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Ecosystem-scale flux of CO_2 from a restored vacuum harvested peatland

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Abstract

At the ecosystem scale, the water and gas exchange processes are strongly coupled. Drainage and removal of a peatland's surface vegetation cover for peat harvesting alters its hydrology, and as a direct consequence the carbon budget. Previous studies have measured peatland-atmosphere carbon exchange using the chamber methodology. These studies have indicated that the spatial and temporal variability is large, suggesting the need for continuous ecosystem-scale measurements. This paper presents ecosystem scale measurements of the atmospheric exchange of water and carbon dioxide (CO_2) from a restored vacuum-harvested peatland in eastern Québec, Canada, using the eddy correlation measurement approach.

Results indicate that the adopted restoration practices reduce the loss of water from the peat. Evapotranspiration from the restored site was 20 and 25% less than that from an adjacent abandoned comparison site in 2000 and 2001 respectively. However, CO_2 emissions remain large during non-snow periods (478 and 468 g C m^{-2} in 2000 and 2001, respectively). The blockage of drainage ditches and the existence of a mulch cover at the site keep the moisture and thermal conditions more or less constant. Consequently, the CO_2 flux, which is predominantly soil respiration, is strongly controlled by peat temperature fluctuations.

Introduction

Peatlands cover over 170 million hectares and represent one of the largest carbon pools in the terrestrial biosphere (Gorham, 1991). The accumulation of organic matter in peatlands occurs over several thousands of years, as a result of low decomposition rates owing to a number of internal feedback mechanisms. However, under a changing climate these feedbacks are projected to shift due to increased microbial activity in projected warmer and drier soils, and vegetation succession, thereby increasing the productivity of the system (Shaver et al., 1986; Shaver et al., 1998; Waddington et al., 1998).

Land-use change may also lead to a shift in peatland hydrology and carbon biogeochemistry on timescales much shorter than that of climatic variability. For example, the drainage and harvesting of peatlands for horticultural and agricultural purposes has increased over the last half-century (Keys, 1992). In Canada, approximately 16 000 ha of peatlands are currently being harvested for such purposes, and in the St. Lawrence Lowlands of southern Québec peatland losses are in the range of 70% (Van Seters and Price, 2001).

In the harvesting process, the peatland is initially drained through the creation of approximately 1 m deep ditches usually spaced 30 m apart. Following drainage surface vegetation and peat is removed by a variety of techniques, most commonly in Canada by vacuum extraction. The removal of the surface layers of the peatland alters the local hydroclimatology and affects greenhouse gas exchange (Armentano and Menges, 1986). Furthermore, the typical diplotelmic structure (Ingram, 1978) of the peat soil no longer applies, as the upper acrotelm layer is destroyed and removed. Consequently, the natural hydrologic functions of the system are lost so that processes affecting the exchange of carbon become much more temporally variable (Schlotzhauer and Price, 1999; Price, 1996). Abandoned harvested sites usually do not revegetate quickly (Lavoie and Rochefort, 1996; Ferland and Rochefort, 1997). Consequently, the peatland shifts to a large and persistent net source of atmospheric CO_2 (Price and Waddington, 2000; Waddington et al., 2001). Thus, restoring the hydrology and active restoration procedures are required to return these peatlands to functioning, carbon accumulating ecosystems.

In harvested peatlands carbon exchange is altered due to changes in peat moisture content, nutrient cycling and vegetation succession. Soil respiration is strongly related to the moisture regime in the peat (Waddington and Price, 2000), which is largely a function of evaporation (Price, 1996; Van Seters and Price, 2001). Furthermore, the momentum processes governing the atmospheric transfer of mass (carbon and water vapour) are similar, so it is instructive to measure evaporation and carbon exchange simultaneously to better understand the effects of their coupling and the implications for restoration. While seasonal studies on greenhouse gas and moisture exchange from extracted and restored peatlands have been conducted (e.g. Tuittila et al., 1999; Waddington et al., 2001; Waddington and Price, 2000; Price et al., 1998), they have generally been limited by the small areal extent of chamber measurements for CO_2 exchange and simplified micro-meteorological installations for evaporation. Moreover, chamber measurements are usually only conducted one or two times per day despite indications of strong diurnal trends (Waddington et al., 2001). To evaluate the effects of harvesting or restoration on an entire peatland ecosystem, measurements of both evaporation and CO_2 exchange must be conducted continuously at the ecosystem scale to account for the spatial and temporal heterogeneity inherent in the landscape.

In this paper we describe a study of the combined evapotranspiration and CO_2 fluxes at the ecosystem scale on a harvested bog in Eastern Québec, Canada. The primary objectives of this paper are: 1) to characterize the diurnal and seasonal variations in net ecosystem exchange (NEE); 2) to demonstrate the effect of restoration on the moisture and CO_2 regimes; and 3) to determine how NEE and its components of gross ecosystem production (GEP) and total respiration (R) change with time post restoration. This study, therefore, demonstrates at the ecosystem scale the success of the restoration of hydrological and carbon sink functions of a cutover peatland.

Study area and methods

This study was conducted at the 200 ha Bois-des-Bel peatland near Rivière-du-Loup (47°53'N, 69°27'W), Québec, Canada. The mean annual temperature and total precipitation for the region is 3 °C and 926 mm (27% falling as snow), respectively (Environment Canada, 1993). The Bois-des-Bel peatland is a treed bog of which 11.5 ha was drained in 1972, and vacuum harvested from 1973 to 1980 after which the site was abandoned. Restoration began in the fall of 1999. Prior to harvesting the area to be cut was divided into eleven 30 × 300 m fields separated by parallel drainage ditches that drained the water south to a regional drainage ditch (Figure 1). Of these eleven fields, numbers one through eight were restored, while ten and eleven were left as a comparison site (nine was left as a buffer zone between the restored and comparison sites). The restoration measures included surface tilling to remove surface debris, partial filling of the drainage ditches with surface debris (mostly wood and peat), construction of a series of bunds along topographic contours, and the spreading of *Sphagnum* diaspores at a density ratio of approximately 1:10 (i.e. the material collected over 1 m^2 on a natural site are spread over 10 m^2 on the restored site) (Campeau and Rochefort, 1996) followed by 3000 kg/ha of straw mulch (Rochefort, 2000). Pre-restoration measurements were taken between May and October 1999, and this paper reports on the first two post-restoration seasons.

The eddy correlation micrometeorological technique was chosen for this study because it leaves the surface undisturbed and larger-scale spatial averaging is obtained directly when compared with the chamber approach (Aurela et al., 1998). Continuous simultaneous half-hourly fluxes of CO_2 and evapotranspiration were measured at the restored site 1.5 m above the peat surface using the eddy covariance technique, from 17 May to 11 October 2000 and 2001. The instrumentation consisted of a 3-D sonic anemometer-thermometer (Campbell Scientific CSAT 3) and an open path infrared gas (CO_2/H_2O) analyzer (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

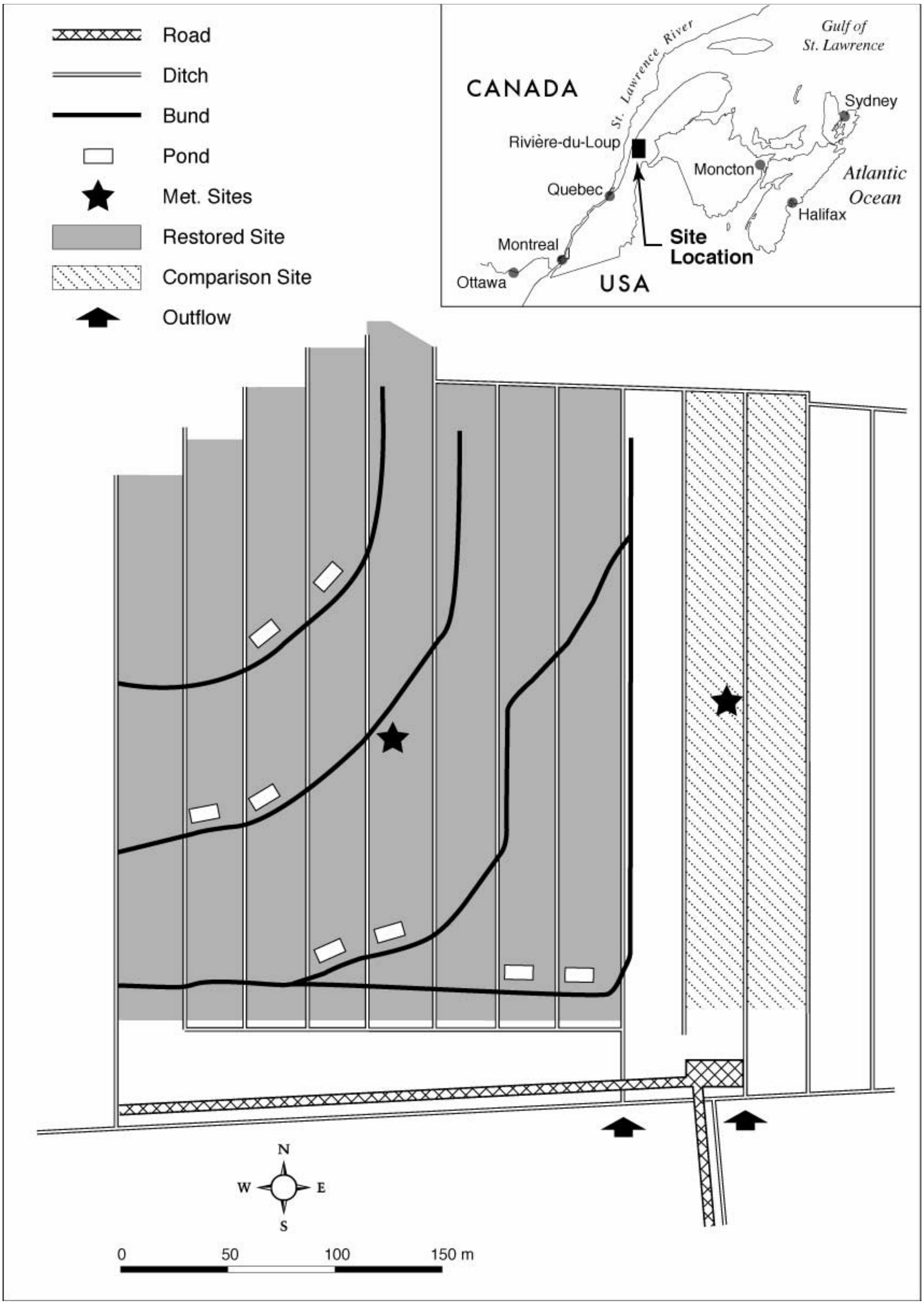

Figure 1. Location of the Bois-des-Bel peatland illustrating the drainage network, restored and comparison plots, and the location of the micrometeorological towers.

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. These measurements were then used to model respiration as a function of soil temperature at a depth of 5 cm, found to be the most closely tied to changes in ecosystem respiration (Bubier et al., 1998; Mathes and Schriefer, 1985; Silvola et al., 1996). Gross ecosystem production (GEP) was then determined as the residual in the carbon balance by subtracting the modeled respiration values from the measured NEE (Griffis et al., 2000).

Moisture conditions at the site were monitored with multiple level TDR (Campbell Scientific CS 615) and tensiometer measurements (5, 10, 20, 30 and 50 cm depths). The TDR probes were calibrated using peat cores collected from the site. Precipitation was collected using both tipping bucket and manual rain gauges, and the ground temperature was obtained using continuously logged thermocouple arrays (0, 2, 5, 10, 25, 50 and 75 cm) installed in the peat at both sites.

Due to the small fetch area of the restored peatland (Figure1), the eddy covariance sensors were placed at ~1.5 m above the peat surface to obtain a flux representative of the restoration site. Detailed analysis of this procedure is outlined in Petrone et al. (2001), which shows that 80% of the flux originates within 75 m of the tower, and an area within 17 m is the source for the maximum flux. The eddy covariance data were also corrected for density effects (Webb et al., 1980; Luening and Judd, 1996) and sensor separation (Leuning and Judd, 1996; Blanford and Gay, 1992), and the energy balance closure was calculated for the study period (Petrone et al., 2001; Twine et al., 2000; Blanken et al., 1997; Barr et al., 1994).

Results

Annual trends in environmental conditions and CO_2 fluxes

Data from both years were divided into three periods generally 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. These periods represent three pivotal phases of the active season in both years; the post-snowmelt initial growth, full summer growth and late summer senescence, respectively. Over the 2000 and 2001 measurement periods the peatland received 366 and 394 mm of precipitation, respectively. Precipitation was greater and more evenly distributed in 2001 (Figure 2). Evapotranspiration was 354 and 467 mm in 2000 and 2001, respectively. Pre-restoration evapotranspiration was approximately 433 mm (Petrone et al., 2001). Evapotranspiration in both seasons was relatively constant throughout the respective seasons (mean daily evapotranspiration rates were 3.2 ± 1.4 and 2.4 ± 1.0 mm/day in 2000 and 2001 respectively), with small changes in slope corresponding with variations in precipitation (Figure 2).

Both study seasons began with high water table positions, with maximum depths occurring in Period 2 (Table 1). The maximum air and soil temperatures occurred in period 2, while minimums occurred in period 3 (Table 1). The study period NEE was 478 g C m^{-2} in 2000 and 468 g C m^{-2} in 2001. The plot of cumulative NEE from both seasons (Figure 2) indicates a marked change in slope over both seasons, coinciding with the period transition points. The increase in NEE corresponded to the warmest and driest period (Table 2). In addition, after the beginning of the peak growth period, there was more uptake in 2001 than the similar period in 2000. Throughout most of both seasons, NEE was a source to the atmosphere (positive values), especially during the middle period when water table positions dropped by at least 50% and air and soil temperatures remained high (Table 1). GEP also increased (negative values) during the peak of the growing season, especially in 2001, (maximum GEP = –0.13 and –0.27 mg CO_2 m^{-2} s^{-1} in 2000 and 2001, respectively), especially in 2001. Cooler and moister conditions after the month of August in both years corresponded with lower respiration rates, and thus decreased NEE (Table 1).

Diurnal CO_2 exchange

Figures 3a and b show the mean diurnal CO_2 exchange components along with soil temperature and photosynthetically active radiation (PAR) for each of the three study periods in 2000 and 2001. The magnitudes of all three CO_2 components in both years' data increased in period 2 and decreased substantially in period 3, with the largest changes observed for GEP (a decrease of ~70%). The peak in GEP appears to have occurred from mid to late afternoon in all periods

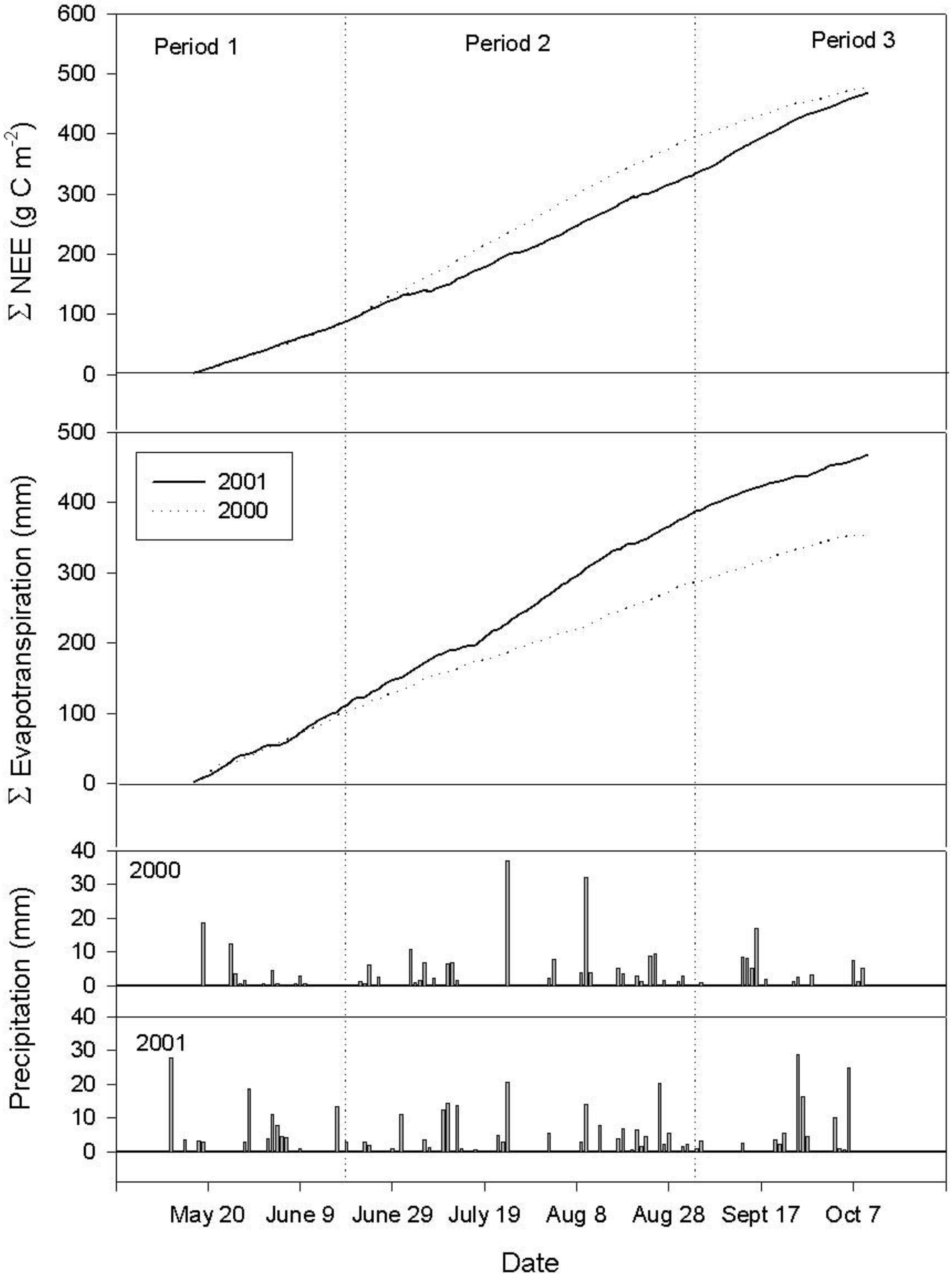

Figure 2. The cumulative net ecosystem CO_2 exchange (ΣNEE), cumulative evapotranspiration and daily rainfall for the restored Bois-des-Bel peatland, in 2000 and 2001. The transition points between periods 1 and 2, and 2 and 3 are illustrated with vertical lines on the cumulative plot.

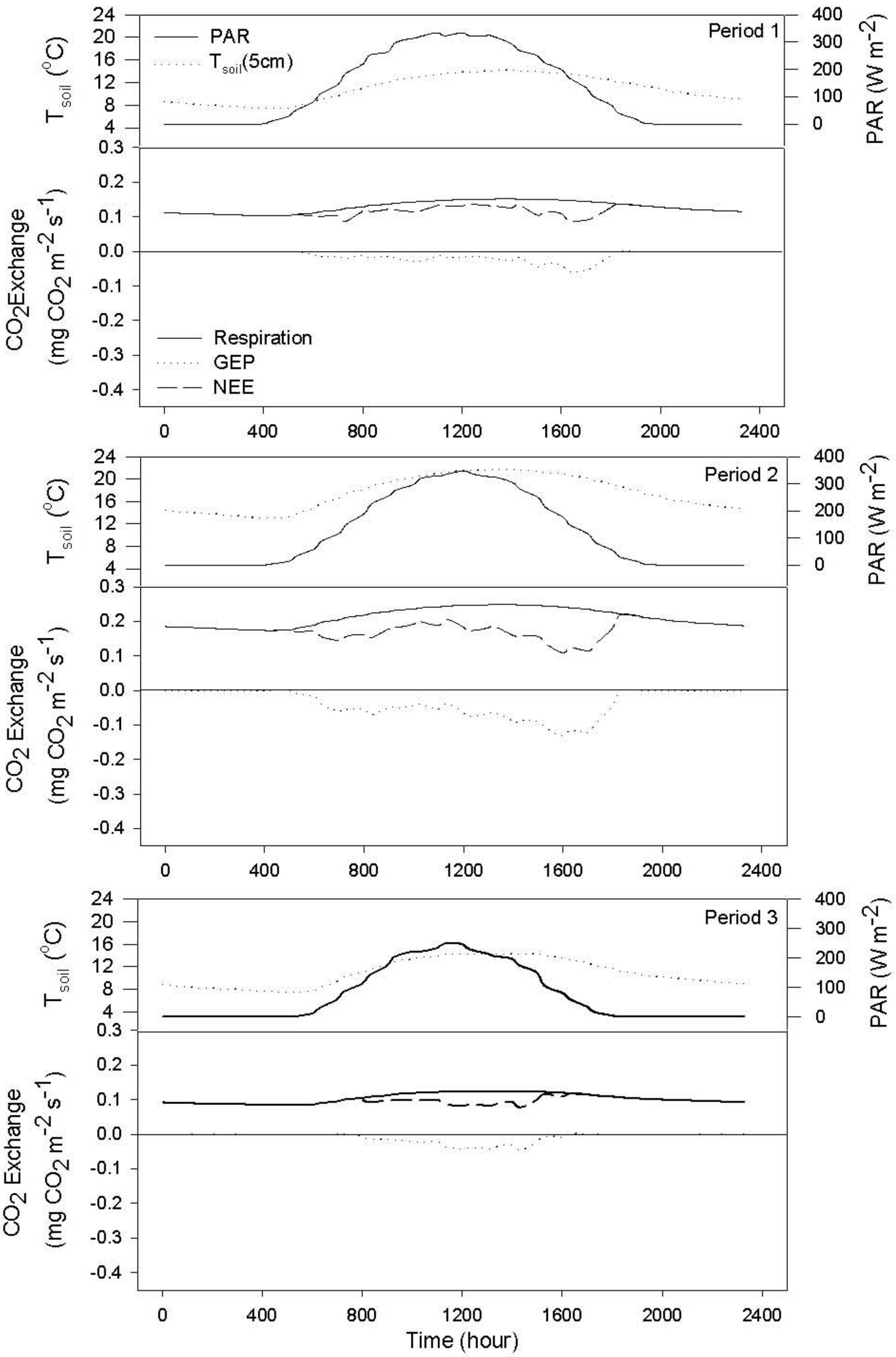

Figure 3a. The mean diurnal net ecosystem CO_2 exchange (NEE), respiration, gross ecosystem production (GEP), soil temperature at 5 cm (T_{soil}) and photosynthetically active radiation (PAR) for each of the three seasonal periods at the restored Bois-des-Bel peatland in (a) 2000 and (b) 2001. Values represent the means for each half hour interval in each seasonal period.

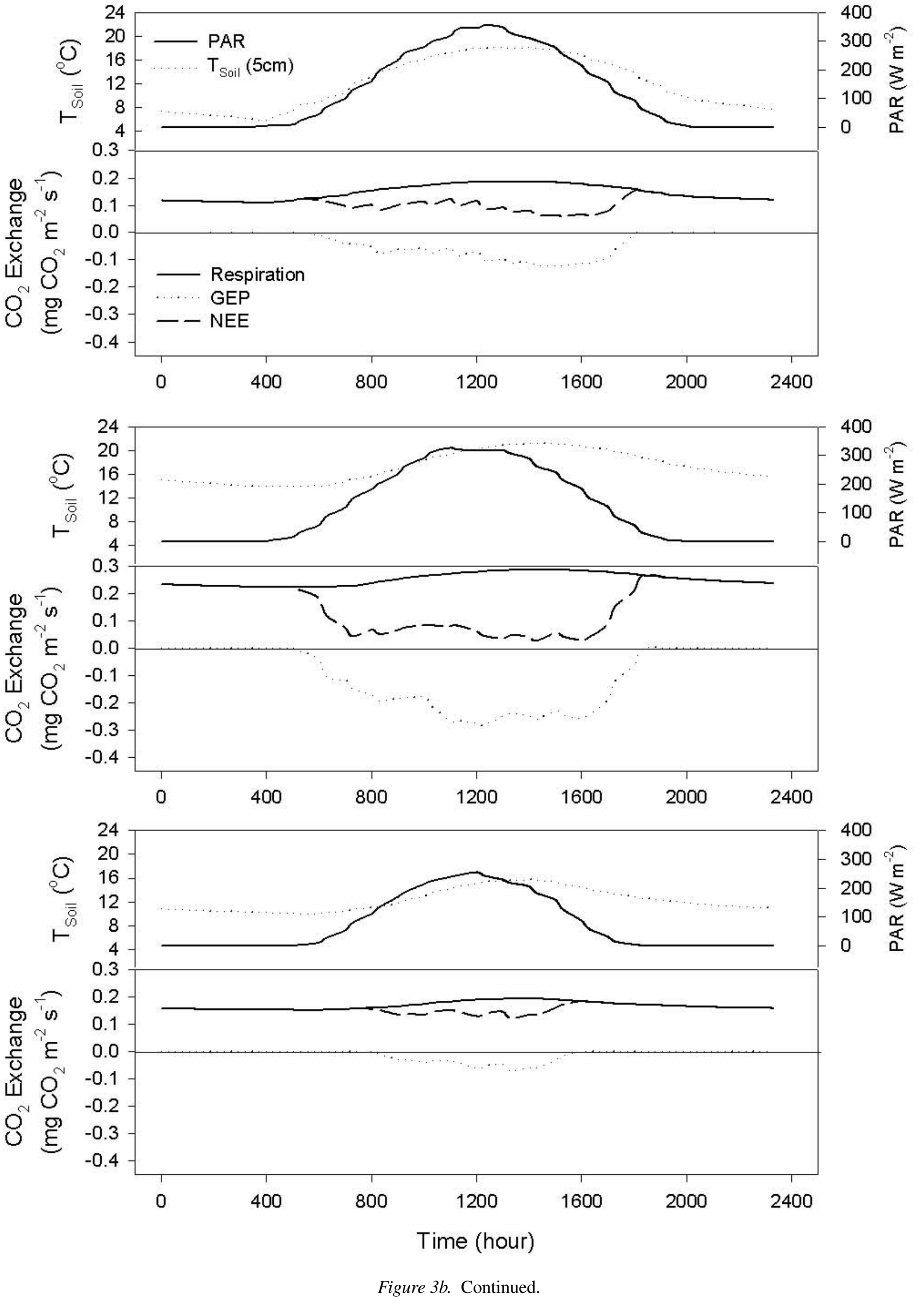

Figure 3b. Continued.

Table 1. Period averages of ecosystem scale net ecosystem exchange (NEE), respiration (R), gross ecosystem production (GEP), air temperature (T_{Air}), soil temperature at a depth of 5 cm (T_{Soil}), and water table depth (wt), Bois-des-Bel peatland, 2000 and 2001. All of the carbon balance components are in units of mg CO_2 m^{-2} s^{-1}.

	Period	NEE	R	GEP	T_{Air} (°C)	T_{Soil} (°C)	wt (cm)
2000	1	0.11	0.13	–0.01	11.4	10.9	24
	2	0.18	0.21	–0.04	17.3	16.9	36
	3	0.09	0.10	–0.01	10.9	10.8	33
2001	1	0.11	0.15	–0.04	12.2	11.9	22
	2	0.14	0.26	–0.14	17.7	17.2	34
	3	0.15	0.18	–0.03	12.0	12.2	30

with a lag time of approximately four hours behind the maximum in PAR. However, the length of this lag decreased by approximately 50% in the 2001 season.

GEP at the ecosystem scale was poorly correlated with PAR (Figure 4). Furthermore, there was more scatter in the data in 2001 when there was more plant cover.

Effects of temperature and soil moisture on CO_2 fluxes

Soil respiration was a strong function of soil temperature (Figure 5). In both 2000 and 2001, respiration during all periods responded similarly to temperature changes (i.e. slopes were similar) but during period 2 respiration had a distinctly higher intercept. In 2001 when plant growth (revegetation) was more developed, the period 2 relationship was even more distinct (higher offset) than in 2000. The relationship between respiration and mean soil moisture content changed between 2000 and 2001 (Figure 6). The soil moisture conditions were distinctly drier in 2001, and respiration slightly higher. The relationship between respiration and soil moisture during period 2 exhibited more scatter in 2001 (r^2 = 0.09), but less scatter in periods 1 and 3 (r^2 values of 0.43 and 0.61, respectively).

Discussion

Vegetation regrowth and CO_2 exchange

The post-snowmelt surfaces (period 1) were characterized by waterlogged areas and increasing but variable plant growth, whereas late summer and early fall (period 3) were characterized by heterogeneous vegetation senescence coupled with frosts. These periods coincided with greater spatial variability in transpiration, photosynthetic activity and soil respiration (Waddington, unpublished data).

The evapotranspiration rate corresponded with the time of peak vegetation growth, being greatest in period 2 in both years. However, in 2001 evaporation increased significantly from the middle of period 2, much more so than during 2000. At least part of the explanation for this is increased transpiration associated with vascular plant growth, which was visibly more prominent in 2001. This growth was also reflected in GEP, which was notably greater in 2001 (Figure 3). The lower GEP in period 1 in both years corresponds with the period of peak growth common for many mosses (Rochefort and Vitt, 1988; Gerdol, 1995) whereas higher GEP in period 2 reflects the strong emergence of various vascular species (Griffis et al., 2000). During the time of peak growth (period 2), the water table depths (Table 1) were lowest and soil moisture conditions were generally at their driest. Transpiration by vascular plants in wetlands rarely experience limiting conditions regarding soil moisture (Griffis et al., 2000), thus higher PAR and air and soil temperatures made conditions most favourable for GEP. Nevertheless, the presence of the mulch layer at this site appears to be important in maintaining generally wetter soil moisture conditions, which is necessary for improving *Sphagnum* productivity during this period.

Mosses, however, undergo their most prolific growth in spring and fall (periods 1 & 3) (Campeau and Rochefort, 1996) when photosynthesis is least limited by soil moisture (i.e. soil moisture variation is least) and when moisture is maintained in the moss layer via condensation or precipitation (Lloyd, 2001;

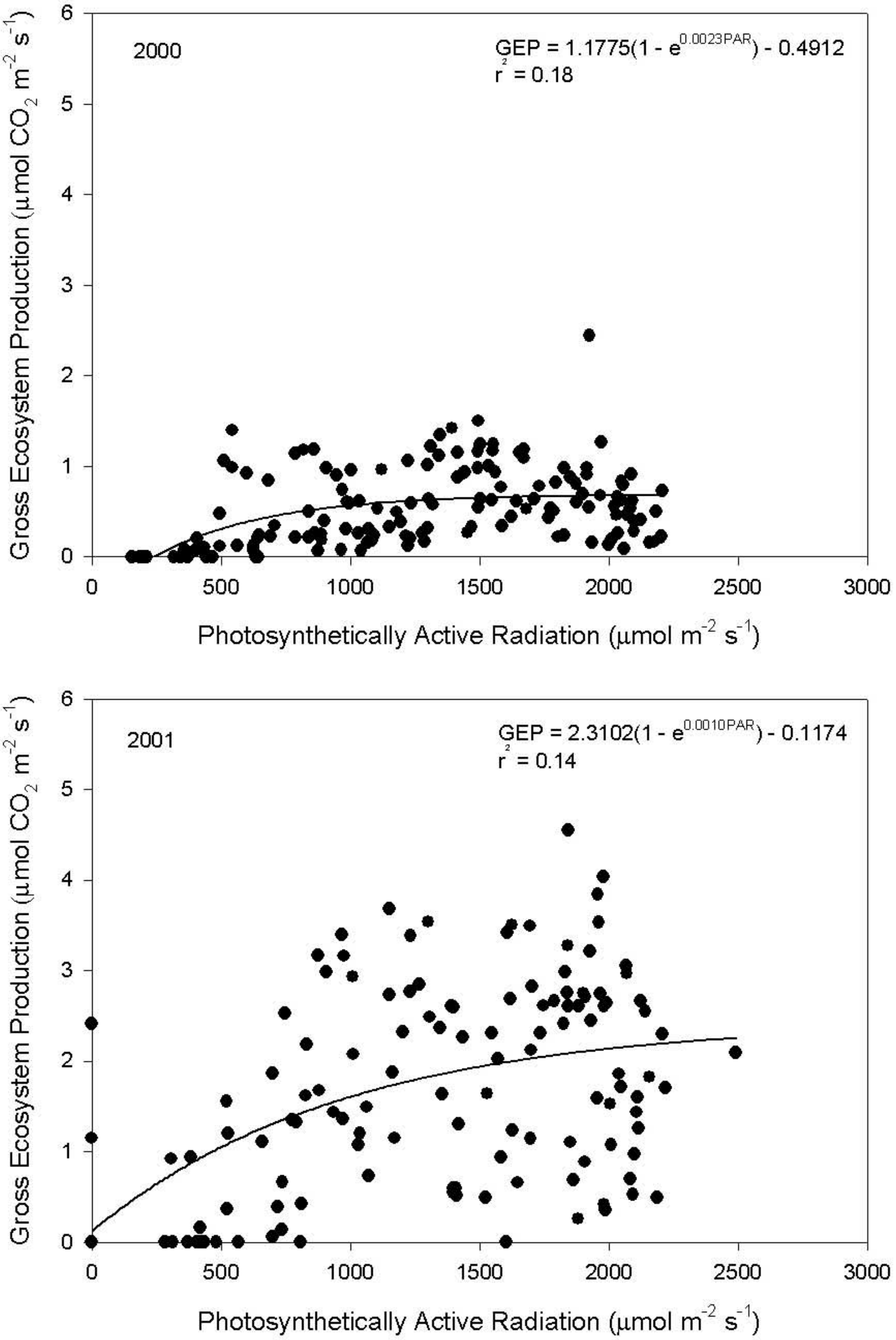

Figure 4. Ecosystem scale gross ecosystem production (GEP) as a function of photosynthetically active radiation (PAR), Bois-des-Bel peatland, (a) 2000 and (b) 2001. Values represent daily means.

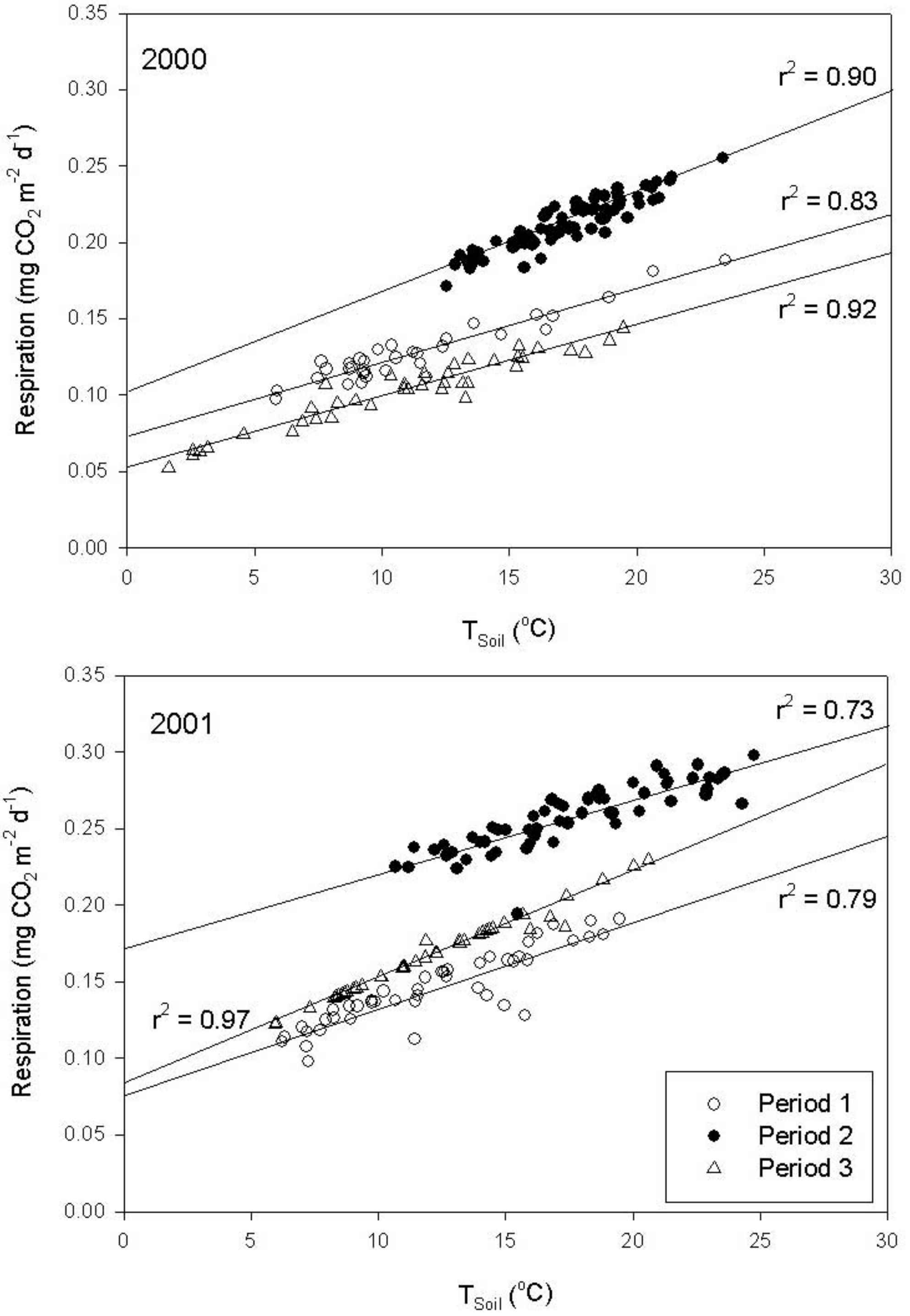

Figure 5. Ecosystem scale respiration as a function of soil temperature at a depth of 5 cm (T_{Soil}), Bois-des-Bel, (a) 2000 and (b) 2001. Values represent daily means.

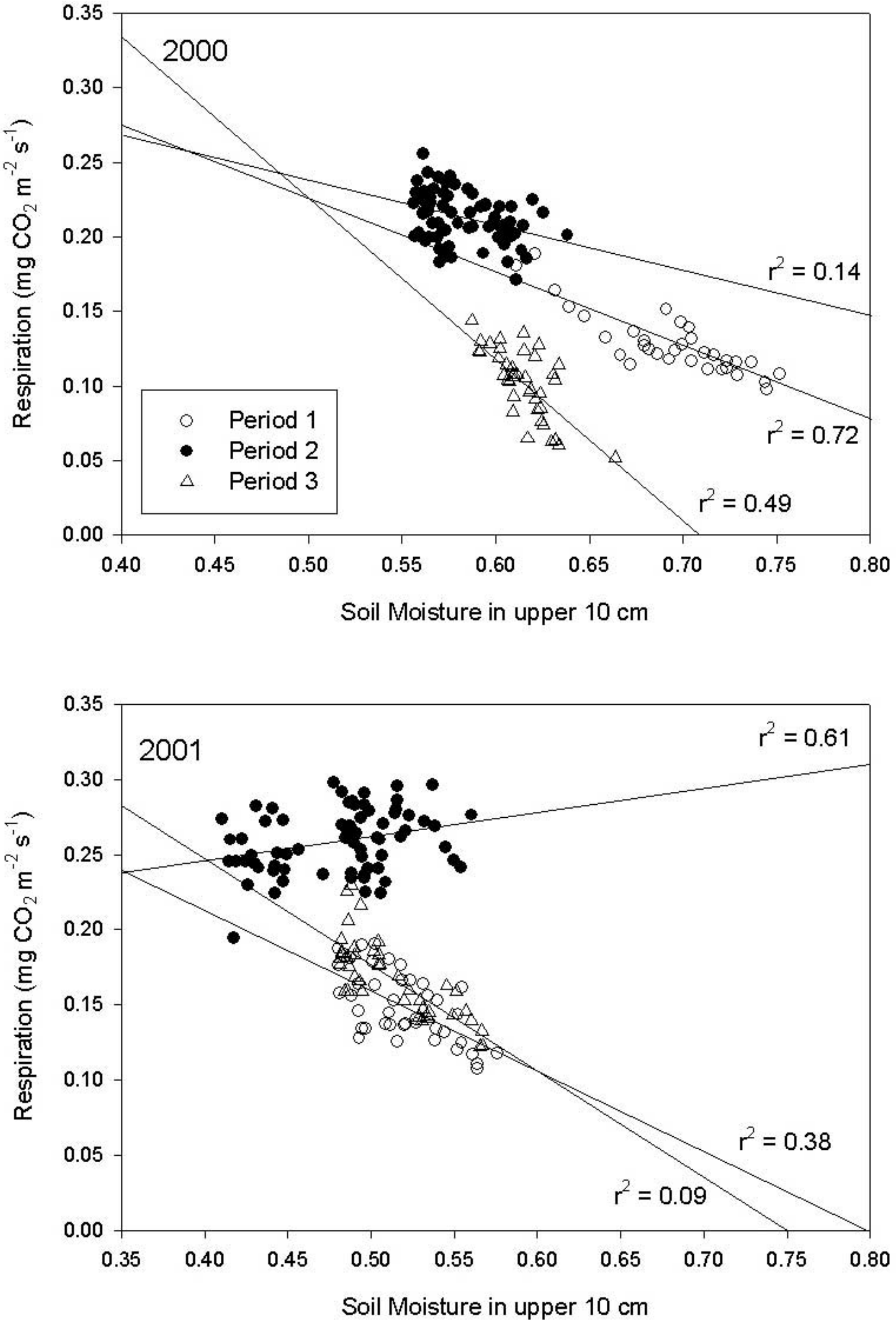

Figure 6. Ecosystem scale respiration as a function of volumetric soil moisture content of the upper 10 cm of peat, Bois-des-Bel, (a) 2000 and (b) 2001. Values represent daily means.

Oechel and Collins, 1976). Here again, higher and more uniform wetness is aided by the straw mulch layer.

Seasonal GEP in chamber studies is often modelled as a function of PAR (light response curve) in natural peatlands (e.g. Frolking et al., 1997). However, this relationship can be complicated by a number of other environmental factors such as vegetation temperature, soil and vegetation water potential, atmospheric moisture deficit, internal and ambient CO_2 concentrations, and nutrient status (Lambers et al., 1998). The low correlation (and low slope in 2000) between GEP and PAR (Figure 4), suggests PAR was not the primary controlling environmental factor, but rather, soil moisture. The greater scatter in the GEP data in 2001 was likely due to spatial (biomass) and temporal (phenological stage) heterogeneity within the peatland, as revegetation began to reestablish more rigorously, which in addition to variations in atmospheric moisture content can produce larger variability in net GEP over a wider range of PAR levels (Griffis et al., 2000). In 2001 vascular species still comprised the majority of the surface vegetation cover, so their variability likely contributed the most to this scatter. Although *Sphagnum* mosses have a much lower photosynthetic rate than the vascular plants, their proportion of the total cover of the site continues to increase, so their contribution to the overall uptake of the site also is expected to rise (Lloyd, 2001). Currently, however, plant reestablishment over the two seasons since restoration is still limited at this site. Therefore, the overall CO_2 exchange was dominated by peat temperature and moisture content (Figures 5 and 6), which controlled the variation in soil respiration and by mulch decomposition which is a function of air temperature and moisture content (Greenwood, unpublished data).

Controls on total respiration

Temperature is one of the numerous environmental factors that control the carbon mineralization processes (soil respiration), through its effect on microbial action (Yavitt et al., 1987; Updegraff et al., 1998). This should be particularly important in a harvested peatland system, where the cutover surface produces more dramatic seasonal and diurnal variations in peat temperature (Price et al. 1998). While the restoration measures have moderated the ground thermal regime (Petrone et al., 2001), there is still significant variability in the response of respiration to temperature change over the course of the season (Figure 5). The increase in respiration in period 2 was mostly the result of increased plant activity measured with CO_2 chambers (Waddington, unpublished chamber data). Soil respiration, on the other hand, is related to changes in soil temperature, which varies among peat types (Updegraff et al., 1998). Hence, during periods 1 and 3 (Figure 5), when soil respiration was more significant than plant respiration, a more gradual slope in the relationship of respiration as a function of soil temperature was observed. In a harvested peatland such as this, the bulk of the labile carbon has been removed in the extraction process, leaving the more decomposed peat, whose mineralization is less sensitive to temperature changes (Updegraff et al., 1998).

The peat soil temperature is probably most important under very wet conditions early in both seasons, but the peat moisture content increases in importance under drier conditions (Linn and Doran, 1984). It is under these drier conditions that mulch decomposition, and plant and soil respiration will increase. Two distinct within year trends between temperature and respiration can be seen in the 2000 relationship (Figure 5) likely because there was a more substantial mulch cover and less vegetation regrowth. Therefore, there was less plant respiration and more soil and mulch production (respiration) leading to a larger increase in net respiration over a smaller range in soil moisture (Figure 6). The impact of soil moisture was greater in 2001 since the mulch layer had degraded through decomposition and compression by snow, thereby permitting more fluctuations in peat moisture contents.

Like soil temperature, the soil moisture content varies seasonally with values often being the lowest when temperatures are the highest (Kirschbaum, 1995) (Table 1). This also explains the scatter in the respiration as a function of soil moisture plot (Figure 6), where there is a decrease in respiration during periods 1 and 3, and an increase during period 2, which is drier but also warmer. Decreasing moisture increases the respiration flux during periods 1 and 3 when soil respiration dominates, but the trend is not as clear in period 2 when plant respiration is more dominant (Figure 6). Thus, the effects of temperature and soil moisture on the partitioning of plant and soil respiration over the course of the season is confounded by the effects of the ever changing surface cover (vegetation and mulch) on not only the peat temperature and moisture regimes but also on the movement of the CO_2 efflux.

Conclusions

The ultimate success of this restoration project will not be realized until *Sphagnum* species are firmly re-established and the system begins to accumulate carbon on a seasonal basis. This accumulation requires not only vigorous new plant growth, but also decreased soil respiration. In the first year following restoration (2000), total respiration (soil and vegetation) was high because of rapid decomposition of the fresh straw mulch and the lack of a substantial surface vegetation layer (Waddington and Greenwood, unpublished data; Petrone et al., 2001). With less labile carbon decomposing from the mulch, and new growth being established, the data indicate the water management undertaken at the site has already been beneficial towards restoration. While success cannot be claimed for a number of years yet, interim conclusions can be drawn about the diurnal and seasonal variations in NEE and the interaction between the moisture and CO_2 regimes following restoration. Seasonal NEE after two years of restoration (468 g C m^{-2}) represented a large net loss of carbon from the site because total respiration still dominated the carbon balance. Soil respiration was slightly greater in 2001 (warmer air and soil temperatures) than in 2000, when mulch decomposition was presumably at its greatest. However, in 2001 *Sphagnum* and other mosses became more established on the peat surface, reflected by the increase in photosynthesis. The result is that NEE was slightly lower in 2001 than 2000. However, a net accumulation of carbon was not recorded, in part due to the lack of a complete cover of carbon fixing vegetation and the decomposing mulch layer. Discounting the effects of respiration from the decomposing straw mulch, however, net carbon accumulation may be occurring in some 'patches' within the peatland as preliminary analysis of chamber measurements indicates that uptake by the surface vegetation is increasing and that the vegetation is also beginning to dominate the respiration component (Waddington, unpublished data).

Thus, the hydroclimatology of the peatland appears to be helping in the establishment of favourable conditions for the rehabilitation practice (e.g. *Sphagnum* regeneration, stable water table position, etc.). The carbon dynamics and plant re-establishment of the system after two post-restoration seasons are indicating that the system is responding to the restoration measures. As the mulch cover continues to decompose and surface vegetation is re-established, carbon uptake and moisture conditions are becoming more stable.

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