance of mined peatlands. Soil respiration increases with drainage as the depth of the aerobic zone increases and soil moisture content decreases. Warner (1999) found that the net CO_2 loss to the atmosphere increased 300% at a mined peatland. Moreover, because Fickian diffusion decreases with an increase in volumetric moisture content, the increase in soil respiration resulting from drainage was more than the loss of the combined components of plant and root respiration, leading to a small increase in net ecosystem respiration. CH_4 flux decreases following peatland drainage and during drier conditions. CH_4 flux at the two-year post-mined peatland (mean = 13.2 mg CH_4 m^{-2} d^{-1}) exceeded the seven-year site (mean = 3.0 mg CH_4 m^{-2} d^{-1}) throughout the summer. The greatest difference occurred early in the season when differences peat volumetric moisture content between sites was greatest (Waddington and Warner, 2000).

The removal of the vegetation at mined sites results in the reduction of plant production (net ecosystem production) to zero. Taking into account the respiration (noted previously), net ecosystem exchange at the natural site (as mentioned earlier) was 138 g C m^{-2}, compared to 363 and 397 g C m^{-2} at the two and seven-year post-mined sites, respectively (Table 3). Moreover, CH_4 flux at the seven-year site was an order of magnitude lower that the natural site for the wet and moist periods of the summer. Seasonally, CH_4 emissions followed the trend: natural > two-year post-mined > seven-year post-mined. Waddington et al. (2000) found that anaerobic CO_2 and CH_4 production also followed this trend. This suggests that greater CH_4 production and emissions at the natural site also is caused by the presence of more labile carbon. The higher CH_4 flux at the more recently abandoned site is caused by the presence of both more labile carbon and wetter conditions.

In abandoned peatlands, natural regeneration by ericaceous shrubs and invasive trees such as birch, represents most of the plant production. The productivity of *Sphagnum* in these sites is much lower than that in natural sites (Warner, 1999). In drained peatlands in Finland, peatland productivity has been shown to increase when forest stand productivity increases (e.g., Minkinnen and Laine, 1998). In the plant introduction restoration plots in this study, however, vascular vegetation and trees are removed such that the increase in carbon sequestration is only from the restoration of *Sphagnum* mosses. Warner (1999) showed that net ecosystem production at the restored sites exceeded that of lawn *Sphagnum* mosses at the adjacent natural site, but was lower than hummock vegetation (that also included production from ericaceous shrubs). Nevertheless, net ecosystem CO_2 exchange at the restored site (170 g C m^{-2}) was only a slightly larger source to the atmosphere than the adjacent natural site (138 g C m^{-2}).

CONCLUSIONS

The effects of peatland drainage, harvest, abandonment, and restoration on atmospheric water and carbon exchange can be summarized in a conceptual model (Fig. 3). Much of the differences in evapotranspiration and greenhouse gas exchange can be attributed to the changes in the structure of the peat. The natural bog peat has a high water table position (Fig. 3A), low density moss cover with large open pores, high specific yield, and limited upward capillary water flow. In contrast, cutover peatlands have a lower water table position, but the peat is denser,

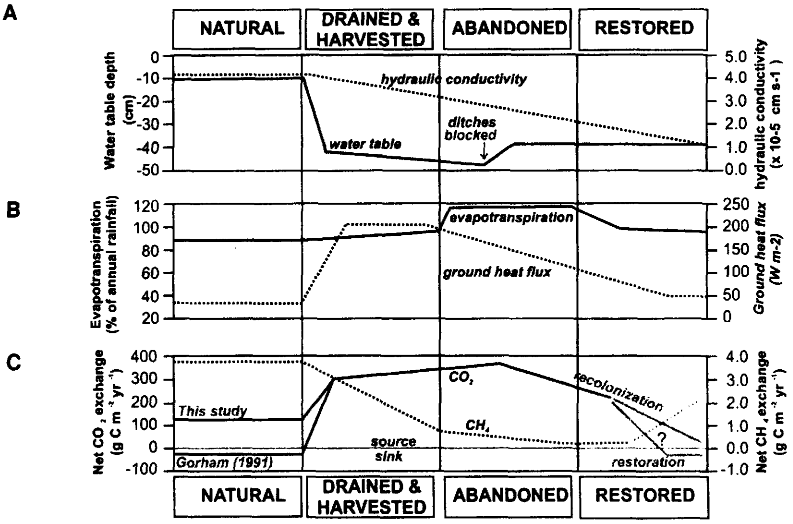

Fig. 3. Conceptual model illustrating the effects of peatland drainage, harvesting, abandonment and restoration on (A) water table position and hydraulic conductivity (upper graph), (B) evapotranspiration and ground heat flux (middle graph), and (C) carbon fluxes (lower graph).

thus less easily drained (lower specific yield), and more effective at sustaining upward capillary water flow.

In the spring, natural sites drain as water moves between linked hollows and through the permeable upper layers of moss, facilitating runoff. The exposed mosses are damp, latent heat flux is strong, and CH_4 emissions are large (Figs. 3B, 3C). However, the drained mosses dry quickly during summer, since capillarity is relatively poor, and the thermal conductivity of the mosses decreases sharply, resulting in lower ground heat flux, warmer surface temperature, increased sensible heat loss, and lower CH_4 emissions. In contrast, on cutover peat surface water drains laterally, but may be retained in the depressions that are artifacts of the harvesting process. This is specific to the type of harvesting, post-abandonment treatment, and time since abandonment. For example, where ditches are maintained, and where cambered surfaces exist (i.e., vacuum sites), surface ponding is generally absent. Nevertheless, the cutover peat has a lower hydraulic conductivity compared to natural sites (Fig. 3A) (Price, 1997), thus following surface drainage, water is retained within the cutover peat, which has a high water retention capacity (Schlotzhauer and Price, 1999). Where drainage ditches are still active, the water table drops relatively quickly, and is followed by a drop in the soil moisture. However, the relatively good capillarity of cutover peat ensures an adequate supply of moisture to the surface, at least until the water table drops below about 70 cm (Price, 1997). Consequently, latent heat fluxes are important throughout the season and, generally speaking, the overall (seasonal) evaporation is not greatly different from the natural bog (Fig. 3B). However, CH_4 emissions are an order of magnitude lower on the cutover surface relative to the natural sites (Fig. 3C). Moreover, owing to the absence of Sphagnum and vascular vegetation, the CO_2 efflux is approximately three times greater on cutover peatlands (Fig. 3C). On the cutover peatlands, the strong capillary water movement compensates for the lack of vascular plants, which on the natural bog become increasingly important as the capillary water movement in drying *Sphagnum* decreases. The lack of vegetation and, therefore, the supply of labile carbon through root exudates (Waddington et al., 1996) at the cutover sites also leads to the low CH_4 fluxes.

The role of vegetation on evapotranspiration is complex. *Sphagnum* is nonvascular, thus latent heat fluxes from the moss involve only a passive role for the plant, as noted in the discussion of capillary water movement. However, since *Sphagnum* recolonization occurs only in the wetter areas of the abandoned block-cut peatland (Whitehead, 1999), relatively high latent heat fluxes from these areas is not necessarily aided by the moss. In these systems, however, strong recolonization of vascular plants boosts the latent heat flux in drier areas, so that evapotranspiration is much greater than from bare peat. The productivity of naturally recolonized *Sphagnum* mosses is lower than that in restored peatlands, however, this does not necessitate a return to a net carbon sink in restored peatlands, at least within the first few years post-restoration.

Different greenhouse gases have different radiative properties, so their role in global warming is also dissimilar. For example, CH_4 is 21 times more effective at global warming than CO_2. Expressing the total greenhouse gas exchange in CO_2 equivalents (CO_2 flux + [CH_4 flux * 21]), therefore, permits an overall assessment of the effects of peatland drainage, harvesting, and restoration on changes in the net global warming potential. Such an analysis indicates an initial increase of approximately 235% (two-year post-mined site) in CO_2-equivalent emissions with a bigger (approximately 255%) increase seven-years post-mining despite a decrease in CH_4 flux (Table 3). Peatland restoration net CO_2-equivalent emissions, however, are only 8% greater than that of the adjacent natural peatland. Consequently, although peatland restoration has not returned the abandoned peatland to a net carbon sink, it has retuned greenhouse gas emissions (in terms of CO_2 equivalents) back to near-natural conditions.

These results support the need to understanding the symbiotic processes governing water and gas exchange. Such an understanding is essential to the development of appropriate management plans for peatland restoration. While this paper has presented some seasonal data on greenhouse gas exchange at restored peatland plots because of their small areal extent, full-scale micrometeorological measurements of evapotranspiration have yet been made. In order to increase our understanding and quantify the synergy between peatland restoration hydroclimatology and greenhouse gas exchange, therefore, it is necessary to undertake a full ecosystem peatland restoration project. Such a project would permit the continuous measurement of atmospheric water and carbon exchange and permit the development of appropriate management plans for peatland restoration.

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BIBLIOGRAPHY

Armentano, T. V. and Menges E. S. (1986) Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. *Journal of Ecology*, Vol. 74, 755–774.

Bartlett, K. B., Crill, P. M., Sass, R. L., Harriss, R. C., and Dise, N. B. (1992) Methane emissions from tundra environments in the Yukon-Kuskikwim delta, Alaska. *Journal of Geophysical Research*, Vol. 97, 16645–16660.

Billings, W. D., Luken, J. O., Mortensen, D. A., and Peterson, K. M. (1982) Arctic tundra: A source or sink for atmospheric carbon dioxide in a changing environment? *Oecologia*, Vol. 53, 7–11.

Billings, W. D., Luken, J. O., Mortensen, D. A., and Peterson, K. M. (1983) Increasing atmospheric carbon dioxide: Possible effects on arctic tundra. *Oecologia*, Vol. 53, 286–289.

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

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

Chanton, J. P., Whiting, G. J., Happell, J. D., and Gerard, G. (1993) Contrasting rates and diurnal patterns of methane emission from emergent aquatic macrophytes. *Aquatic Botany*, Vol. 46, 111–128.

Clymo, R. S. (1984) The limits to peat bog growth. *Philosophical Transactions of the Royal Society of London*, Vol. B303, 605–654.

Crill, P. M., Bartlett, K. B., Harriss, R. C., Gorham, E., Verry, E. S., Sebacher, D. I., Madzar, L., and Sanner, W. (1988) Methane flux from Minnesota peatlands. *Global Biogeochemical Cycles*, Vol. 2, 371–384.

Eggelsmann, R. R. F. (1988) Rewetting for protection and renaturation/regeneration of peatland after or without peat mining. In *Proceedings of the Eight International Peat Congress*. Leningrad, Soviet Union, 231–260.

Environment Canada (1993) *Canadian Climate Normals, 1961-1990. Quebec*. Ottawa, Canada: Atmospheric Environment Service, Canadian Climate Program, Environment Canada.

Glenn, S., Heyes, A., and Moore, T. (1993) Carbon dioxide and methane fluxes from drained peat soils, southern Quebec. *Global Biogeochemical Cycles*, Vol. 7, 247–257.

Gorham, E. (1991) Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications*, Vol. 1, 182–195.

Harriss, R. C., Sebacher, D. I., and Day, F. P., Jr. (1982) Methane flux in the Great Dismal Swamp. *Nature*, Vol. 297, 673–675.

Hayward, P. M. and Clymo, R. S. (1982) Profiles of water content and pore size in *Sphagnum* peat and their relation to peat bog ecology. *Proceedings of the Royal Society of London*, Vol. B215, 299–325.

Ingram, H. A. P. (1983) Mires—swamp, bog, fen and moor. In A. J. P. Gore, ed., *Ecosystems of the World 4A*. Amsterdam, The Netherlands: Elsevier, 67–158.

Keys, D. (1992) *Canadian Peat Harvesting and the Environment*. Ottawa, Canada: North American Wetlands Conservation Council Report No.1992–93.

Komulainen, V-M., Nykänen, H., Martikainen, P. J., and Laine, J. (1998) Short-term effect of restoration on vegetation change for methane emissions from peatlands drained for forestry in southern Finland. *Canadian Journal of Forest Research*, Vol. 28, 402–411.

Komulainen, V-M., Tuittila, E-S., Vasander, H., and Laine, J. (1999) Restoration of drained peatlands in southern Finland: Initial effects on vegetation change and CO_2 balance. *Journal of Applied Ecology*, Vol. 36, 634–648.

Lafleur, P. M. (1990) Evapotranspiration from sedge-dominated wetland surfaces. *Aquatic Botany*, Vol. 37, 341–353.

Lafleur, P. M., McCaughey, J. H., Joiner, D. W., Bartlett, P. A., and Jelinski, D. E. (1998) Seasonal trends in energy, water and carbon dioxide fluxes at a northern boreal wetland. *Journal of Geophysical Research*, Vol. 102, 29009–29020.

Lafleur, P. M. and Rouse, W. R. (1988) The influence of surface cover and climate on energy partitioning and evaporation from a subarctic marsh. *Boundary-Layer Meteorolology*, Vol. 44, 327–347.

Laine, J., Silvola, J., Tolonen, K., Alm, J., Nykanen, H., Vasander, H., Sallantaus, T., Savolainen, I., Sinisalo, J., and Martikainen, P. (1996) Effect of water-level draw-down on global climate warming: Northern peatlands. *Ambio*, Vol. 25, 179–184.

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

Lavoie, C. and Rochefort, L. (1996) The natural revegetation of a harvested peatland in southern Quebec: A spatial and dendroecological analysis. *Ecoscience*, Vol. 3, 101–111.

Minkinnen, K. and Laine, J. (1998) Long-term effect of forest drainage on the peat carbon stores of pine mires in Finland. *Canadian Journal of Forest Research*, Vol. 28, 1267–1275.

Morin, G. (1981) *Atlas Régional du Saguenay-Lac-Saint-Jean* [Regional Atlas of the Saguenay-Lac-Saint-Jean]. Chicoutimi, Canada: Les Laboratoires de Géographie de L'université du Québec à Chicoutimi.

National Wetland Working Group (1997) The Canadian Wetland Classification System, 2nd edition. In B. G. Warner and C. D. A. Rubec, eds., *Wetlands of Canada*. Waterloo, Canada: Wetland Research Centre Publication, 201.

Nykänen, H., Silvola, J., Alm, J., and Martikainen, P. J. (1995) Emissions of CH_4, N_2O, and CO_2 from a virgin fen and a fen drained for grassland in Finland. *Journal of Biogeography*, Vol. 22, 351–357.

Nykänen, H., Silvola, J., Alm, J., and Martikainen, P. J. (1997) The Effect of Peatland Forestry on fluxes of carbon dioxide, methane, and nitrous oxide, In C. C. Trettin et al., eds., *Northern Forested Wetlands: Ecology and Management*. Boca Raton, FL: CRC/Lewis, 325–339.

Okruszko, H. (1995) Influence of hydrological differentiation of fens on their transformation after dehydration and on possibilities for restoration. In B. D. Wheeler, S. C. Shaw, W. Fojt, and R. A. Robertson, eds., *Restoration of Temperate Wetlands*. Chichester, UK: John Wiley and Sons, 113–120.

Price, J. S. (1991) Evaporation from a blanket bog in a foggy coastal environment. *Boundary-Layer Meteorology*, Vol. 57, 391–406.

Price, J. S. (1994) Evapotranspiration from a lakeshore *Typha* marsh and adjacent open water systems. *Aquatic Botany*, Vol. 48, 261–272.

Price, J. S. (1996) Hydrology and microclimate of a partly restored cutover bog, Quebec. *Hydrological Processes*, Vol. 10, 1263–1272.

Price, J. S. (1997) Soil moisture, water tension, and water table relationships in a managed cutover bog. *Journal of Hydrology*, Vol. 202, 21–32.

Price, J. S. and Maloney, D. A. (1994) Hydrology of a patterned bog-fen complex in southeastern Labrador, Canada. *Nordic Hydrology*, Vol. 25, 313–330.

Price, J. S., Rochefort, L., and Campeau, S. (in press) On the use of shallow basins to restore cutover peatlands: 1. Hydrology. *Restoration Ecology*.

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

Price, J. S. and Schlotzhauer, S. M. (1999) Importance of shrinkage and compression in determining water storage changes in peat: The case of a mined peatland. *Hydrological Processes*, Vol. 13, 2591–2601.

Priestley, C. and Taylor, R. (1972) On the assessment of the surface heat flux and evaporation using large scale parameters. *Monthly Weather Review*, Vol. 100, 81–92.

Quinty, F. and Rochefort, L. (1997) Plant reintroduction on a harvested peat bog. In C. C. Trettin, M. F. Jurgensen, D. F. Grigal, M. R. Gale, and J. K. Jeglum, eds., *Northern Forested Wetlands: Ecology and Management*. Boca Raton, FL: CRC/Lewis, 133–145.

Roulet, N., Moore, T., Bubier, J., and LaFleur, P. (1992) Northern fens: Methane flux and climatic change. *Tellus*, Vol. 44B, 100–105.

Sagot, C. and Rochefort, L. (1996) Tolèrance des sphaignes a la dessiccation [Tolerance of sphagnum to dessication]. *Cryptogamie, Bryolology and Lichenolology*, Vol. 17, 171–183.

Schlotzhauer, S. M. (1998) Modeling Soil Water Dynamics in Cutover Peat Fields, Quebec: A Peat-Ditch Recharge System. Unpublished master's thesis, Department of Geography, University of Waterloo, Waterloo, Ontario, Canada.

Schlotzhauer, S. M. and Price, J. S. (1999) Soil water flow dynamics in a managed cutover peat field, Quebec: 1. Field and laboratory investigations. *Water Resources Research*, Vol. 35, 3675–3684.

Schotorst, C. J. (1977) Subsidence of a low moor peat in the western Netherlands. *Geoderma*, Vol. 17, 265–291.

Schouwenaars, J. M. (1988) Hydrological research in disturbed bogs and its role in decisions on water management in the Netherlands. In *Proceedings of the Inter-*

national Symposium on the Hydrology of Wetlands in Temperate and Cold Regions, August 6, 1988. Joensuu, Finland: 170.

Silvola, J. (1986) Carbon dioxide dynamics in mires reclaimed for forestry in eastern Finland. *Annals Bot. Fennici*, Vol. 23, 59–67.

Van Seters, T. (1999) Linking the Past to the Present: The Hydrological Impacts of Peat Harvesting and Natural Regeneration on an Abandoned Cut-Over Bog, Quebec. Unpublished master's thesis, Department of Geography, University of Waterloo, Waterloo, Ontario, Canada.

Van Seters, T. and Price, J. S. (in press) The impact of peat harvesting and natural regeneration on the water balance of an abandoned bog, Quebec. *Hydrological Processes*.

Waddington, J. M., Griffis, T. J., and Rouse, W. R. (1998) Northern Canadian wetlands: Net ecosystem CO_2 exchange and climatic change. *Climatic Change*, Vol. 40, 267–275.

Waddington, J. M., Rotenberg, P. A., and Warner, K. D. (2000) Effect of temperature and soil moisture on peat CO_2 and CH_4 production in a natural and mined peatland. *Biogeochemistry*, submitted.

Waddington, J. M. and Roulet, N. T. (1996) Atmosphere-wetland carbon exchanges: Scale dependency of CO_2 and CH_4 exchange on the developmental topography of a peatland. *Global Biogeochemical Cycles*, Vol. 10, 233–245.

Waddington, J. M. and Roulet, N. T. (in press) Carbon balance of a boreal patterned peatland. *Global Change Biology*.

Waddington, J. M., Roulet, N. T., and Swanson, R. V. (1997) Water table control of CH_4 emission enhancement by vascular plants in boreal peatlands. *Journal of Geophysical Research*, Vol. 101, 22775–22785.

Waddington, J. M. and Warner, K. D. (2000) Effect of peatland drainage and harvesting on CO_2 efflux. *Global Biogeochemical Cycles*, submitted.

Warner, K. D. (1999) Net Ecosystem CO_2 Exchange in Natural, Harvested and Restored Peatlands. Effect on Peatland Drainage and Harvesting on CO_2 Efflux. Unpublished master's thesis, School of Geography and Geology, McMaster University, Hamilton, Ontario, Canada.

Whitehead, G. S. (1999) The hydrological processes influencing the natural recolonisation of *Sphagnum* in a cutover bog after 25 years of abandonment, Quebec. Unpublished master's thesis, Department of Geography, University of Waterloo, Waterloo, Ontario, Canada.

Whiting, G. J. and Chanton, J. P. (1993) Primary production control of methane emission from wetlands. *Nature*, Vol. 364, 794–795.