SCIENTIFIC BRIEFING

HYDROLOGICAL PROCESSES
Hydrol. Process. **15**, 2839–2845 (2001)
DOI: 10.1002/hyp.475

Ecosystem scale evapotranspiration and net CO_2 exchange from a restored peatland

Richard M. Petrone,[1]*
J. M. Waddington[2] and
Jonathan S. Price[1]

[1] *Wetlands Research Centre and Department of Geography, University of Waterloo, 200 University Ave West, Waterloo, Ont. N2L 3G1, Canada*
[2] *School of Geography & Geology, McMaster University, 1280 Main St. West, Hamilton, Ont. L8S 4K7, Canada*

Correspondence to:
Richard M. Petrone, Wetlands Research Centre and Department of Geography, University of Waterloo, 200 University Ave West, Waterloo, Ont. N2L 3G1, Canada.

Abstract

An understanding of the symbiotic water and gas exchange processes at the ecosystem scale is essential to the development of appropriate restoration plans of extracted peatlands. This paper presents ecosystem scale measurements of the atmospheric exchange of water and carbon dioxide (CO_2) from a restored vacuum extracted peatland in eastern Québec, utilizing full-scale micrometeorological measurements of both evaporation and CO_2. The results indicate that the adopted restoration practices reduce the loss of water from the peat, but CO_2 emissions are ∼25% greater than an adjacent nonrestored comparison site. The blockage of drainage ditches and the existence of a mulch cover at the site keep the moisture conditions more or less constant. Consequently, the CO_2 flux, which is predominantly soil respiration, is strongly controlled by peat temperature fluctuations. Copyright © 2001 John Wiley & Sons, Ltd.

Key Words peatland; restoration; evapotranspiration; carbon dioxide; eddy correlation

Introduction

Globally, peatlands cover over 170 million hectares and represent one of the largest carbon pools in the terrestrial biosphere (Gorham, 1991), because of their wet conditions that limit plant and soil decomposition. Many peatlands have been drained and extracted for horticultural and agricultural purposes. The peatland is initially drained via ditches and the surface vegetation and peat is removed by a variety of techniques. Recently, the vacuum extraction technique has become the most commonly used method in the horticultural industry. However, owing to dramatic changes in peatland hydrology (Price, 1996) the drier and abandoned extraction sites usually do not revegetate quickly (Lavoie and Rochefort, 1996; Ferland and Rochefort, 1997). This switches the peatland to a large net source of atmospheric CO_2 (Price and Waddington, 2000). Thus, restoring the hydrology is required to return these peatlands to functioning, carbon accumulating, ecosystems.

When peatlands are rewetted, conditions within the peat that control the carbon exchange are dominated by evaporation over the summer period (Price, 1996; Van Seters and Price, 2001), leading to a strong coupling between the carbon and moisture regimes (Waddington and Price, 2000).

Received 12 March 2001
Accepted 21 April 2001

An understanding of the symbiotic water and gas exchange processes is therefore essential to the development of appropriate restoration plans of extracted peatlands. Although seasonal studies on greenhouse gas (e.g. Tuittila *et al*., 1999; Waddington and Warner, 2001; Waddington and Price, 2000) and moisture exchange (Price, 1996, 1997; Price *et al*., 1998) from extracted and restored peatlands have been conducted, they are limited by either the small areal extent of chamber measurements for CO_2 exchange measurements and/or the simplified micrometeorological installations for evaporation. This paper presents the first ecosystem scale measurements of atmospheric exchange of water and carbon dioxide (CO_2) from a restored vacuum extracted peatland in eastern Québec and is the first study designed to test, at the ecosystem scale, the success of a restoration project in restoring the natural hydrological and carbon sink functions of an extracted peatland.

Methods

Data presented were collected from the 11·5 ha Bois-des-Bel peatland near Rivière-du-Loup (47°53′N, 69°27′W), Québec. The mean annual temperature and total precipitation for the region are 3 °C and 926 mm (27% falling as snow), respectively (Environment Canada, 1993). Restoration measures were undertaken during fall 1999. These measures included blocking of the drainage ditches, surface tilling and the spreading of 3000 kg ha^{-1} of straw mulch (Rochefort, 2000). Prerestoration measurements were taken between May and October 1999, and this paper reports on the first postrestoration monitoring season.

Continuous half-hourly CO_2 and evapotranspiration fluxes were measured at 1·5 m above the peat surface using the eddy covariance technique from 17 May to 11 October 2000. The instrumentation consisted of a 3-D sonic anemometer–thermometer (Campbell Scientific CSAT 3) and an open path infrared gas (CO_2/H_2O) analyser (IRGA) (Li7500, LI-COR Inc., Lincoln, NE) sampled at 10 Hz and averaged every half hour on a Campbell Scientific 23X datalogger. The IRGA was calibrated as outlined in the LI-COR Instruction Manual (LI-COR Inc., 2000). Quality controlled eddy covariance measurements of evaporation and CO_2 had an error of approximately 20% prior to correction. Respiration was separated from the tower net ecosystem CO_2 exchange (NEE) measurements using ensemble averages of quality nighttime tower measurements, which were then used to model respiration as a function of soil temperature (at a depth of 5 cm). Gross ecosystem production (GEP) was then determined as the residual in the carbon balance by subtracting the modelled respiration values from the measured NEE. Moisture conditions were monitored with multiple level TDR and tensiometer measurements. The TDR probes were calibrated using peat cores collected from the site, and their volumetric moisture contents used to refine the calibration equation. Precipitation was collected using both tipping bucket and manual rain gauges, and the ground thermal regime was obtained using thermocouple arrays (0, 2, 5, 10, 25, 50 and 75 cm) installed in the peat.

Due to the small fetch area of the restored peatland, the eddy covariance sensors were placed at $\sim$1·5 m to obtain a flux representative of the 'restored peatland'. Detailed footprint analysis demonstrated that 80% of the measured flux originated from within 77 m of the tower, and the maximum flux from within 17 m. To ensure that the low position of the sensors captured a representative flux, a power spectral density function was computed using high frequency eddy covariance data (20 Hz) to determine if the sensor location and sampling intervals were sufficient to capture both the large lower frequency and small higher frequency eddies. The results of this analysis showed that the tower measurements captured 83% of the energy being transferred. Finally, prior to analysis, the eddy covariance data was corrected for density effects (Webb *et al*., 1980; Luening and Judd, 1996) and sensor separation (Leuning and Judd, 1996; Blanford and Gay, 1992). As a final correction to the flux data the energy balance closure was calculated and forced for the study period. Closure is most reasonably forced by assuming that the measured available energy is representative of the plot that the eddy covariance sensors are measuring, leaving the sensible and latent heat fluxes to be adjusted (Twine *et al*., 2000). Thus it was assumed that the Bowen ratio was correctly measured by the eddy covariance system and individual values of the sensible and latent heat fluxes were adjusted to balance the energy budget (Barr *et al*., 1994; Blanken *et al*., 1997; Twine *et al*., 2000). After corrections the energy balance fluxes for this study period averaged a closure of 0·98 for the season.

Results and Discussion

The study season was divided into three periods delimited by air temperature, photosynthetically active radiation (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. Between 17 May and 11 October, the study site received 368 mm of precipitation, while losing 354 mm of moisture through evapotranspiration. The study period NEE was 478 g C. Evapotranspiration was fairly constant throughout the entire season, with small changes in slope corresponding with variations in precipitation (Figure 1). The cumulative NEE plot (Figure 1) indicates that total respiration (positive flux) dominated gross ecosystem production (GEP) (negative flux) over the entire season with quite marked changes in slope coinciding with the period transition points, increasing slightly during period 2 (Figure 1).

The study period began with the peat at saturation, with little water loss over the course of the period (Figure 2). The maximum decrease in the soil volumetric water content (VMC) of the upper peat layers was ~20% by the middle of the study period. However, as the period drew to a close the moisture values approached those of the early study season (~70% VMC) (Figure 2). The study period range in mean daily air temperature was approximately 21 °C (Figure 2), with the temperature increasing steadily during period 1 from 9 to 24 °C, remaining fairly constant in period 2 before decreasing to 3 °C in period 3 (Figure 2). Throughout most of the season, NEE was a source to the atmosphere (positive values), especially during the middle period as soil moisture decreased by ~10% and air and soil temperatures remained high (Figure 2). GEP also increased slightly (negative values) during the peak of the growing season, suggesting that as the season progressed

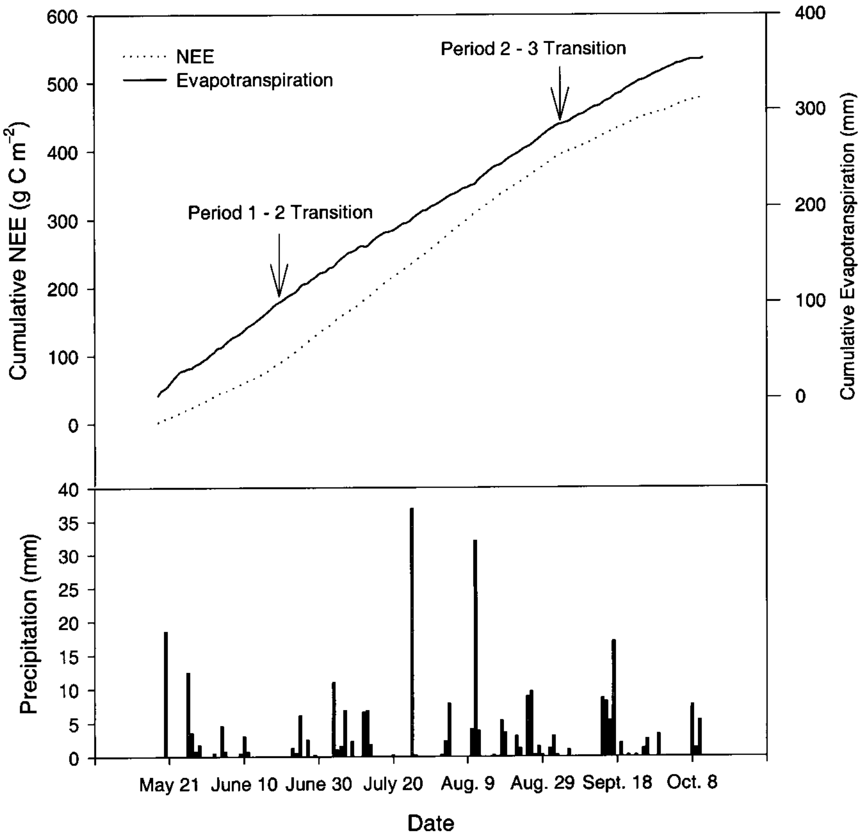

Figure 1. The cumulative net ecosystem CO_2 exchange (NEE), cumulative evapotranspiration and daily rainfall for the restored Bois-des-Bel peatland, 2000. The transition points between periods 1 and 2, 2 and 3 are illustrated with arrows on the cumulative plot

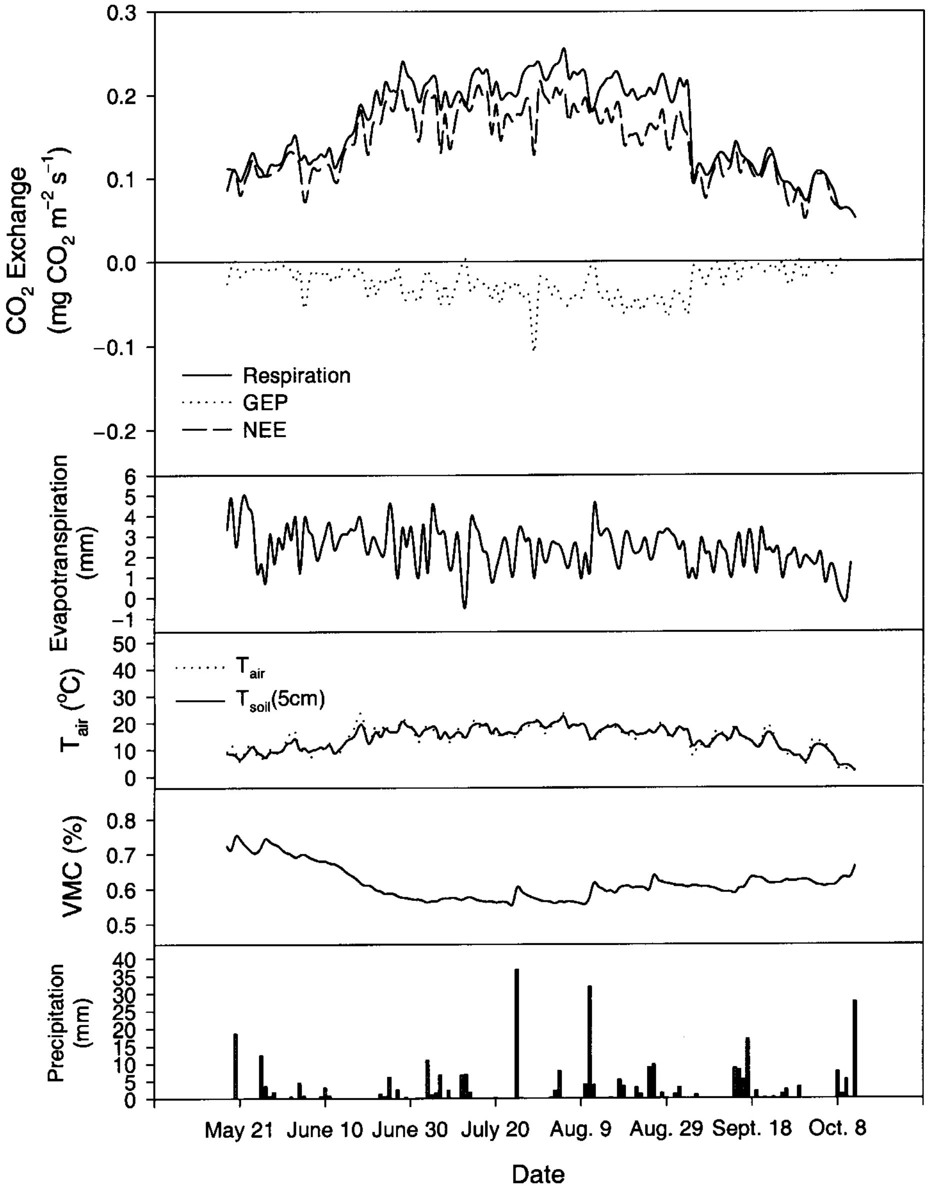

Figure 2. Mean daily respiration, gross ecosystem production (GEP), net ecosystem CO_2 exchange (NEE), evaporation, air temperature (T_{air}), soil temperature at 5 cm (T_{soil}), soil moisture (VMC) and precipitation at the restored Bois-des-Bel peatland, 2000

some vegetation regrowth was occurring. Cooler and moister conditions beyond the month of August have lowered respiration rates, decreasing NEE.

Figure 3 shows the mean diurnal CO_2 exchange components along with air temperature and photosynthetically active radiation (PAR) for each of the three study periods. The magnitudes of all three components increased in period 2 and decreased substantially in period 3, with the largest changes observed for GEP (a decrease of ~70%). The period (~13 h) over which total respiration (soil and vegetation) dominated NEE remained similar over all three periods, whereas the period of significant GEP decreased by more than half in period 3 (Figure 3). The peak in GEP (0·05, 0·15, 0·05 mg CO_2 m^{-2} s^{-1} in periods 1, 2 and 3 respectively) appears to have

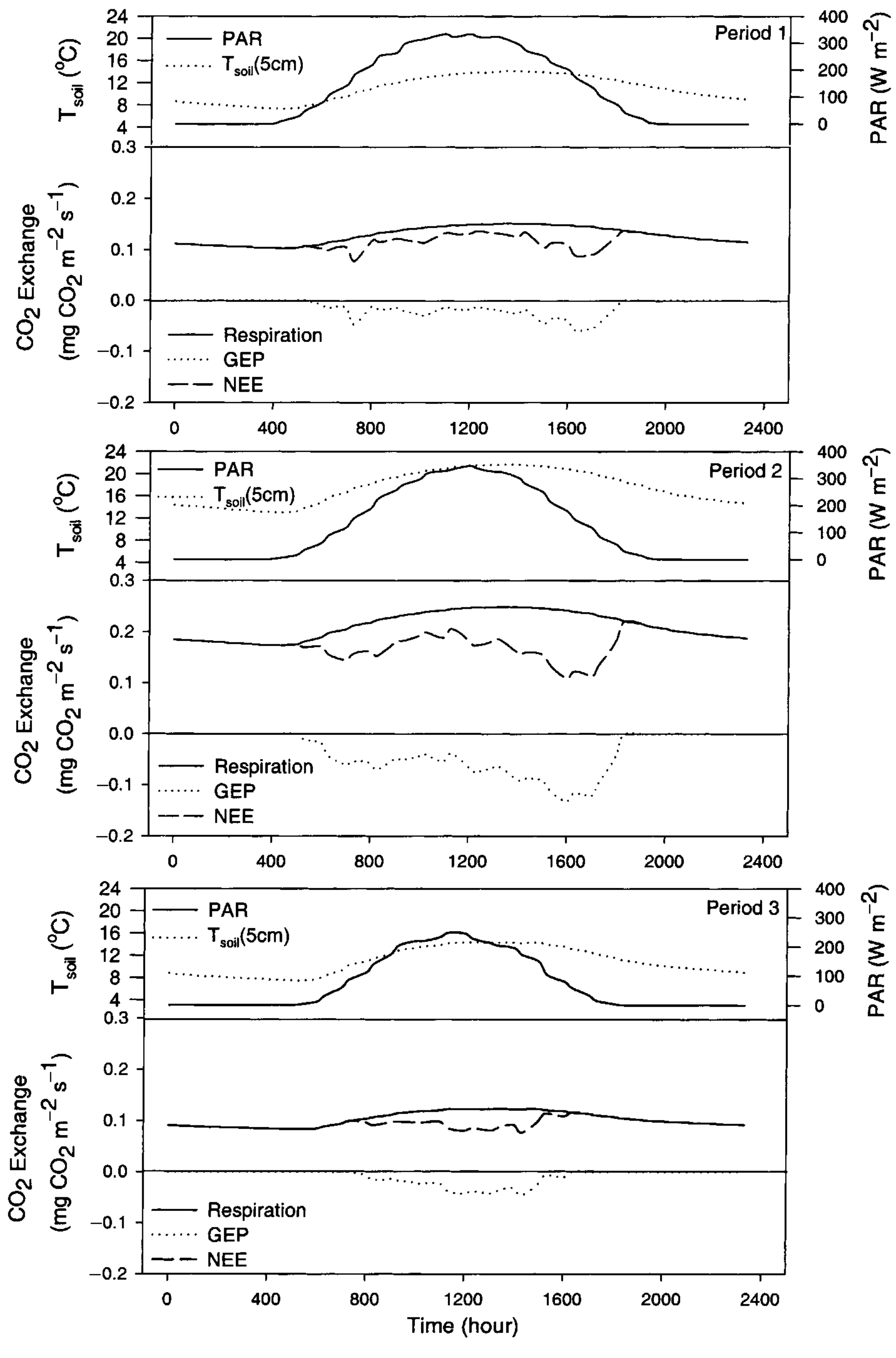

Figure 3. The mean diurnal net ecosystem CO_2 exchange (NEE), respiration, gross ecosystem production (GEP), soil temperature at 5 cm (T_{soil}) and photosynthetically active radiation (PAR) for each of the three seasonal periods at the restored Bois-des-Bel peatland, 2000. Values represent the means for each half hour interval in each seasonal period

occurred from mid to late afternoon in all periods with a lag time behind the maximum in PAR. This likely reflects the importance of moisture control on photosynthesis.

The cumulative seasonal evaporation (354 mm) and seasonal volumetric soil moisture content suggest that the evaporative flux from the system has decreased from a prerestoration value of approximately 433 mm (Price, unpublished data). Thus, the straw mulch application has succeeded in maintaining much more constant soil moisture conditions. Furthermore, trends in GEP show that plants have begun to recolonize the peatland. The uptake in period 1 corresponds with the period of peak growth common for many mosses (Rochefort and Vitt, 1988; Gerdol, 1995) whereas that in period 2 shows the strong emergence of various vascular species (Griffis *et al*., 2000). Consequently, while the ultimate success will not be realized until *Sphagnum* species are re-established (vegetation cover after first year: *Sphagnum* 3·2%, other mosses 17·8%, vasculars 10·0%—Rochefort, unpublished data), the water management undertaken at the site appears to be beneficial to revegetation. However, total respiration (soil and vegetation) appears to have increased despite the water management. This enhanced respiration was likely due to the decomposing mulch contributing to the positive CO_2 flux (Waddington and Greenwood, unpublished data).

Summary

After one year of restoration three interim conclusions can be established. First, water management is likely unnecessary from a carbon sequestration perspective since the respiration component of the CO_2 flux is primarily temperature controlled (Waddington and Warner, 2001). Because total respiration dominates the carbon balance at this stage of restoration, NEE follows the seasonal temperature trend quite closely. However, it is expected that when *Sphagnum* mosses are re-established on the peat surface then water management may be necessary due to the effects of drought on photosynthesis (Campeau and Rochefort, 1996). Second, the role of the hydrological restoration is working. That is, the system is meeting the goal of *Sphagnum* accumulation. However, it is not yet accumulating carbon, which can be attributed to the lack of a complete carbon fixing surface vegetation layer and the decomposing straw mulch. This work has highlighted the importance of mulch decomposition on the carbon balance. Other as yet unpublished data supports this speculation (Waddington *et al*., 2001; Waddington and Greenwood, unpublished data) and current field experimentation is quantifying the mulch contribution to the atmospheric CO_2 exchange. Finally, other studies show that it is likely that the straw will be decomposed within three years (Waddington *et al*., 2001), at which time the peat surface will be covered by mosses and stabilized. It is then hoped that this new surface (after the mulch has gone) with enough vegetation will naturally regulate moisture conditions (e.g. Whitehead and Price, 2001) while accumulating carbon.

Thus, the hydroclimatology of the peatland is integral to establishing favourable conditions for the rehabilitation practice (e.g. *Sphagnum* regeneration, stable water table position, etc.). The accurate quantification of the carbon dynamics and plant re-establishment of the system will yield the most realistic measure of the state of restoration of the peatland (i.e. how well the system is responding to the restoration measures). In future, this research will be used to model the moisture and carbon exchange between the atmosphere and peat surface of natural and harvested peatlands. Integrated into this will be components describing the effects of volume changes and biogenic gas production on the hydrology of the peatland. This research and the resulting model can then be utilized as a key component of any management strategy: (1) by testing the response of restoration to the regional climate and possible hydroclimatic feedbacks; (2) by testing various restoration strategies; and (3) as a diagnostic tool to determine the best management (restoration) approach.

Acknowledgements

This research was made possible by grants from NSERC Canada to JMW and JSP, with the assistance of our industrial partners. The authors would like to thank the editor and the anonymous reviewers of this paper for their helpful criticisms and suggestions.

References

Barr AG, King KM, Gillespie TJ, denHartog G, Neumann HH. 1994. A comparison of Bowen ratio and eddy correlation sensible and latent heat flux measurements above deciduous forest. *Boundary-Layer Meteorology* **71**: 21–41.

Blanford JH, Gay LW. 1992. Tests of a robust eddy correlation system for sensible heat flux. *Theoretical and Applied Climatology* **46**: 53–60.

Blanken PD, Black TA, Yang PC, Newmann HH, Nesic Z, Staebler R, denHartog G, Novak MD, Lee X. 1997. Energy balance and canopy conductance of a boreal aspen forest: partitioning overstory and understory components. *Journal of Geophysical Research* **102**(D4): 28 915–28 928.

Campeau S, Rochefort L. 1996. *Sphagnum* regeneration on bare peat surface: field and greenhouse experiments. *Journal of Applied Ecology* **33**: 599–608.

Environment Canada. 1993. *Canadian Climate Normals, 1961–1990, Québec*. Atmospheric Environment Service, Canadian Climate Program, Environment Canada: Ottawa, Canada.

Ferland C, Rochefort L. 1997. Restoration techniques for *Sphagnum*-dominated peatlands. *Canadian Journal of Botany* **75**(7): 1110–1118.

Gerdol R. 1995. The growth dynamics of *Sphagnum* based on field measurements in a temperate bog and on laboratory cultures. *Journal of Ecology* **83**: 431–437.

Gorham E. 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. *Ecological Applications* **1**(2): 182–195.

Griffis TJ, Rouse WR, Waddington JM. 2000. Scaling net ecosystem CO_2 exchange from the community to landscape-level at a subarctic fen. *Global Change Biology* **6**: 459–473.

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

Leuning R, Judd MJ. 1996. The relative merits of open- and closed-path analyzers for measurement of eddy fluxes. *Global Change Biology* **2**: 241–253.

LI-COR Inc. 2000. *LI-7500 CO_2/H_2O Analyzer Instruction Manual*. LI-COR Inc.: Lincoln, NE.

Price JS. 1996. Hydrology and microclimate of a partly restored cutover bog, Québec. *Hydrological Processes* **10**: 1263–1272.

Price JS. 1997. Soil moisture, water tension, and water table relationships in a managed cutover bog. *Journal of Hydrology* **202**: 21–32.

Price JS, Waddington JM. 2000. Advances in Canadian wetland hydrology and biogeochemistry. *Hydrological Processes* **14**: 1579–1589.

Price JS, Rochefort L, Quinty F. 1998. Energy and moisture considerations on cutover peatlands: surface microtopography, mulch cover and *Sphagnum* regeneration. *Ecological Engineering* **10**: 293–312.

Rochefort L. 2000. *Sphagnum*—A keystone genus in habitat restoration. *The Bryologist* **103**: 503–508.

Rochefort L, Vitt DH. 1988. Effects of simulated acid rain on *Tomenthypnum nitens* and *Scorpidium scorpioides* in a rich fen. *The Bryologist* **91**: 121–129.

Tuittila E-S, Komulainen VM, Vasander H, Laine J. 1999. Restored cut-away peatland as a sink for atmospheric CO_2. *Oecologia* **120**: 563–574.

Twine TE, Kustas WP, Norman JM, Cook DR, Houser PR, Meyers TP, Prueger JH, Starks PJ, Wesely ML. 2000. Correcting eddy-covariance flux underestimates over a grassland. *Agricultural and Forest Meteorology* **103**: 279–300.

Van Seters TE, Price JS. 2001. The impact of peat harvesting and natural regeneration on the water balance of an abandoned cutover bog, Québec. *Hydrological Processes* **15**: 233–248.

Waddington JM, Price JS. 2000. Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. *Physical Geography* **21**(5): 433–451.

Waddington JM, Warner KD. 2001. Effect of peatland drainage and harvesting on CO_2 efflux. *Global Biogeochemical Cycles*, in press.

Waddington JM, Rochefort L, Campeau S. 2001. *Sphagnum* production and decomposition in restored peatlands: a comparison of methods. *Wetland Ecology and Management*, submitted.

Webb EK, Pearman GI, Leuning R. 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. *Quarterly Journal of the Meteorological Society* **106**: 85–100.

Whitehead GS, Price JS. 2001. Developing hydrologic thresholds for *Sphagnum* recolonization on an abandoned cutover bog. *Wetlands* **21**(1): 32–40.