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Surface moisture and energy exchange from a restored peatland, Québec, Canada

Richard M. Petrone^{a,*}, Jonathan S. Price^b, J.M. Waddington^c,
H. von Waldow^b

^a*Department of Geography and Environmental Studies and Cold Regions Research Centre, Wilfrid Laurier University,
75 University Ave West, Waterloo, Ont., Canada N2L 3C5*

^b*Wetlands Research Centre and Department of Geography, University of Waterloo, Waterloo, Ont., Canada*

^c*School of Geography and Geology, McMaster University, 1280 Main St. West, Hamilton, Ont., Canada L8S 4K1*

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Abstract

Measurements of micrometeorological variables were made for two snow-free periods at a Restored vacuum harvested and non-restored (Comparison) section of a peatland in eastern Québec, Canada. Measurements of evapotranspiration and surface heat fluxes were obtained using an eddy correlation energy balance system at the Restored site and a combination Priestley–Taylor and lysimeter approach at the Comparison site. At the ecosystem scale, the energy, water and gas exchange processes are strongly coupled. Through harvesting, a peatland may lose most of its surface vegetation cover, altering the thermal regime of the peat, while the drier conditions required for the harvesting drastically alters the system's hydrology. The measurements indicate that the adopted restoration practices (blockage of drainage ditches and the spreading of a surface mulch layer) reduce the loss of water from the peat leading to the regrowth of natural vegetation at the Restored site. The Restored site lost approximately 13 and 8% less water to evapotranspiration than the Comparison site in 2000 and 2001, respectively.

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1. Introduction

Peatlands cover 14% of Canada's land surface (Zoltai and Pollett, 1983). In peatlands, the exchange and storage of water in the upper peat layers (acrotelm) are strongly linked to photosynthetic processes and ecological succession of vegetation in

the peatland ecosystem, as well as the partitioning of surface energy and water balances (Clymo and Hayward, 1982; Kim and Verma, 1992). Processes operating at the land-atmosphere interface in peatland systems are important to both regional hydroclimatology as well as the peatland ecosystem itself. For example, the general distribution, or occurrence, of peatlands is determined largely by their thermal or energy regime (Moore, 1987). Approximately 16,000 ha of peatland are currently, or have been, harvested for horticultural and related products.

* Corresponding author. Tel.: +1-519-884-0710x3744; fax: +1-519-725-1342.

E-mail address: rpetrone@wlu.ca (R.M. Petrone).

In areas such as the St Lawrence Lowlands peatland losses are in the range of 70% (Keys, 1992). Thus the loss of these peatland systems has the potential to impact regional hydroclimatology and greenhouse gas exchange (Waddington et al., 2002).

In Canada, peatlands are initially drained via ditches (usually approximately 30 m apart) and the surface vegetation and peat are removed by vacuum extraction, leading to the destruction and removal of the acrotelm. Thus, the natural hydrologic function of the system is lost, surface runoff is much quicker, and water table position becomes prone to greater fluctuations (Schlotzhauer and Price, 1999; Price, 1996). Owing to these dramatic changes in peatland hydrology the drier abandoned harvested sites usually do not revegetate quickly (Lavoie and Rochefort, 1996; Ferland and Rochefort, 1997). Furthermore, the loss of a surface vegetation cover also reduces thermal regulation of the peat substrate and accumulation of organic matter.

The physical properties that influence the thermal behaviour of a peatland include the botanical composition of the peat, the degree of compaction of the plant material, and the degree to which pores between plant material can be water or ice filled (Romanov, 1968). The thermal properties that determine the amount and rate of heat transfer within the substrate are the volumetric heat capacity and thermal conductivity of the peat (Williams, 1970). The heat capacity of a peat soil is much higher than that in most mineral soils because of the high moisture content in peat (Novak and Black, 1985). Therefore, for the same imposed surface heat exchange, the depth of freezing and thawing in a peat soil is shallower than in most mineral soils. However, the predominance of *Sphagnum* mosses in many peatland systems complicates the thermal and energy regimes. The thermal conductive capacity of a substrate is a function of its volumetric heat capacity (C_V) and thermal conductivity (k_T). *Sphagnum* mosses have a very low thermal conductive capacity ($\sqrt{C_V k_T}$) when dry, which is a measure of the amount of heat that will be transferred into the surface from the atmosphere (Williams, 1970). Thus, heat will be transferred into, and out of, a dry peat surface at a slower rate than for wet peat or mineral soils under the same imposed surface heating.

Phase transformations of water (especially evaporation and freezing) are important factors

establishing the moisture conditions in peatlands. Therefore, when trying to re-establish pre-disturbance water conditions in a bog, a quantification of its energy regime is essential. The freezing of a peat substrate converts water in the acrotelm into an immobile solid state that impedes surface runoff (Romanov, 1968). Furthermore, the soil temperature regime and energy balance of a peatland will be affected by changes in water table position. During dry seasons, as a result of the lower water table position, less heat energy will go into evaporation if evaporation is soil limited, thereby increasing the warming of the peat. This effect may be offset somewhat by the increase in thermal insulation of the surface peat layers due to the decrease in soil moisture. These processes have not been well documented in cutover peatlands.

It is clear, therefore, that quantification of the coupling of the water and energy exchange processes is essential to the development of appropriate restoration plans of harvested peatlands. Current restoration measures used in Canada involve the blockage of drainage ditches, surface tilling, the installation of surface bunds (to retain surface runoff), and the application of a straw mulch and *Sphagnum* diaspores (seeds). The objective of this peatland restoration is the renewal of functional peat-accumulating ecosystems. However, it is difficult to evaluate how successful the adopted measures are at restoring the fundamental ecological and hydrological processes unless they are studied within the context of the entire ecosystem and for periods longer than one season. Most previous seasonal studies on energy and moisture exchange (e.g. Price, 1997; Price et al., 1998) have used simplified micrometeorological installations, often because of constraints caused by insufficient fetch in many harvested peatlands, and were limited to one season (summer). Multiseason studies are needed because recent experiments (c.f. Waddington et al., submitted) indicate that the surface cover of the peatland changes after restoration measures have been implemented. For example, the moss cover and vascular plant biomass increase, while the mulch cover applied to increase soil moisture (Price et al., 1998) decomposes after several years. The mulch cover may produce higher soil moisture contents and water table levels largely due to reductions in incoming radiation, wind and turbulence

interacting with the peat surface. However, the re-emergence of the vegetation has the potential to counteract this barrier imposed by the mulch.

Like most micrometeorological techniques the eddy correlation approach is well suited for studies of surface change effects on energy and moisture exchanges because it leaves the surface undisturbed, and difficult upscaling problems are avoided (Aurela et al., 1998). That is, larger-scale spatial averaging at the ecosystem scale is obtained directly and continuous measurements can be made over the entire growing season. This study uses the eddy correlation method to examine the atmospheric exchange of water and energy from a restored vacuum harvested peatland in eastern Québec, Canada. Energy balance and evapotranspiration data of this system are presented over two snow-free seasons after the restoration measures have been implemented. The data presented investigate the restoration effects by contrasting the energy and moisture regimes between a restored (Restored) site and an adjacent non-restored (Comparison) site to suggest the influence of the changing surface covers (i.e. re-emerging vegetation and decomposing mulch at the Restored site, and relatively constant and sparse conditions at the Comparison site). The objective of this study is to quantify the extent to which these ecosystem scale restoration measures have been successful in reducing evapotranspiration and runoff, and moderating heat exchange.

2. Methods

2.1. Study area

This study was conducted at the 200 ha Bois-des-Bel peatland near Rivière-du-Loup (47°53'N, 69°27'W), Québec, Canada (Fig. 1). The mean annual temperature is 3 °C and total precipitation is 926 mm (27% falling as snow) for the region (Environment Canada, 1993). The region's growing season averages 170 days in length, with growing degree-days averaging 2300 °C (Environment Canada, 1993). The Bois-des-Bel peatland is a treed bog of which 11.5 ha were drained in 1972, and vacuum harvested from 1973 to 1980, after which time peat cutting operations ceased. The peatland remained abandoned

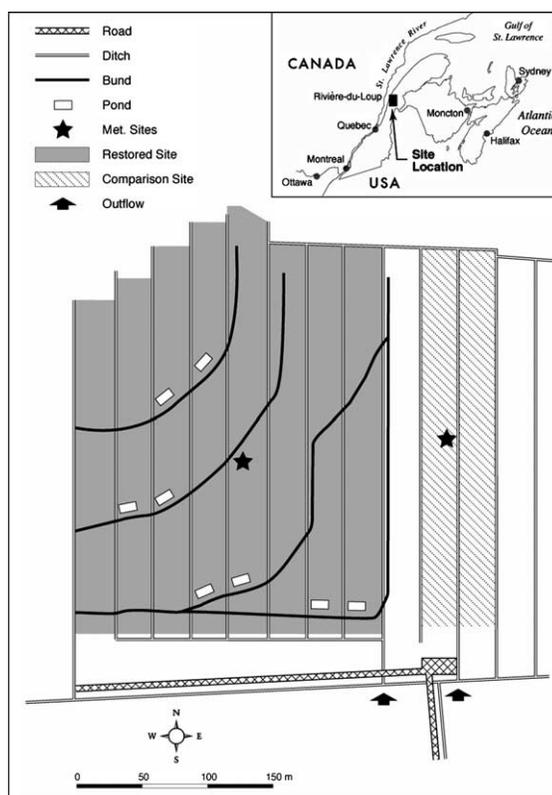


Fig. 1. Location of the Bois-des-Bel peatland, showing the Restored and Comparison fields and their respective meteorological tower locations. The location of the study site in Québec, Canada is shown in the map insert.

until the fall of 1999 when restoration measures were undertaken. At this time all but two drainage ditches were blocked in the harvested area, which was divided into eleven $30 \times 300 \text{ m}^2$ fields separated by parallel drainage ditches that drain the water south to the main drainage ditch (Fig. 1). Of these 11 fields, numbers 1–8 became the Restored site, while 10 and 11 were left as the Comparison site. As described above, the surface of the Restored site was then reprofiled (to decrease drainage from the eight restored fields into their adjacent ditches), surface bunds were installed to retain surface runoff, and 3000 kg/ha of straw mulch was uniformly spread as part of the restoration measures (Rochefort, 2000). This article reports on the first two post-restoration growing seasons (spanning mid-May to early October).

2.2. Instrumentation

Two micrometeorological towers were installed in the peatland, one at the Comparison site (with short shrubs, sparse grasses and bare peat) and the second in the Restored area (predominantly sparse shrubs, straw mulch, and re-emerging mosses and vascular vegetation) (Fig. 1). The Comparison site tower provided continuous measurements of net radiation using a net radiometer (REBS, Washington); air temperature using a thermocouple; peat temperatures and heat flux, using a probe with thermocouples at 0, 2, 5, 10, 25, 50 and 75 cm, and two soil heat flux plates (REBS, Washington) installed at approximately 5 cm below the peat surface. Soil moisture was measured with Campbell CS615 moisture probes at 5 and 50 cm (Campbell Scientific, Utah). All measurements were recorded on a CR21X datalogger (Campbell Scientific, Utah) every 10 s and were later averaged to give half-hourly values. Both the net radiation and air temperature were measured at 1.5 m above the peat surface. Evapotranspiration was measured using three plastic bucket lysimeters (each $0.12 \text{ m}^2 \times 0.2 \text{ m}$) filled with peat monoliths and vegetation representative of the major surface types within the comparison area. These lysimeters were perforated through their bases and a second bucket below captured the drainage water to prevent undue moisture build-up. All lysimeters were sunk level to the surface in representative location and weighed daily (including drainage water when necessary) to determine the rate of evapotranspiration during the previous 24-h period. Soil moisture in the lysimeters and the surrounding soil was monitored regularly using TDR probes with 20-cm wave-guides. Water was added when the lysimeter soil moisture was found to be less than that in its immediate surroundings. At the end of the study period, the bulk density for each lysimeter was calculated using the oven-dried weights of the monoliths and their saturated volumes. These data were used with the daily weight measurements in the field to determine the volumetric moisture content of lysimeters throughout the study periods.

At the Restored site, continuous half-hourly evapotranspiration and energy fluxes were measured 1.5 m above the peat surface using the eddy covariance technique. The instrumentation consisted of a 3-D sonic anemometer-thermometer (CSAT 3,

Campbell Scientific, Utah) and an open path infrared gas ($\text{CO}_2/\text{H}_2\text{O}$) analyzer (IRGA) (Li7500, LI-COR Inc., Nebraska) sampled at 10 Hz and averaged every half hour on a CR23X datalogger (Campbell Scientific, Utah). The IRGA was calibrated as outlined in the Li7500 instruction Manual (LI-COR, Inc., 2000). The eddy covariance sensors must be at a height that satisfies fetch requirements and the sampling sensitivity of the instruments. Due to the small fetch area of the Restored peatland, the sensors were placed at $\sim 1.5 \text{ m}$ to obtain a representative flux. Petrone et al. (2001) showed that 80% of the flux observed by the Restored site tower originated from within 77 m of the tower, and that the maximum flux originated from approximately 17 m away from the tower. Finally, the eddy covariance data were also corrected for density effects (Webb et al., 1980; Leuning and Judd, 1996), sensor separation (Leuning and Judd, 1996; Blanford and Gay, 1992), and energy balance closure for the study period (Petrone et al., 2001; Twine et al., 2000; Barr et al., 1994; Blanken et al., 1997). In addition, photosynthetically active radiation (PAR) was measured using a LI-COR Quantum sensor (LI-COR Inc., Nebraska), precipitation was measured using a tipping bucket rain gauge (Campbell Scientific, Utah) and fine wire thermocouples were inserted near the top, middle and bottom of the mulch layer at the Restored site. Continuous measurements of net radiation, air temperature, peat temperatures and heat flux, and soil moisture were also monitored, as outlined above, for the Comparison site.

2.3. Surface energy fluxes

The surface energy balance is given by,

$$Q^* = Q_G + Q_H + Q_E \text{ [W m}^{-2}\text{]} \quad (1)$$

where Q^* is the net radiative flux at the surface, Q_G is the ground heat flux, Q_H is the sensible heat flux and Q_E is the latent heat flux. Vegetated surfaces generally have a mean daily soil heat flux (Q_G) one or two orders of magnitude smaller than the major terms in the surface energy balance (Brutsaert, 1982). However, on shorter temporal scales, Q_G can be quite important. The subsurface soil temperatures, and Q_G , are a function of solar radiation, soil texture, soil moisture content and state, in addition to surface

vegetation cover and weather conditions (wind, air temperature, humidity) (Williams and Smith, 1989).

The ground thermal regime was obtained using the thermocouple arrays and heat flux plates installed in the peat at both sites as described above. Ground heat flux plates provide a good account of the diurnal behaviour of the subsurface heat flux in mineral soils, but previous studies indicate that they can significantly underestimate the flux in organic soils due to poor contact between the plate and peat, and the disruption of vapor flow (Rouse, 1984, 1987; Halliwell and Rouse, 1987). At both sites, the ground heat flux was measured with two soil heat flux plates as described above. Q_G was also calculated using the calorimetric method (Halliwell and Rouse, 1987) using the ground temperature profile and heat capacity calculations for each soil layer accounting for changes in moisture amount and state. The ratios between the seasonal mean heat flux plate measurements and the calorimetric calculations of the total seasonal Q_G were 0.77 and 0.64 for the Restored and Comparison sites, respectively.

At the Comparison site, Q_E was obtained using the lysimeter evapotranspiration data, and Q_H was solved as the residual of Eq. (1). This method also required the measurements of the net radiation and ground heat flux described above. At the Restored site, the eddy correlation method (EC) was employed to obtain the sensible and latent heat fluxes. The eddy correlation method of measuring the surface energy fluxes is based on determining the turbulent fluxes of water vapour, momentum and sensible heat from the covariances of their respective eddies. This measures the turbulent exchange directly without restrictive assumptions as to the nature of the surface and the transfer mechanisms involved (Peixoto and Oort, 1992). The mean vertical flux of the sensible and latent heat fluxes were obtained via

$$Q_H = \rho C_p \overline{w'T'} \text{ [W m}^{-2}\text{]} \quad (2)$$

$$Q_E = L \rho \overline{w'q'} \text{ [W m}^{-2}\text{]} \quad (3)$$

where ρ (kg m^{-3}) is the density of air, C_p ($\text{MJ kg}^{-1} \text{K}^{-1}$) is the specific heat of the air at a constant pressure, L ($\text{MJ kg}^{-1} \text{kPa}^{-1}$) is the latent heat of vaporization, w' (m/s), T' (K) and q' (kPa) are

the instantaneous variances in the vertical wind-speed, air temperature and specific humidity all measured at the same height.

The covariance between w' , q' and T' was made by electronic analog computation consisting of a multiplication and averaging process on the CR23X datalogger. The CR23X processor calculated a simple statistical covariance for a given time period (10 Hz) every 15 min, which were then averaged for the 30-min measurement interval.

3. Results

3.1. Hydrology and microclimate

The two study seasons were divided into three periods generally delimited by air temperature, PAR and net ecosystem CO_2 exchange (NEE). Periods 1, 2 and 3 spanned 17 May to 18 June, 19 June to 2 September, and 3 September to 11 October, respectively. These periods represent three fundamental phases of the active season in both years; the post-snowmelt initial growth (1), full summer growth (2) and late summer senescence periods (3).

Over the two experimental growing seasons the peatland received 368 mm of precipitation in 2000 and 394 mm in 2001, falling below the 30-year normals for this region. The Restored site lost 354 (467) mm through evapotranspiration in 2000 (2001), while the Comparison site lost 406 (509) mm, respectively (Table 1). The 2000 season was slightly warmer, while 2001 received approximately 7% more precipitation (Table 1). The mean water table position was about 27% deeper at the Comparison compared to the Restored site over each season. Water table positions were obtained using 35 and 9 wells in the Restored and Comparison sites, respectively, including one at each of the main tower locations (Fig. 1). The mean water table position of all 35 wells in the Restored site was 19.6 ± 6.2 cm, while at the Comparison site the mean depth was 47.9 ± 14.9 cm. Thus, the mean values from the towers can be assumed to be representative of the bulk of the peatland. Mean soil moisture contents at 5 cm decreased at both sites from 2000 to 2001, while remaining double the Comparison values at the Restored site (Table 1).

Table 1

Seasonal values of precipitation (P), air temperature (T_{Air}), peat temperature at 5 cm (T_{Soil}), water table depth (WT) (standard deviations in water table depth are shown in brackets), evapotranspiration (ET) and volumetric soil moisture content at 5 cm (θ) (standard deviations in soil moisture content are shown in brackets) for the Restored and Comparison sites, Bois-des-Bel peatland, Québec, Canada, 2000 and 2001

Year	Site	P (mm)	T_{Air} (°C)	T_{Soil} (5 cm) (°C)	WT (cm)	ET (mm)	θ
2000	Restored	368	17.7	14.2	31(9)	354	0.80 (0.06)
	Comparison	368	17.7	13.9	43(10)	406	0.44(0.03)
2001	Restored	394	14.4	14.5	27(11)	467	0.50(0.06)
	Comparison	394	14.4	14.8	37(6)	509	0.21(0.01)

3.2. Energy flux partitioning

Seasonal trends in the energy flux components at the Restored and Comparison sites, expressed as a ratio of Q^* , in both seasons are illustrated in Table 2. Net radiation (Q^*) at the Comparison site was slightly larger than the Restored site in both seasons. Seasonal Q_{H}/Q^* was greater at the Restored site in 2000 (Comparison = 0.58 and Restored = 0.51) and greater at the Restored site in 2001 (Comparison = 0.17 and Restored = 0.37). The Comparison site had a larger Q_{E}/Q^* than the Restored site in all periods in 2001 (Table 2). The ground heat flux (Q_{G}/Q^*) was generally larger at the Comparison site in both seasons, especially in 2000 before there was significant mulch decomposition or compaction (Table 2). The mean standard error in the energy flux measurements was approximately 0.01 for the Restored site and 0.004 for the Comparison site in both seasons. Furthermore, an analysis of the root mean square errors inherent in the instrumentation yielded a mean error of approximately 0.200. However, this instrumental error analysis is further improved by the corrections outlined above.

Therefore, these relative differences must be evaluated with respect to their accuracy based on the residual and instrumental errors in addition to possible biases introduced by the method's ability to capture the spatial heterogeneity of the system.

3.3. Evapotranspiration

Evapotranspiration was 25–32% higher in 2001 than 2000, and the Comparison site lost moisture to evapotranspiration at a higher rate than the Restored site in both years (Fig. 2). Water table position responds to increases in the slope of cumulative evapotranspiration and precipitation events (Fig. 2). To explain the changing patterns in evapotranspiration at the two sites over the two study seasons it is constructive to examine their respective equilibrium evaporation rates (or equilibrium latent heat flux) (Q_{EQ}).

The equilibrium evaporation is the rate at which a sufficiently large wet surface will evaporate into an air mass that has come into equilibrium with the surface (Priestley and Taylor, 1972). That is, the atmosphere has no vapor pressure deficit so that this rate of equilibrium

Table 2

The mean net radiation (Q^*), relative sensible heat flux (Q_{H}/Q^*), relative latent heat flux (Q_{E}/Q^*) and relative ground heat flux (Q_{G}/Q^*) for each of the three seasonal periods at the Restored and Comparison sites, Bois-des-Bel peatland, 2000 and 2001

Site	Period	Q^* (W m^{-2})		Q_{H}/Q^*		Q_{E}/Q^*		Q_{G}/Q^*	
		2000	2001	2000	2001	2000	2001	2000	2001
Restored	1	252	273	0.53	0.45	0.66	0.74	0.020	0.020
	2	245	256	0.57	0.29	0.57	0.86	0.020	0.010
	3	140	138	0.64	0.57	0.80	1.10	0.010	-0.010
Comparison	1	286	286	0.48	0.17	0.58	0.84	0.040	0.020
	2	259	260	0.43	0.12	0.67	0.93	0.020	0.020
	3	143	158	0.64	0.23	0.78	1.10	0.100	-0.001

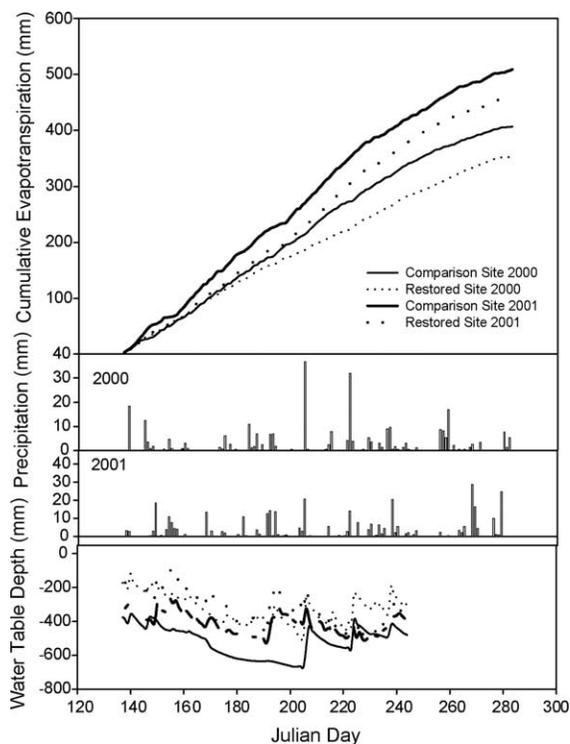


Fig. 2. The cumulative evapotranspiration, daily precipitation amounts and water table depths for the Restored and Comparison site, Bois-des-Bel peatland, 2000 and 2001.

evaporation is a function of the quantity of available energy ($Q^* - Q_G$) only. Thus, comparison of the relative equilibrium evaporation rates between the two sites will provide some insight into whether or not the surface cover at each location can have an influence on the evaporative flux. The equilibrium evaporation from the Comparison site (with seasonally larger Q^* and Q_G) was approximately 15% greater than that from the Restored site in 2000. Whereas in 2001 Q^* and Q_G were both more similar between the sites, and the two sites were almost identical in their Q_{EQ} , with the Comparison site's values still being larger (slope of 0.97) (Fig. 3a). Focusing just on the Restored site, which experienced the most drastic changes in surface cover (decomposing mulch layer and re-emerging vegetation), it can be seen that its latent heat flux began to approach potential rates in 2001 (Fig. 3b). By the end of the 2001 season, mosses and vascular plants covered approximately 13 and 30% of the restored portion of the peatland, respectively (Campeau pers. Comm.). That is, these are areas where the vegetation, and not the decomposing

straw mulch, dominates the surface cover. Vegetation growth was minimal at the Comparison site with the surface cover remaining relatively constant. Furthermore, the Priestley–Taylor α coefficient for the Restored site increased from 0.67 in 2000 to 0.87 in 2001, a value in the range found for most natural bog systems (Price, 1991). Whereas, the Comparison site α values changed very little (0.67 in 2000, and 0.69 in 2001). The α coefficients were calculated for the Restored site using daily averages of the energy balance components obtained using the eddy correlation system, and for the Comparison site using lysimeter data and average energy balance values for corresponding periods of lysimeter sampling.

3.4. Peat thermal regime

Table 3 shows daily average, maximum and minimum peat temperatures at 5 cm in each period for both sites, along with standard deviations. This temperature data close to the surface demonstrate the effects of surface cover on temperature changes in the Restored site soil. This was evident in the standard deviations and mean temperatures during Period 2 in 2000. In 2001, as the mulch has been decomposed and compacted, temperatures become more similar (Table 3). However, minimum temperatures were warmer at the Restored site due to the insulative properties of the now more abundant moss layer (Campeau unpublished data). The ground temperatures in the upper peat layers were similar at both sites in 2000, while maximum temperatures were greater at the Comparison site and minimum temperatures greater at the Restored site (Table 3). This trend is a result of the sheltering effect of the mulch layers, which will permit less warming of the upper peat layers under high solar radiation conditions. In 2001, mean temperatures are observed to be slightly larger at the Restored site as well as the maximum and minimum values (Table 3). Maximum temperatures have increased because of the decrease in the mulch layer and the re-emergence of vegetation producing lower surface albedos and more heat penetration. Minimum temperatures also increased because of the greater insulative properties of the surface (e.g. more mosses, straw mulch still present, and greater soil moisture).

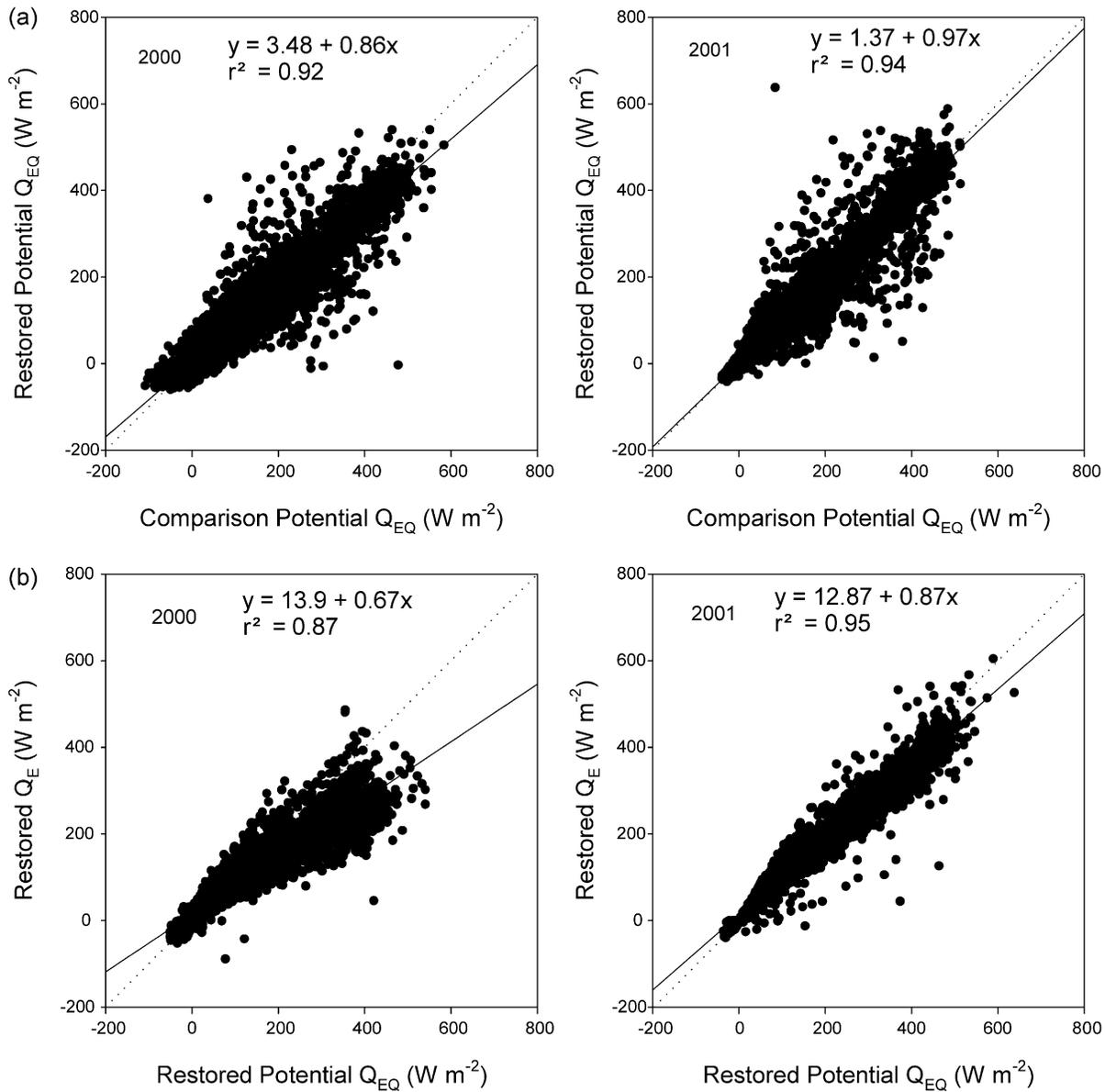


Fig. 3. Comparison of (a) the potential equilibrium evaporation rates for both the Restored and Comparison sites, and (b) the actual latent heat flux and potential equilibrium evaporation at the Restored site, Bois-des-Bel, 2000 and 2001.

4. Discussion

4.1. The effects of restoration on the surface energy balance

In general, Q^* was very similar at both sites in both seasons, showing a gradual decrease over the course

of the season and an increase in the seasonal mean in 2001 (Table 2). Seasonally, the presence of a straw mulch cover contributed to significant changes in the microclimate of the peat system, as illustrated in Table 2. Q^* was very similar between the two sites, but the Restored site had a high surface temperature due to its poor conductivity and low heat storage

Table 3
The daily mean, maximum and minimum temperatures from 5 cm depths in the peat soils

Site	Period	2000			2001		
		Mean	Max	Min	Mean	Max	Min
Restored	1	9.9(2.5)	11.5(2.6)	8.4(2.7)	13.4(3.3)	17.5(5.1)	11.0(3.6)
	2	16.5(1.3)	17.5(1.5)	15.2(1.5)	16.6(1.5)	16.9(1.6)	16.2(1.5)
	3	11.7(2.7)	13.4(2.3)	10.1(3.3)	12.5(2.7)	12.8(2.7)	12.3(2.7)
Comparison	1	9.9(1.9)	10.8(1.9)	8.7(2.1)	11.8(2.9)	13.3(3.1)	10.1(2.9)
	2	16.5(1.6)	18.5(1.8)	14.5(1.5)	16.7(1.8)	18.2(2.2)	15.2(1.8)
	3	10.9(3.3)	11.9(3.4)	10.3(3.2)	12.1(3.2)	13.5(3.4)	11.1(3.2)

Averages are calculated for each of the three seasonal periods at both the Restored and Comparison sites, Bois-des-Bel peatland, 2000 and 2001. Standard deviations are shown for all values in brackets.

capacity. Therefore, the straw lost more of the incoming solar energy as (long-wave) re-radiation or conduction to the atmosphere producing a slightly lower Q^* at the Restored site (Novak et al., 2000).

4.2. The effects of mulch on the surface energy and moisture exchange

Q_E at the Comparison site was greater than that at the Restored site, except during low energy conditions (e.g. spring and fall 2000) when moisture diffusion through the mulch was stronger (Table 2). Greenwood (unpublished data) has shown that the percentage area cover of the mulch layer decreased by approximately 25% between the ends of the 2000 and 2001 seasons. A mulch cover will decrease substantially after being in the field for 1 year because of decomposition and disturbances such as wind and rain, decreasing the thermal and mass diffusivities by as much as 50% (Wagner-Riddle et al., 1996; Novak et al., 2000). Thus, in the later stages of drying and/or decomposition, the vapour pressure gradient above the mulch will be very similar to that above a bare soil. This was evident in Table 2 where in 2001 Q_E from the Restored site exceeded Q_H in all periods, while still remaining lower than the flux at the Comparison site.

In general, mulch covered surfaces tend to exchange less Q_E than a bare soil. Straw mulches, like other porous surface covers, do not block as much water as precipitation as more dense, impermeable covers, but they do allow greater recharge of soil moisture from precipitation than a more dense surface cover would permit (Price et al., 1998; McDonald

and Helgerson, 1990). Thus, the moisture exchange from the Restored site increased during the 2001 season when the mulch had further decomposed and become even less dense. However, this enhanced moisture exchange observed for the Restored site in 2001 may also be the result of other changing surface characteristics like the re-emergence of a substantial vegetation cover, which would have enhanced the turbulent regime of the system as well as the transpiration component.

4.3. The effects of vegetation regrowth on the surface energy and moisture exchange

Mass and heat exchange processes in a mulch covered surface involve molecular diffusion and turbulent transfer that increase linearly with wind-speed above the mulch surface (Tanner and Shen, 1990). By the end of the second season, the mulch layer had substantially decreased (Greenwood, unpublished data), thereby decreasing the surface roughness (z_0) and thus, the potential turbulent transfer of heat and mass. However, at the same time, the vegetation layer made a significant emergence from 2000 to 2001, which may counteract the effects of the decreasing mulch cover, making the surface rougher. The changing surface characteristics can be examined by studying the changes in the surface roughness (z_0) and frictional velocity (u^*) at the two sites during the two seasons. The surface roughness length (z_0) is a measure of the aerodynamic roughness of the surface, and is a function of the height, shape and density distribution of the surface

roughness elements (Oke, 1987). z_0 is generally described by,

$$z_0 = \frac{z - d}{e^{k(u_z/u^*)}} \tag{4}$$

where u_z is the mean windspeed at height z , k is von Karman’s constant (~ 0.40), d is the displacement height (approximated as $\frac{2}{3}h_0$, where h_0 is the mean height of the vegetation), and u^* is the friction velocity. The windspeed (u_z) is measured at a height (z) of 1.5 m, and u^* is calculated as

$$u^* = \sqrt{-\overline{u'w'}} \tag{5}$$

where u' and w' are the fluctuations of the horizontal and vertical wind components about their respective means, and $-\overline{u'w'}$ is the kinematic shear stresses. However, Eq. (4) only applies to neutral conditions. For stable or non-stable conditions the above relationship must be corrected with an appropriate profile function (Brutsaert, 1982). Thus, for non-neutral conditions, Eq. (4) becomes

$$z_0 = \frac{z - d}{e^{k(u_z/u^*) + \psi(\zeta)}} \tag{6}$$

where $\psi(\zeta)$ is the profile function that depends on Q_H and Q_E . For unstable conditions $\psi(\zeta)$ is given by

$$\psi(\zeta) = 2 \ln \left[\frac{(1+x)}{2} \right] + \ln \left[\frac{(1+x^2)}{2} \right] - 2 \tan^{-1} x + \frac{\pi}{2} \tag{7}$$

where

$$x = (1 - \gamma\zeta)^{1/4} \tag{8}$$

and γ is an empirical constant in the Monin–Obukhov equations (~ 20 for this type of surface), and

$$\zeta = \frac{z - d}{L} \tag{9}$$

in which L is the stability length given by

$$L = \frac{-u^{*3} \rho}{kg \left[\left(\frac{Q_H}{T_a c_p} \right) + 0.61 T_a Q_E \right]} \tag{10}$$

where the sign of L indicates whether conditions are stable or unstable, and varies diurnally, ρ is the density of moist air, g is the acceleration due to

gravity, and c_p is the specific heat for a constant pressure (Brutsaert, 1982; Garratt, 1992).

For stable conditions, the profile function is given by

$$\psi(\zeta) = -\beta\zeta \tag{11}$$

where β is also an empirical constant from the Monin–Obukhov equations (~ 6) (Garratt, 1992).

Estimations of both u^* and z_0 have significant short-term variability, thus the long-term trends are best observed as a cumulative function (Fig. 4). The friction velocity (u^*) measured over the Restored site increased substantially in 2001 (despite similar mean windspeeds between the two seasons), from approximately Julian Day 186 onward, and the slope of the 2000 plot changed downward (Fig. 4b). Similarly, z_0 also increases in 2001. By the end of 2000, substantial vegetation had already begun to re-grow, especially vascular plants (Petrone et al., 2001). This is seen in

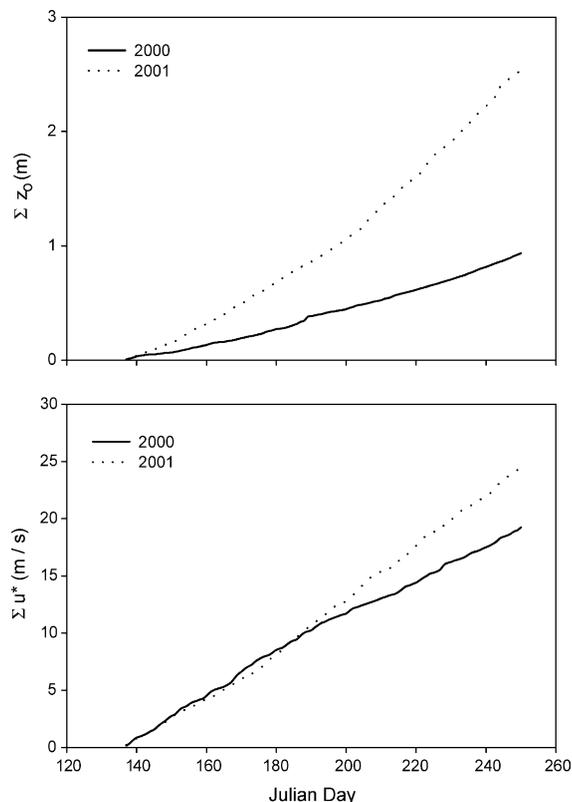


Fig. 4. Cumulative changes in surface roughness length (Σz_0) and surface friction velocity (Σu^*) for the Restored site, Bois-des-Bel, 2000 and 2001.

the slight increase in cumulative z_o in 2000 (Fig. 4a). This trend is significantly increased in 2001 when all species of plants made a strong re-emergence. These trends of u^* and z_o correlate very well with the cumulative evapotranspiration trends shown in Fig. 2. Thus, it is thought that the increase in Q_E and evapotranspiration at the Restored site in 2001 is due more to the denser surface vegetation cover than the further decomposed straw mulch layer.

Further support for the role of a changing turbulent regime as a result of the vegetation growth and altered surface characteristics is shown by the variation of z_o with wind direction (Fig. 5a). First, the highest z_o values were observed when the winds were out of the south southwest, south and west in both seasons. These directions corresponded with flow perpendicular to the surface bunds (Fig. 1) or the blocked drainage ditches. The blocked drainage ditches support much larger vascular plants, especially *Typha*, and as such larger surface roughness elements. Furthermore, in 2001 re-growth had significantly increased the magnitude of z_o in all directions. Fig. 5b shows the distribution of mean daily wind direction during the two study seasons. There was only a slight shift in the frequency of wind directions

corresponding to the zone of lower surface roughness in 2001, suggesting that the enhanced fluxes observed for this season cannot be attributed to changes in the dominant local flow pattern.

Thus, there are two main contributions to the transfer of moisture in this system. First, the increase in vegetation cover since restoration, especially that of the vascular plants, has led to more use of the available soil moisture and enhanced the evapotranspiration rate. Second, the main contribution to heat and mass transfer in a mulch covered system comes from the convective component, which is due to air flow over the mulch that partially penetrates this surface layer (Finnigan, 1979). Thus, as the mulch layer becomes shallower and vegetation growth increases the turbulence regime becomes greater due to the increased surface roughness, this convective component will also enhance the evapotranspiration rate. This is illustrated by the increased evapotranspiration at the Restored site in the second study season.

4.4. Restoration implications

After 2 years of restoration, the hydrologic conditions (stable water table position and moisture conditions in the upper peat profile) that are integral to *Sphagnum* re-establishment and accumulation are improving. Much of the peatland's energy balance relates directly to the soil moisture regime. That is, as soil moisture increases, the heat capacity and thermal conductivity of the substrate also increase, ameliorating peat temperature extremes. The effects of the blocked drainage ditches and the mulch cover further contribute to these interactions. In general, mulches dampen the annual and daily temperature fluctuations of the peat by increasing the minimum and/or decreasing the maximum peat temperatures. An extensive mulch cover suppresses heat exchange both into and out of the peat, producing a small positive ground heat flux in the spring, and negative in the fall (Petrone et al., 2001). As the mulch cover continues to decompose, and vegetation becomes more established, its effects on the thermal moisture regime are also evident.

Under conditions of large available energy, a mulch cover suppresses evapotranspiration. Thus, under most energy conditions a mulch cover will

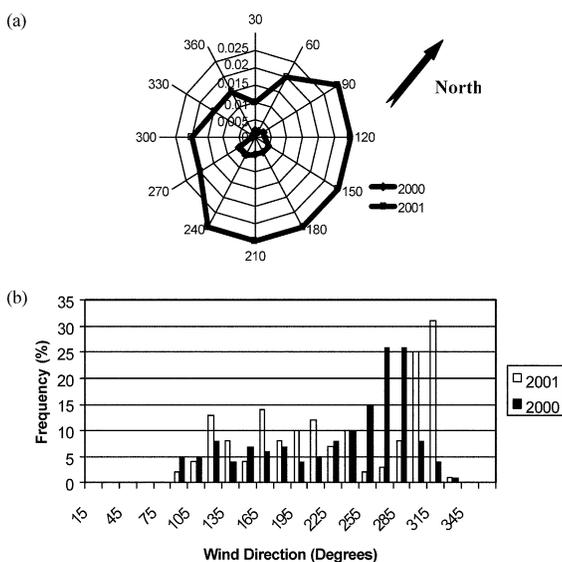


Fig. 5. (a) Surface roughness length (z_o) for different wind directions at the Restored site, and (b) histogram of wind direction, Bois-des-Bel, 2000 and 2001.

prevent moisture loss (evaporation), but may also prevent moisture recharge to the water table due to interception (Price unpublished data). In the 2001 season there was more available energy, and the mulch cover was trapping less moisture. However, more moisture was allowed to recharge the water table. Thus, there was more evapotranspiration and lower volumetric moisture contents in the upper peat profile in 2001, but similar water table positions to 2000 (Table 1). Furthermore, ditch blocking and reduced drainage have also contributed to more stable water table positions.

Other studies show it is likely that the straw will be mostly decomposed within three years (Waddington et al., submitted), at which time the peat surface will be covered by mosses and stabilized against erosion. It is then hoped that with enough vegetation this new surface (after the mulch has gone) will naturally regulate moisture conditions (e.g. Whitehead and Price, 2001) while accumulating carbon.

The hydrologic conditions of the system have become more stable (seen through the water table positions at the Restored site (Table 1)), and evapotranspiration from the Restored site is less than that from the non-restored Comparison site. The larger evapotranspiration in 2001 reflects, to some degree, the increased precipitation in that season, but most importantly the strong re-emergence of vascular plant and moss species as well as the changing mulch cover conditions two seasons after restoration. As the density of vascular plant species increased in the 2001 season more moisture was lost through transpiration. Furthermore, the increased surface roughness caused by this vegetation growth further enhanced the evapotranspiration rate through increased turbulent transport.

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