

## Response of peatland carbon dioxide and methane fluxes to a water table drawdown experiment

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[1] Northern peatlands play an important role in the global carbon cycle representing a significant stock of soil carbon and a substantial natural source of atmospheric methane (CH<sub>4</sub>). Peatland carbon cycling is affected by water table position which is predicted to be lowered by climate change. Therefore we compared carbon fluxes along a natural peatland microtopographic gradient (control) to an adjacent microtopographic gradient with an experimentally lowered water table (experimental) during three growing seasons to assess the impact of water table drawdown on peatland-atmosphere carbon exchange. Water table drawdown induced peat subsidence and a change in the vegetation community at the experimental site. This limited differences in carbon dioxide (CO<sub>2</sub>) exchange between the control and experimental sites resulting in no significant differences between sites after three seasons. However, there was a trend to higher respiration rates and increased productivity in low-lying zones (hollows) and this was coincident with increased vegetation cover at these plots. In general, CH<sub>4</sub> efflux was reduced at the experimental site, although CH<sub>4</sub> efflux from control and experimental hollows remained similar throughout the study. The differential response of carbon cycling to the water table drawdown along the microtopographic gradient resulted in local topographic high zones (hummocks) experiencing a relative increase in global warming potential (GWP) of 152%, while a 70% reduction in GWP was observed at hollows. Thus the distribution and composition of microtopographic elements, or microforms, within a peatland is important for determining how peatland carbon cycling will respond to climate change.

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### 1. Introduction

[2] Northern peatlands are important in terms of the global carbon cycle storing an estimated 500 Pg of carbon in soil [Gorham, 1991]. This carbon is stored primarily owing to low decomposition rates as a result of the predominantly saturated soils present in peatland ecosystems [Clymo, 1984]. These saturated conditions and the stock of organic carbon enable northern peatlands to act as significant sources of atmospheric methane (CH<sub>4</sub>) [Matthews and Fung, 1987] releasing approximately 46 Tg C-CH<sub>4</sub> each year [Gorham, 1991]. The latitudes at which northern peatlands are situated are expected to be strongly influenced by global climate change [Intergovernmental Panel on Climate Change, 2001]. For example, Roulet *et al.* [1992] determined that water tables in northern peatlands would be lowered by 14–22 cm and

peat temperatures would increase by 0.8°C for a 2 × CO<sub>2</sub> scenario in which temperature and precipitation increased by 3°C and 1 mm day<sup>-1</sup>, respectively [Mitchell, 1989] by using a simple peatland hydrological model and relationships between air and peat temperature. Since the rate of carbon cycling in peatlands is dependent on peat temperature and the hydrologic regime [e.g., Dunfield *et al.*, 1993; Roulet *et al.*, 1992; Moore and Dalva, 1993] these climatic changes may alter carbon storage and greenhouse gas emissions from these ecosystems causing them to act as positive or negative feedbacks to climate change.

[3] To date the assessment of the effects of climate change on peatland carbon cycling has been made using (1) paleo-reconstruction, (2) the comparison of carbon fluxes from climatically different years, (3) the comparison of carbon fluxes from natural and drained sites after long-term drainage for forestry, or (4) laboratory experiments. In general these studies have not considered the variability of peatland-atmosphere carbon exchange at different microtopographic elements, or microforms, thus limiting their applicability between locations. Finally, there has generally been a lack of consideration of the interaction between peatland hydrology and ecology for determining peatland carbon fluxes. As a consequence, the temporal scale of past investigations does

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**Table 1.** Climatic Data From Quebec City (30 km From the St. Charles-de-Bellechasse Research Site) During the Four Seasons of the Study and the 30-Year (1971–2000) Normal for the Same Location

|        |                   | May   | June  | July  | August | September | Seasonal |
|--------|-------------------|-------|-------|-------|--------|-----------|----------|
| 2001   | precipitation, mm | 58.4  | 103.1 | 72.2  | 105.7  | 93.8      | 433.2    |
|        | temperature, °C   | 13.5  | 17.6  | 17.7  | 18.8   | 14.0      | 16.3     |
| 2002   | precipitation, mm | 107.6 | 67.7  | 63.4  | 11.8   | 107.7     | 358.2    |
|        | temperature, °C   | 9.5   | 14.9  | 19.8  | 19.4   | 15.6      | 15.8     |
| 2003   | precipitation, mm | 100.6 | 97.4  | 129.6 | 153.2  | 85.0      | 565.8    |
|        | temperature, °C   | 10.8  | 17.1  | 18.4  | 18.1   | 15.3      | 15.9     |
| 2004   | precipitation, mm | 122.9 | 117.0 | 168.8 | 71.6   | 115.6     | 595.9    |
|        | temperature, °C   | 10.5  | 14.9  | 19.5  | 17.7   | 13.7      | 15.3     |
| Normal | precipitation, mm | 105.5 | 114.2 | 127.8 | 116.7  | 125.5     | 589.7    |
|        | temperature, °C   | 11.2  | 16.5  | 19.2  | 17.6   | 12.5      | 15.5     |

not allow for determination of the timescale required for vegetation response to hydrological perturbation and the changing role of this vegetation community for controlling peatland-atmosphere carbon fluxes.

[4] Therefore the objective of this study was to use a controlled field experiment to (1) assess the effect of a 20 cm water table drawdown on CO<sub>2</sub> and CH<sub>4</sub> emissions along a peatland microtopographic gradient during the initial three seasons following water table manipulation and (2) investigate the importance of ecological and hydrological controls on these fluxes through time.

## 2. Study Site

[5] The study was carried out in a poor fen (46°40'N 71°10'W) near St. Charles-de-Bellechasse (SCB), Quebec, Canada. Within the fen are several pool-lawn-ridge complexes. Two of these were monitored from July 2001 to June 2002. On 10 June 2002 (day of year 161) a ditch was dug connecting one of these pools (the experimental site) to a larger drainage network thus lowering the water table in the pool about 20 cm. This was compared, between June 2002 and August 2004, to another sector (the control site) of the same poor fen which remained undisturbed. Peat depth at the control site was approximately 120 cm, while the initial peat depth at the experimental site was 100 cm. Nine sampling plots were arranged along the microtopographic gradient: three plots were in each of hummock, lawn and hollow microforms. The study was divided into four periods in relation to the water table drawdown: (1) pre-drawdown (July 2001 to June 2002), (2) first season post-drawdown (June–August 2002), (3) second season post-drawdown (May–August 2003), and (4) third season post-drawdown (May–August 2004).

[6] The 1971–2000 30-year normal precipitation and temperature from May–September for the region is 590 mm and 15.5°C, respectively (climate data available from Environment Canada at <http://www.climate.weather-office.ec.gc.ca>). During the study, 2001 and 2002 were drier than normal while 2003 and 2004 were close to the long-term average (Table 1).

## 3. Methods

### 3.1. Environmental Variables

[7] Water table position was measured continuously at a central meteorological station within the SCB experimental fen in 2001 and at lawns at each site (experimental and

control) from 2002–2004 using counterbalanced pulleys on potentiometers. Air temperature and soil temperature at 2, 5, 10 and 20 cm below the peat surface were measured continuously with thermocouples at the SCB fen meteorological station. At this location photosynthetically active radiation (PAR) was also recorded continuously using a quantum sensor (LI-190, LI-COR, Nevada, USA). Water level recorders, thermocouples and quantum sensor were connected to a data logger, measured each minute and averaged at 20 minute intervals (CR10X, Campbell Scientific, Alberta, Canada). In 2001, instrumental problems resulted in large data gaps for soil temperature. Air temperature measurements from Quebec City (30 km from the site) were well correlated ( $R^2 = 0.87$ ) to available air temperature data from the site and these temperatures were used for modeling seasonal CO<sub>2</sub> flux, discussed below. At the time of each carbon flux measurement water table was measured manually adjacent to each of the sampling plots in 1.9 cm diameter PVC wells and soil temperature was manually measured with a thermocouple thermometer at 2, 5, 10, 15, 20, 25 and 30 cm below the peat surface.

### 3.2. Vegetation

[8] Leaf area index (LAI) was determined at each sampling plot according to *Strack et al.* [2006]. As well, the percentage cover of all vegetation species was determined visually in each sampling plot in August 2001, 2002 and 2004. Also in August each year, three vegetation transects that extended from hummock into the hollow/pool were sampled at each site. At each meter along the transects, the percentage cover of vascular species was determined visually within a 50 × 50 cm quadrat and the cover of understory species (e.g., mosses, liverworts) was determined in a 20 cm diameter round sampling ring. Each quadrat was classified as a microform (hummock, lawn, hollow) prior to water table drawdown at the experimental site and the average surface cover of vascular and moss vegetation at each of these microforms was computed for each site. The relative vegetation cover (RV) was determined for each quadrat and sampling plot according to

$$RV = (M + V)/(M_{\max} + V_{\max}), \quad (1)$$

where RV is a value between 0 and 1, M is the percentage moss cover in the quadrat, V is the percentage vascular cover in the quadrat,  $M_{\max}$  is the maximum moss cover

**Table 2.** Growing Season Average (Standard Error) Peat Temperature and Water Table Position Relative To the Peat Surface Control and Experimental Microforms Predrawdown and in the Third Season PostDrawdown

|                           | Control                         |             |               | Experimental  |             |               |
|---------------------------|---------------------------------|-------------|---------------|---------------|-------------|---------------|
|                           | Hummock                         | Lawn        | Hollow        | Hummock       | Lawn        | Hollow        |
|                           | <i>Peat Temperature (5 cm)</i>  |             |               |               |             |               |
| Predrawdown               | 18.4 (0.35)                     | 18.2 (0.31) | 19.2 (0.29)   | 17.5 (0.33)   | 17.6 (0.52) | 19.9 (0.40)   |
| Third season postdrawdown | 18.0 (0.30)                     | 18.5 (0.27) | 18.1 (1.1)    | 17.4 (0.34)   | 17.8 (0.71) | 17.0 (0.11)   |
|                           | <i>Peat Temperature (20 cm)</i> |             |               |               |             |               |
| Predrawdown               | 14.40 (0.058)                   | 14.9 (0.13) | 16.06 (0.071) | 14.17 (0.042) | 14.5 (0.16) | 15.41 (0.067) |
| Third season postdrawdown | 16.0 (0.26)                     | 16.4 (0.25) | 16.6 (0.84)   | 14.5 (0.38)   | 14.9 (0.40) | 14.9 (0.20)   |
|                           | <i>Water Table</i>              |             |               |               |             |               |
| Predrawdown               | -17 (2.1)                       | -9 (1.6)    | 5 (3.2)       | -13 (1.7)     | -5 (2.4)    | 5 (1.5)       |
| Third season postdrawdown | -11.9 (0.29)                    | -6 (1.4)    | 19 (9.6)      | -23 (4.7)     | -15 (3.6)   | 4 (2.1)       |

observed in all quadrats at the study site and  $V_{\max}$  is the maximum vascular cover observed in all quadrats at the study site.

### 3.3. Net Ecosystem Exchange and Respiration

[9] Net ecosystem exchange (NEE) was measured using a clear acrylic glass chamber placed on water-filled 60 × 60 cm aluminum collars permanently installed into the peat at each of the sampling plots. Carbon dioxide concentration inside the chamber was determined every 30 seconds for 2–3 minutes using a PP systems portable infrared gas analyzer (Massachusetts). The temperature inside the chamber was maintained within 5°C of ambient temperatures using a radiator cooling system. These measurements were carried out at several levels of PAR created using shades. Values of apparent quantum efficiency determined from light response curves may be underestimated when shades are used to reduce light levels during midday manual chamber measurement [Burrows *et al.*, 2005]; however, since the experimental design allowed for comparison between CO<sub>2</sub> fluxes at the control and experimental sites any underestimation will occur at both sites and not affect the conclusions of the study. Ecosystem respiration (R<sub>tot</sub>) was determined by obscuring the chamber with an opaque shroud. Gross ecosystem photosynthesis (GEP) was calculated as the difference between NEE and R<sub>tot</sub>. We use the convention that positive values of CO<sub>2</sub> exchange indicate uptake by the ecosystem while negative values represent a release of CO<sub>2</sub> to the atmosphere.

[10] Maximum rates of GEP and NEE were determined by considering values determined when PAR was greater than 1000 μmol m<sup>-2</sup> s<sup>-1</sup> [Bubier *et al.*, 2003]. Differences in maximum GEP, maximum NEE and R<sub>tot</sub> between sites and microforms were tested at the 95% confidence level using two-way analysis of variance, with factors of drainage treatment and microform, using Minitab release 14 statistical software (Minitab Inc., Pennsylvania). A seasonal average value of maximum GEP, maximum NEE and R<sub>tot</sub> was computed for each sampling plot resulting in three replications at each microform. The overall design was pseudoreplicated (one control site and one experimental site; [Hurlbert, 1984]) because it was not feasible to replicate the water table drawdown at the ecosystem level.

[11] Values for GEP were divided into different time periods (mid and late season in 2001 and early, mid and

late season in 2002–2004) and fitted to PAR values with a nonrectangular hyperbola using Photosyn Assistant 1.1 software (Dundee Scientific, UK) according to the equation,

$$GEP = \frac{\phi Q + GP_{\max} - \sqrt{(\phi Q + GP_{\max})^2 - 4\phi Q k GP_{\max}}}{2k}, \quad (2)$$

where Q is the level of PAR,  $\Phi$  is the apparent quantum efficiency,  $GP_{\max}$  is the light saturated maximum rate of GEP and k is the convexity which describes the progressive rate of bending of the hyperbola. Residuals around this relationship were regressed with additional environmental variables (water table, air temperature, LAI) to determine if the variability was related to these parameters. The relationships were then combined with continuously measured PAR, water table, and temperature and LAI in order to estimate seasonal CO<sub>2</sub> uptake at each sampling plot. Respiration was regressed against air temperature measured 30 km from the site in Quebec City in 2001 and peat temperature at 5 cm depth in 2002–2004 and water table position. These regressions were combined with the continuously measured temperature and/or water table data to estimate seasonal R<sub>tot</sub> at each plot. Seasonal values of GEP and R<sub>tot</sub> were combined to compute cumulative net ecosystem exchange during the growing season.

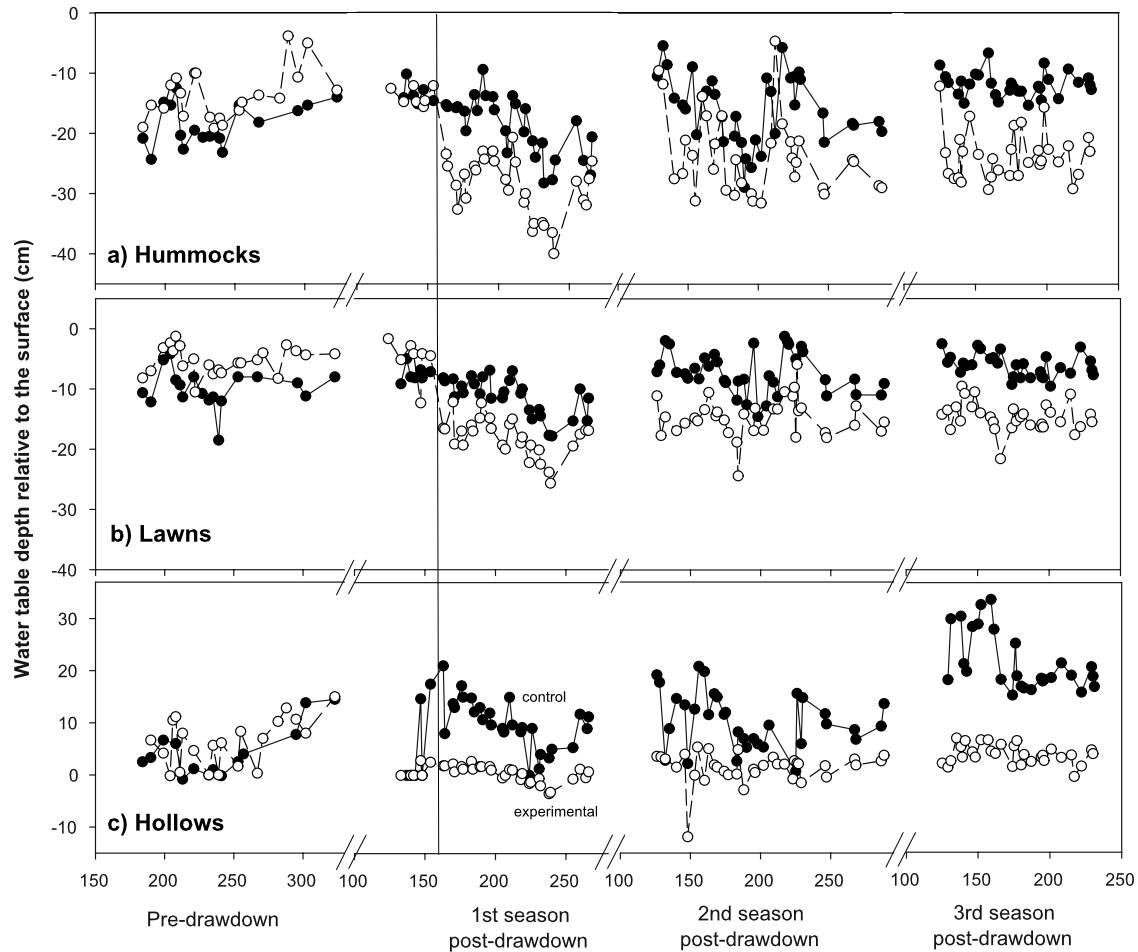
### 3.4. CH<sub>4</sub> Efflux

[12] CH<sub>4</sub> efflux was measured weekly between July and October 2001, May and October 2002–2003 and May–August 2004 using the static chamber method [Tuittila *et al.*, 2000] at the sampling plots described above. Samples were analyzed within 48 hours of collection on a Varian 3800 gas chromatograph (GC) equipped with a flame ionization detector and Porapak N column. Cumulative growing season (May–August) release of CH<sub>4</sub> was computed using a weighted sum to account for the number of days between measurements.

## 4. Results

### 4.1. Environmental Variables

[13] Prior to the water table drawdown, average water tables were similar between the control and experimental site at all microforms (Table 2). The water table drawdown reduced the water table in the pool by about 20 cm and



**Figure 1.** Average water table position through time at (a) hummocks, (b) lawns, and (c) hollows for control (solid symbols) and experimental (open symbols) sites. Standard errors between plots of one microform type are generally 3–6 cm; however, error bars have been omitted for clarity. Units on the x axis give the day of year. The vertical line indicates the timing of the water table drawdown.

average seasonal water tables at the experimental site were lowered at all microforms (Figure 1). Owing to peat subsidence the surface dropped 5, 15 and 20 cm at hummocks, lawns, and hollows thus limiting the water table drawdown.

[14] Prior to water table drawdown average seasonal peat temperature at 5 cm depth was slightly warmer at hollows than at lawns and hummocks, although the difference between microforms was significant (ANOVA,  $p < 0.05$ ) only at the experimental site. During the third season post-water table drawdown (2004) 5 cm peat temperature was not significantly different between microforms or sites; however, the experimental site was generally 1°C cooler at this depth than the control site (Table 2). Similar temperature differences were observed at 20 cm depth (Table 2).

#### 4.2. Vegetation Community

[15] Dominant species at hummocks were *Sphagnum magellanicum*, *Sphagnum rubellum*, *Chamaedaphne calyculata*, and *Vaccinium oxycoccus*. Vegetation at lawns was dominantly *Sphagnum papillosum*, *Sphagnum majus*,

*Carex oligosperma* and *Carex limosa*. There was little *Sphagnum* present at hollows which had a cover of liverworts (*Gymnocolea inflata* and *Cladopodiella fluitans*), *Scirpus subterminalis* and *Rhynchospora alba*.

[16] On the basis of a one-way analysis of variance (ANOVA) moss cover during the predrainage period was significantly higher at hummocks and lawns compared to hollows at both the control and experimental sites (Table 3). Water table drawdown produced no significant change. In contrast, while vascular vegetation cover was similar at all microforms at both sites prior to the drawdown ( $p = 0.381$ ), in the second and third season postdrawdown there was a significant increase in vascular vegetation cover at all experimental microforms, particularly lawns and hollows. During the predrawdown period the relative vegetation cover (RV) was significantly higher at hummocks and lawns than in hollows at both the experimental and control sites. This pattern was maintained for the first season postdrawdown; but, in the second and third season postdrawdown the vegetation cover at experimental hollows was significantly higher than the control cover (Table 3) although RV at hummocks and lawns remained significantly higher than

**Table 3.** Percent Moss Cover, Percent Vascular Vegetation Cover, and Relative Vegetation Cover at Control and Experimental Sites Throughout the Study Period<sup>a</sup>

|   |          | 2001             | 2002                         | 2003                          | 2004                         |
|---|----------|------------------|------------------------------|-------------------------------|------------------------------|
|   |          | Predrawdown      | First Season<br>PostDrawdown | Second Season<br>PostDrawdown | Third Season<br>PostDrawdown |
| <i>Percent Moss Cover: Mean (Standard Error)</i>                |          |                  |                              |                               |                              |
| ANOVA   |          | F(5, 98) = 39.85 | F(5, 98) = 37.25             | F(5, 97) = 27.83              | F(5, 101) = 22.06            |
| Results   |          | p < 0.001        | p < 0.001                    | p < 0.001                     | p < 0.001                    |
| Control   | Hummocks | 102 (5.4)b       | 94 (8.2)b                    | 85 (5.6)b                     | 80 (11)b                     |
|   | Lawns    | 68 (8.4)b        | 74 (8.6)b                    | 79 (7.5)b                     | 74 (8.8)b                    |
|   | Hollows  | 3 (2.1)a         | 3 (1.9)a                     | 4 (2.2)a                      | 7 (3.4)a                     |
| Experimental  | Hummocks | 77 (9.5)b        | 80 (10)b                     | 70 (11)b                      | 60 (12)b                     |
|   | Lawns    | 69 (9.3)b        | 74 (9.5)b                    | 64 (9.5)b                     | 61 (9.0)b                    |
|   | Hollows  | 1.8 (0.90)a      | 4 (1.9)a                     | 11 (7.0)a                     | 6 (4.2)a                     |
| <i>Percent Vascular Vegetation Cover: Mean (Standard Error)</i> |          |                  |                              |                               |                              |
| ANOVA   |          | F(5, 98) = 1.07  | F(5, 98) = 1.59              | F(5, 97) = 8.50               | F(5, 101) = 14.04            |
| Results   |          | p = 0.381        | p = 0.169                    | p < 0.001                     | p < 0.001                    |
| Control   | Hummocks | 14 (3.5)a        | 22 (7.2)a                    | 38 (6.1)abc                   | 51 (7.8)bc                   |
|   | Lawns    | 11 (2.3)a        | 25 (4.3)a                    | 30 (4.5)ab                    | 25 (4.6)ab                   |
|   | Hollows  | 10 (2.7)a        | 36 (6.8)a                    | 16 (2.7)a                     | 13 (1.6)a                    |
| Experimental  | Hummocks | 21 (6.2)a        | 39 (7.0)a                    | 58 (7.2)c                     | 65 (7.3)c                    |
|   | Lawns    | 11 (3.3)a        | 38 (6.6)a                    | 47 (6.2)bc                    | 48 (7.3)c                    |
|   | Hollows  | 15 (3.9)a        | 47 (6.5)a                    | 42 (6.8)bc                    | 53 (6.7)c                    |
| <i>Relative Vegetation Cover: Mean (Standard Error)</i>         |          |                  |                              |                               |                              |
| ANOVA   |          | F(5, 98) = 35.16 | F(5, 98) = 22.91             | F(5, 97) = 38.73              | F(5, 101) = 31.50            |
| Results   |          | p < 0.001        | p < 0.001                    | p < 0.001                     | p < 0.001                    |
| Control   | Hummocks | 0.43 (0.019)b    | 0.53 (0.013)b                | 0.57 (0.032)c                 | 0.62 (0.040)c                |
|   | Lawns    | 0.29 (0.032)b    | 0.46 (0.038)b                | 0.51 (0.033)c                 | 0.46 (0.040)c                |
|   | Hollows  | 0.05 (0.012)a    | 0.18 (0.031)a                | 0.09 (0.019)a                 | 0.09 (0.017)a                |
| Experimental  | Hummocks | 0.37 (0.034)b    | 0.54 (0.046)b                | 0.60 (0.064)c                 | 0.58 (0.067)c                |
|   | Lawns    | 0.30 (0.037)b    | 0.52 (0.031)b                | 0.52 (0.037)c                 | 0.51 (0.038)c                |
|   | Hollows  | 0.06 (0.016)a    | 0.23 (0.029)a                | 0.24 (0.034)b                 | 0.27 (0.034)b                |

<sup>a</sup>Quadrats and sampling plots were grouped according to site and microform (e.g., control hummock, control lawn) and ANOVA results compare these groups. Within a period, groups are significantly different if they have no letters in common. Vegetation cover was not compared across seasons; thus letters should only be compared within one column.

hollows and was not different between control and experimental sites.

#### 4.3. CO<sub>2</sub> Exchange

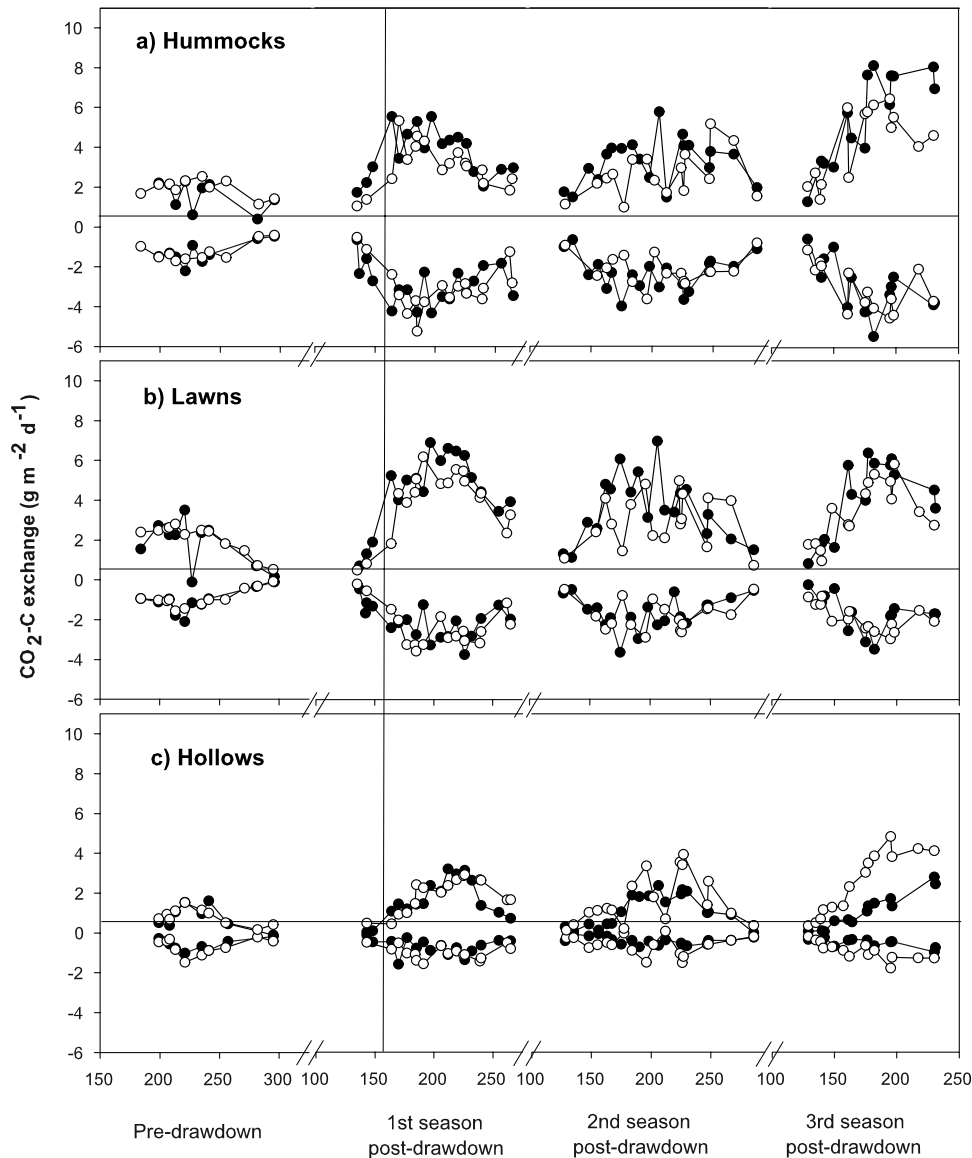
[17] There were no significant differences in rates of maximum GEP, maximum NEE or R<sub>tot</sub> between the control and experimental sites over the study period. However, an increase in GEP and R<sub>tot</sub> was evident at experimental hollows following water table drawdown, particularly by the third season postdrawdown (Figures 2 and 3). There was a significant difference in maximum NEE between microforms in 2001–2003 with lawns taking up more CO<sub>2</sub> than hummocks and hollows where CO<sub>2</sub> exchange was usually closer to zero (results for 2001 shown in Figure 3c). While a similar pattern was observed in 2004, the difference between microforms was not significant (Figure 3c). There were also significant differences in maximum GEP between microforms in all years with hummocks and lawns being more productive than hollows; however, there was no significant difference between the control and experimental sites (Figure 3a). Similar results were observed for R<sub>tot</sub> with significant differences between microforms but no significant difference between the control and experimental sites in any of the study periods. Rates of R<sub>tot</sub> were highest at hummocks, lowest at hollows, and intermediate at lawns (Figure 3b). The limited extent of the change in NEE is also reflected in the seasonal estimates of carbon exchange

(Table 4). In the third season postdrawdown there are no substantial differences in fluxes at any of the microforms, although it appears GEP and R<sub>tot</sub> were slightly reduced at experimental hummocks and lawns and increased at hollows.

[18] Despite the lack of significant differences between NEE at the control and experimental sites there is evidence of shifts in productivity at the experimental site following the water table drawdown. A comparison of the quotient of experimental divided by control modeled seasonal GEP and R<sub>tot</sub> at individual sampling plots (Figures 4a and 4b) reveals that most of the change has occurred at plots along the gradient in the transition between lawns and hollows. Also, when seasonal estimates of GP<sub>max</sub> were compared between the experimental and control sites, it is evident that the quotient of this parameter between these sites (experimental/control) has increased with time post–water table drawdown at hollows while the increase at lawns is less apparent and there appears to be no change at hummocks (Figure 5a). This shift in GP<sub>max</sub> with time is mirrored by similar increases in the quotient of RV between experimental and control sites at lawns and hollows (Figure 5b).

#### 4.4. CH<sub>4</sub> Efflux

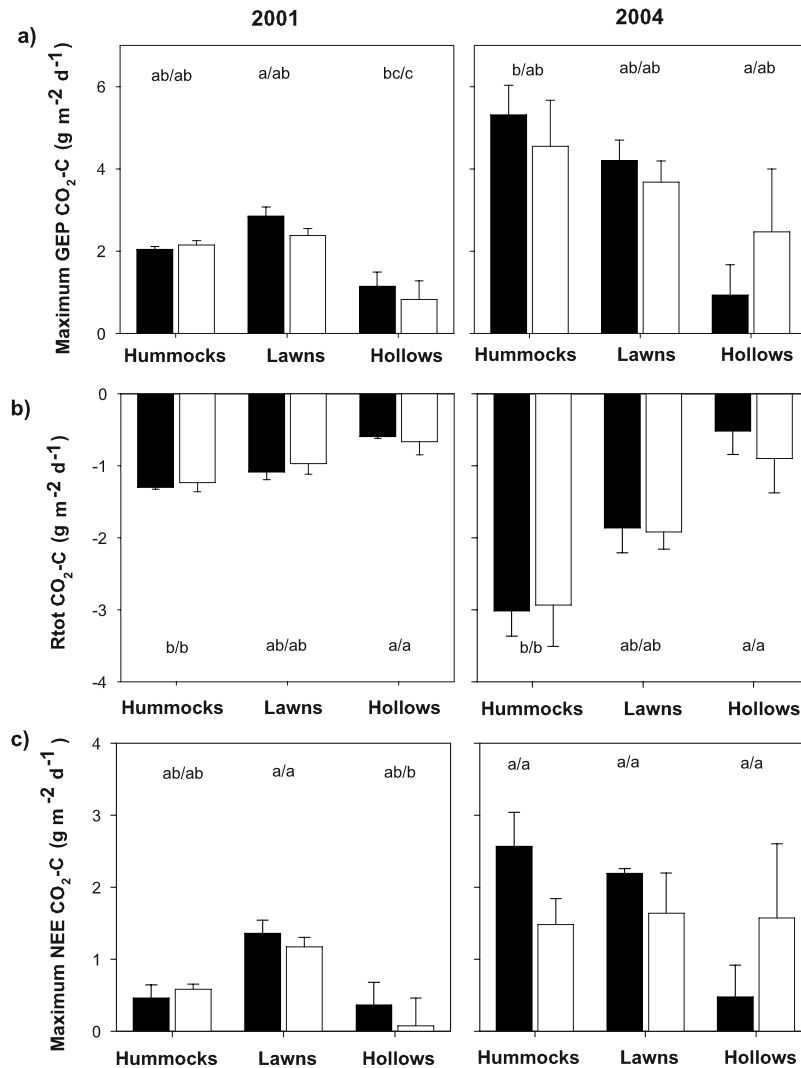
[19] The average efflux of CH<sub>4</sub>-C during the growing season (May–August) from the sampling plots was 42.7, 34.5, 11.4 and 16.1 mg m<sup>-2</sup> d<sup>-1</sup> at the control site and 77.0, 55.0, 8.3, and 7.6 mg m<sup>-2</sup> d<sup>-1</sup> at the experimental site



**Figure 2.** Average values of GEP (positive) and Rtot (negative) through time at (a) hummocks, (b) lawns, and (c) hollows for control (solid symbols) and experimental (open symbols) sites. Standard errors between plots of one microform are generally 0–6 for GEP and 0–2 for Rtot; however, error bars have been omitted for clarity. Units on the x axis give the day of year. The vertical line indicates the timing of the water table drawdown at the experimental site.

during the predrawdown season, first, second and third season postdrawdown, respectively. The measured efflux of  $\text{CH}_4$  was highly spatially and temporally variable with coefficients of variation of 0.4–8.7 across a season at individual plots and 0.5–1.9 between plots at each site. The distribution of the efflux values is highly right-skewed, so the mean can be substantially raised by the few large values. However, if this temporal variability is representative of the natural pattern of  $\text{CH}_4$  emissions then these few events would contribute a large portion of the total  $\text{CH}_4$  emitted, thus making the mean a more accurate representation of the total  $\text{CH}_4$  emitted. Both mean and median revealed the same general trends. Therefore only means are shown in Figure 6.

[20] Prior to water table drawdown the effluxes of  $\text{CH}_4$  were dissimilar between the control and experimental site. Effluxes from control hummocks and lawns were higher than those at the experimental site while experimental hollows had larger  $\text{CH}_4$  emissions than control hollows resulting in higher average emissions from the experimental site as a whole (Figure 6). Because of these large intersite differences, we compared the quotient of experimental to control effluxes through time in order to observe the pattern of change at the experimental site relative to the control site. This also helps to eliminate confusion resulting from interannual climatic differences. During the first season following water table drawdown there was a 5% reduction in the relative  $\text{CH}_4$  efflux at the experimental hummocks but



**Figure 3.** (a) Maximum GEP, (b) R<sub>tot</sub>, and (c) maximum NEE in 2001 and 2004 at control (black) and experimental (white) sites. Error bars give standard errors. On the basis of results of ANOVA, comparing plots grouped by microform and drainage, groups are significantly different ( $p < 0.05$ ) if they have no letters in common. Fluxes were not compared across seasons; thus letters should only be compared within one study season.

increases in relative CH<sub>4</sub> emissions at lawns and hollows of 33 and 19%, respectively. However, by the third season CH<sub>4</sub> emissions were reduced at all microforms (Figures 4c and 6) being statistically significant (ANOVA,  $p < 0.05$ ) only at hollows. Similar to changes in CO<sub>2</sub> exchange, most change occurred in the transition from lawns to hollows, with large reductions in effluxes also observed at the wettest lawn (Figure 4c). Although there was a large reduction in effluxes from experimental hollows, they appear to stabilize during the second season postdrawdown and remain at levels similar to the control site three seasons post-water table drawdown.

#### 4.5. Carbon Balance

[21] In general, both the control and experimental sites were sources of carbon to the atmosphere with the majority of carbon exchange resulting from CO<sub>2</sub> emissions (Table 4).

CH<sub>4</sub> emissions played a minor role except at hollows. Control lawns stored a small amount of carbon in 2002 and 2003 (54 and 14 g m<sup>-2</sup>), with experimental lawns also experiencing carbon uptake (4 g m<sup>-2</sup>) in 2002. Hollows were small carbon sinks at the control site in 2002 and 2004 (18 and 2 g m<sup>-2</sup>) and at the experimental site in 2004 (10 g m<sup>-2</sup>).

[22] Despite large reductions in CH<sub>4</sub> emissions at the experimental site, there was little difference in the carbon balance of the control and experimental sites three seasons post-water table drawdown (Table 4). In general most sites were sources of carbon to the atmosphere during the growing season. Winter carbon emissions were measured in 2002 and 2003 and there were no significant differences between the control and experimental sites. Evidence from a nearby site, which had the water table lowered in 1993, suggests that this similarity in winter fluxes following water table drawdown is maintained with time [Strack *et al.*, 2004,

**Table 4.** Calculated Growing Season Rates of Carbon Exchange Throughout the Study Periods at Control and Experimental Sites<sup>a</sup>

|  | Carbon Exchange | Control          |                  |                  | Experimental     |                 |                   |
|--|-----------------|------------------|------------------|------------------|------------------|-----------------|-------------------|
|  |                 | Hummocks         | Lawns            | Hollows          | Hummocks         | Lawns           | Hollows           |
| Predrawdown 3 July to 20 Aug 2001<br>and 12 May to 9 June 2002 (79 days) | GEP             | 74 (4)           | 84 (0)           | 28 (13)          | 79 (11)          | 78 (3)          | 27 (14)           |
|  | Rtot            | -89 (10)         | -96 (4)          | -32 (14)         | -98 (4)          | -93 (5)         | -41 (19)          |
|  | NEE             | -15 (7)          | -12 (4)          | -4 (1)           | -19 (7)          | -15 (2)         | -14 (6)           |
|  | CH <sub>4</sub> | -10 (6)          | -12 (4)          | -15 (7)          | -1 (0)           | -5 (1)          | -38 (27)          |
|  | <b>Total</b>    | <b>-25 (4)</b>   | <b>-24 (0)</b>   | <b>-19 (7)</b>   | <b>-20 (7)</b>   | <b>-19 (2)</b>  | <b>-52 (26)</b>   |
|  | <b>GWP</b>      | <b>364 (164)</b> | <b>403 (117)</b> | <b>489 (225)</b> | <b>104 (28)</b>  | <b>198 (21)</b> | <b>1223 (825)</b> |
| First season postdrawdown<br>10 June to 31 Aug 2002 (93 days)            | GEP             | 154 (20)         | 205 (23)         | 70 (30)          | 125 (10)         | 164 (38)        | 74 (40)           |
|  | Rtot            | -172 (18)        | -140 (3)         | -43 (26)         | -197 (13)        | -152 (7)        | -68 (19)          |
|  | NEE             | -18 (6)          | 65 (22)          | 27 (5)           | -72 (3)          | 12 (35)         | 6 (9)             |
|  | CH <sub>4</sub> | -6 (1)           | -11 (3)          | -9 (5)           | -1 (0)           | -8 (5)          | -32 (16)          |
|  | <b>Total</b>    | <b>-24 (5)</b>   | <b>54 (21)</b>   | <b>18 (4)</b>    | <b>-73 (3)</b>   | <b>4 (30)</b>   | <b>-26 (21)</b>   |
|  | <b>GWP</b>      | <b>243 (13)</b>  | <b>85 (104)</b>  | <b>174 (143)</b> | <b>307 (7)</b>   | <b>215 (16)</b> | <b>966 (513)</b>  |
| Second season postdrawdown<br>12 May to 31 Aug 2003 (112 days)           | GEP             | 167 (17)         | 201 (4)          | 62 (23)          | 132 (5)          | 142 (29)        | 90 (43)           |
|  | Rtot            | -211 (19)        | -135 (3)         | -36 (25)         | -198 (25)        | -152 (20)       | -51 (28)          |
|  | NEE             | -44 (26)         | 66 (8)           | 26 (23)          | -66 (20)         | -10 (42)        | 39 (16)           |
|  | CH <sub>4</sub> | -38 (28)         | -52 (14)         | -81 (39)         | -7 (5)           | -43 (16)        | -74 (18)          |
|  | <b>Total</b>    | <b>-82 (15)</b>  | <b>14 (15)</b>   | <b>-55 (56)</b>  | <b>-73 (16)</b>  | <b>-53 (26)</b> | <b>-35 (1)</b>    |
|  | <b>GWP</b>      | <b>168 (91)</b>  | <b>-233 (29)</b> | <b>-85 (88)</b>  | <b>245 (74)</b>  | <b>42 (152)</b> | <b>-135 (57)</b>  |
| Third season postdrawdown<br>9 May to 19 Aug 2004 (103 days)             | GEP             | 218 (33)         | 168 (9)          | 47 (27)          | 175 (33)         | 139 (18)        | 110 (60)          |
|  | Rtot            | -324 (46)        | -194 (31)        | -40 (24)         | -277 (52)        | -185 (23)       | -95 (48)          |
|  | NEE             | -106 (22)        | -26 (35)         | 7 (12)           | -102 (25)        | -46 (25)        | 15 (12)           |
|  | CH <sub>4</sub> | -5 (1)           | -7 (2)           | -5 (2)           | 0 (0)            | -2 (1)          | -5 (2)            |
|  | <b>Total</b>    | <b>-111 (23)</b> | <b>-33 (34)</b>  | <b>2 (12)</b>    | <b>-102 (24)</b> | <b>-48 (24)</b> | <b>10 (10)</b>    |
|  | <b>GWP</b>      | <b>531 (110)</b> | <b>316 (100)</b> | <b>136 (46)</b>  | <b>382 (85)</b>  | <b>217 (71)</b> | <b>102 (13)</b>   |

<sup>a</sup>All values are given as mean (standard error) of three sampling plots at each microform. All values give flux of carbon in  $\text{g m}^{-2}$  for the period described except global warming potential (GWP) which is expressed in grams of  $\text{CO}_2$  equivalents ( $\text{g CO}_2\text{-e}$ ). Negative values of carbon exchange indicate a release of carbon to the atmosphere and negative values of GWP indicate that the peatland has a net cooling effect on the atmosphere.

2006]. However, since these winter fluxes represent a loss of carbon from the system, this fen was probably a source of carbon to the atmosphere in all years studied.

## 5. Discussion

### 5.1. $\text{CO}_2$ Exchange

[23] The rate of net ecosystem exchange (NEE) under natural water table conditions at the control site varied both spatially and temporally. Spatial variability in NEE across a peatland in relation to microtopography has been reported previously [e.g., Moore, 1989; Heikkinen *et al.*, 2002]. Interannual variability in peatland  $\text{CO}_2$  exchange has also been reported. Shurpali *et al.* [1995] measured a  $\text{CO}_2\text{-C}$  source of  $71 \text{ g m}^{-2}$  from an open Minnesota peatland in a dry year and an uptake of  $32 \text{ g m}^{-2}$  in the subsequent wet year. Similarly, Joiner *et al.* [1999] monitored a boreal fen and observed a  $\text{CO}_2\text{-C}$  loss of  $31 \text{ g m}^{-2}$  during a season with early snowmelt and a dry growing season and an uptake of  $92 \text{ g m}^{-2}$  in a cooler, wetter year. Thus the variability in  $\text{CO}_2$  observed in this study is not uncommon for northern peatlands.

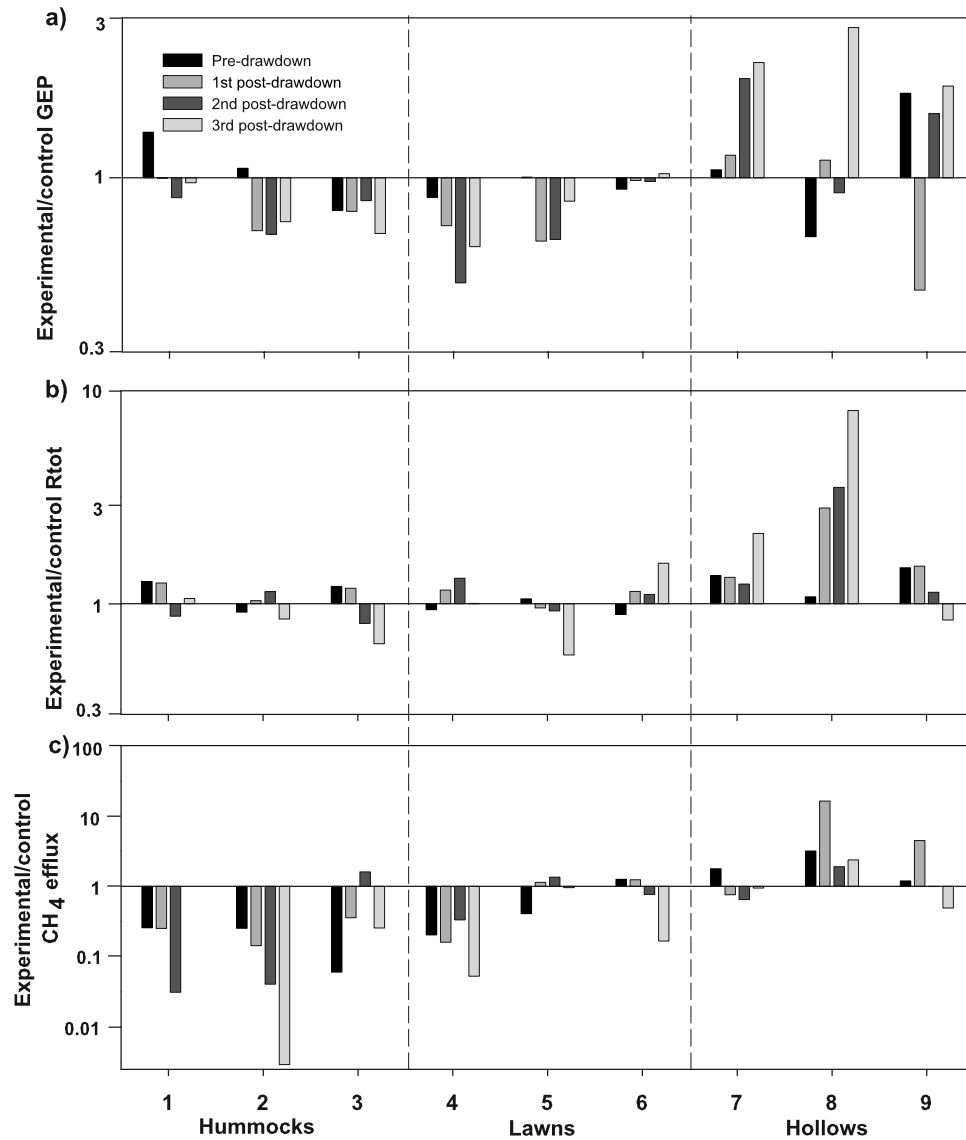
[24] It has generally been predicted that lower water tables in peatlands will reduce rates of  $\text{CO}_2$  uptake or lead to a net release of stored carbon as  $\text{CO}_2$ . The results of this study do not support such predictions. Short-term relationships between water table position and  $\text{CO}_2$  release from peat soils [e.g., Moore and Dalva, 1993] suggest that respiration rates should increase following water table drawdown. While this is evident at experimental hollows, there were no significant differences between the control and experimental sites in the third season following the water table drawdown. Changes in Rtot have probably been

minimized by peat subsidence which occurred following drainage helping to maintain water tables closer to the surface than expected on the basis of the  $\sim 20 \text{ cm}$  water table drawdown. The adjustment of the peat surface with water table fluctuations has been observed in other peatlands [Kellner and Halldin, 2002; Price, 2003] and has been noted to maintain water tables closer to the surface than predicted by considering water storage changes alone [Price and Schlotzhauer, 1999]. Thus subsidence has limited the increase in the size of the peat oxic zone following water table drawdown maintaining lower rates of soil respiration.

[25] While subsidence has also occurred at experimental hollows, the water table drawdown has primarily resulted in the reduction or removal of standing water at these locations. This reduction in the extent of inundation at hollows has encouraged increased productivity of the vegetation and some shifts in the community composition. This increased productivity is evident through the increase in maximum GEP (Figure 3),  $\text{GP}_{\text{max}}$ , and vascular plant cover (Figure 5). The increase in Rtot at experimental hollows may thus result from increased vegetation respiration as the community becomes more productive. Higher rates of ecosystem respiration have been observed in vegetated plots compared to bare peat soil [Tuittila *et al.*, 1999].

[26] Moreover, enhancement of the rate of Rtot in response to lower water tables may be limited by the shift in the thermal regime at the experimental site. Despite similar peat temperatures at 5 and 20 cm depth prior to water table drawdown, by the third season after the water table decline the experimental site peat temperatures were lower at all microforms than the control site (Table 2). Generally there is a thin layer of soil ice ( $<20 \text{ cm}$ ) at the site from November until early May, but we have observed that dry locations





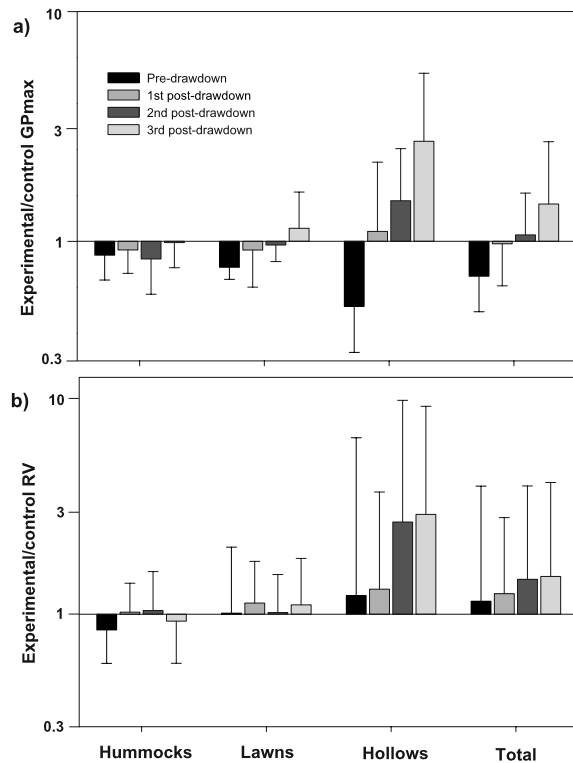
**Figure 4.** Log-transformed quotient experimental/control for seasonal total (a) GEP, (b) Rtot, and (c) CH<sub>4</sub> efflux at individual sample plots through time. Sample plots are arranged from the driest at the left to the wettest at the right. Vertical dashed lines indicate the transition from (left) hummocks to lawns and (right) lawns to hollows. Horizontal lines at 1 indicate no difference between experimental and control sites.

maintain soil ice later into the season than adjacent wet microforms and this may lead to the lower peat temperatures following water table drawdown. Since Rtot is positively related to temperature [Moore and Dalva, 1993], this shift may help mediate increases in Rtot induced by the larger oxic zone.

[27] Productivity has not been altered significantly following the water table drawdown; however, the vegetation community at experimental hollows changed and GEP at these locations increased. GP<sub>max</sub> increased linearly through time at experimental hollows and there is some indication that this is also the case at experimental lawns (Figure 5). Increases in the cover of vascular vegetation at lawns and hollows across the site support these trends. Manipulation

of water table position in peatland mesocosms suggests that maximum *Sphagnum* [Weltzin *et al.*, 2001] and graminoid and forb productivity [Weltzin *et al.*, 2000] occurs under wet conditions. These studies did not consider flooded conditions but only water table position at or below the surface. In contrast, descriptions from pools naturally drained by soil pipes suggest that the removal of standing water can induce an ecological succession that involves the colonization of bare peat substrate by *Sphagnum* mosses and sedges [Foster *et al.*, 1988] and a similar process is occurring at the experimental site.

[28] A comparison of maximum GEP at the control site and a nearby site drained for eight seasons [Strack *et al.*, 2006] showed significantly higher productivity at drained



**Figure 5.** Log transformed quotient experimental/control (a) seasonal GPmax and (b) relative vegetation cover (RV) at the experimental hummocks, lawns, hollows, and average site conditions (total) through time. Horizontal lines at 1 indicate no difference between experimental and control sites.

hollows compared to those at the control site. Since control and experimental hollows are not yet significantly different, this suggests that the vegetation community at the experimental site is continuing to develop three seasons post-water table drawdown. Thus, despite the fact that the change in vegetation is an important driver for resulting CO<sub>2</sub> exchange, we suggest that the development of a new equilibrium vegetation community requires more than three growing seasons of persistent water table drawdown. This response may be missed by studies investigating CO<sub>2</sub> exchange under short-term drought.

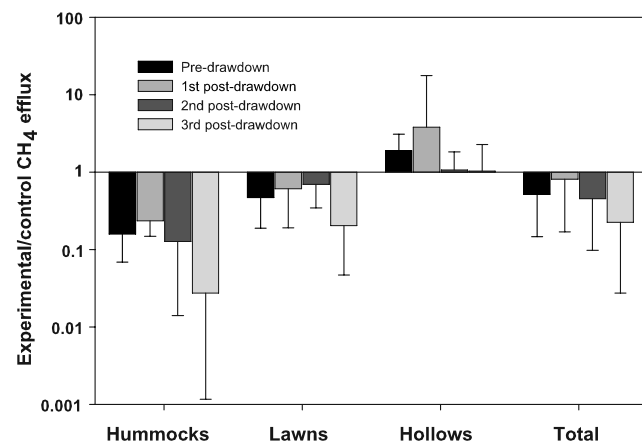
[29] The balance between the shifts in GEP and R<sub>tot</sub> resulted in very little change in NEE during the three seasons since the water table manipulation. This is unexpected on the basis of the majority of previous research. Water table manipulation in laboratory columns of peat have shown that lower water tables result in large releases of CO<sub>2</sub> [Moore and Dalva, 1993; Blodau et al., 2004] while field investigations of drained peatlands generally support these findings [Moore and Roulet, 1993; Silvola et al., 1996]. Similarly, comparisons of peatland NEE between wet and dry years also suggest that drying results in reduced uptake of CO<sub>2</sub> or a shift to net CO<sub>2</sub> release [Shurpali et al., 1995; Bubier et al., 2003; Lafleur et al., 2003]. In contrast, studies of drained peatlands in Finland have revealed that lower water tables can enhance carbon accumulation at some sites

[Minkinen et al., 2002; Laiho et al., 2003]. On the basis of field derived relationships between GEP and water table [Waddington et al. 1998] predicted that the change in NEE resulting from climate change would be dependent on the initial water table position at the peatland with wet sites becoming larger carbon sinks while dry sites were shifted toward carbon sources. This prediction was supported by field data from the SCB peatland at a site drained for eight seasons [Strack et al., 2006] and the present study also suggests that a similar pattern will develop over time. Within site variability in NEE limits our ability to assess significant differences between the control and experimental site although the data show limited increases in CO<sub>2</sub> emissions at hummocks and lawns and the potential for enhanced CO<sub>2</sub> uptake at hollows (Table 4).

## 5.2. CH<sub>4</sub> Efflux

[30] As has been suggested by other studies [Moore and Roulet, 1993; Moore and Dalva, 1993; Daulat and Clymo, 1998], a water table drawdown has resulted in reduced CH<sub>4</sub> emissions from the experimental site. Despite the fact that peat subsidence has minimized the water table drawdown across the microtopographic gradient, all microforms at the experimental site have lower water tables compared to the control site. This has reduced the size of the anoxic zone in the peat profile and increased the oxic zone. Thus the amount of CH<sub>4</sub> produced has probably been reduced while CH<sub>4</sub> oxidation has increased thereby diminishing CH<sub>4</sub> emissions. Decreases in peat temperatures at the experimental site following the water table drawdown may also reduce CH<sub>4</sub> production rates [Dunfield et al., 1993] contributing to the reduction in CH<sub>4</sub> efflux from this site.

[31] Substantial spatial and temporal variability in CH<sub>4</sub> efflux was observed at the control site with average seasonal emissions of CH<sub>4</sub>-C from individual study plots ranging from 1 to 90 mg m<sup>-2</sup> d<sup>-1</sup> and even a single plot varying from 3 to 60 mg m<sup>-2</sup> d<sup>-1</sup> between the four years of the study. However, this variability is commonly reported for peatland CH<sub>4</sub> studies [e.g., Bellisario et al., 1999; Heikkinen



**Figure 6.** Log-transformed quotient experimental/control average CH<sub>4</sub> efflux through time. Horizontal lines at 1 indicate no difference between experimental and control sites.

*et al.*, 2002; *Bubier et al.*, 2005]. This extent of spatial and temporal variability in CH<sub>4</sub> effluxes makes it difficult to draw firm conclusions about the reduction in emissions. This is particularly evident at hollows where significant reduction in CH<sub>4</sub> emissions from experimental hollows has resulted in effluxes that are still similar to those from the control site (Figure 6), owing to the large differences between sites initially.

[32] There was no clear relationship between water table position and CH<sub>4</sub> efflux, likely due to the high degree of spatial variability in CH<sub>4</sub> emissions. The water table–CH<sub>4</sub> efflux relationship was primarily obscured by large differences between the control and experimental hollows. Prior to water table manipulation the CH<sub>4</sub> efflux at flooded experimental plots was substantially higher than that measured at any other plots within the SCB fen. This may be due to ebullition which has been reported from flooded zones [*MacDonald et al.*, 1998; *Dove et al.*, 1999]. In contrast, CH<sub>4</sub> effluxes at flooded control plots were lower than nearby plots with water tables at or just below the peat surface during the entire study period. Vascular vegetation cover was initially higher at control hollows than experimental hollows (Table 3) and the presence of vascular vegetation has been observed to reduce ebullition rates [*Dove et al.*, 1999]. We hypothesize that the large reduction in CH<sub>4</sub> observed at experimental hollows is related to the limitation of ebullition resulting from changes in peat properties following water table manipulation. Peat subsidence occurred at these locations in response to the lowered water table, increasing bulk density [*Whittington and Price*, 2006]. It has been suggested that a denser peat structure can help to entrap CH<sub>4</sub> gas bubbles and limit ebullition [e.g., *Glaser et al.*, 2004; *Strack et al.*, 2005], although further investigation into these interactions is required.

[33] Methane effluxes may also be influenced by the increase in productivity at experimental hollows. Vascular vegetation can enhance CH<sub>4</sub> production by providing labile carbon substrates for methanogenesis and providing rapid transport of CH<sub>4</sub> from below the water table to the atmosphere, potentially bypassing the oxic zone in the peat profile [e.g., *Tyler et al.*, 1997]. However, CH<sub>4</sub> emissions may also be reduced by the presence of vascular plants resulting from potential oxidation in the rhizosphere [e.g., *Popp et al.*, 2000], although this is generally small relative to the potential for efflux enhancement. Moreover, a significant positive relationship has been found between net ecosystem productivity and average CH<sub>4</sub> efflux [*Whiting and Chanton*, 1993]. Thus the increase in vascular plant cover and GEP at experimental hollows may potentially increase CH<sub>4</sub> emissions at these plots. CH<sub>4</sub> effluxes may increase from these microforms in the future as the vegetation community continues to evolve.

### 5.3. Carbon Balance

[34] There is no clear difference between the control and experimental sites in the mass of carbon emitted at any microform in the third season post–water table drawdown. As discussed above, at hummocks and lawns there has not been any significant change in CO<sub>2</sub> exchange and this accounts for the majority of the carbon exchange at these

microforms. There is evidence that, experimental hollows have shifted from emitting more carbon than control hollows prior to the water table drawdown to storing more carbon during the third season after a water table drawdown. Thus the change in the overall carbon balance at a plot in response to water table drawdown appears to be related to its initial water table position and location along the microtopographic gradient. While this effect is not conspicuous after three seasons, a significant relationship between changes in NEE and initial water table position has been observed following eight and nine seasons of persistent water table drawdown [*Strack et al.*, 2006] indicating that this pattern will develop in time. The pattern and cover of peatland microforms varies greatly between peatlands [*Ivanov*, 1975; *Glaser and Janssens*, 1986]. Since microforms vary in their response to disturbance, their distribution should be considered when predicting rates of future peatland carbon cycling.

### 5.4. Implications for Climate Change

[35] Since northern peatlands represent a globally significant stock of soil carbon [*Gorham*, 1991] and contribute substantially to the global CH<sub>4</sub> budget [*Fung et al.*, 1991] they may act as an important biological feedback to climate change. Enhanced aerobic soil respiration under lower water tables and higher peat temperatures may release stored soil carbon to the atmosphere as CO<sub>2</sub> acting a positive climatic feedback. On the other hand, drier peatlands should have reduced CH<sub>4</sub> emissions, providing a negative feedback to climate change. The balance of these two processes will determine the shift in a peatland's net climatic influence. To assess this we determined the global warming potential (GWP) of each microform at the control and experimental sites throughout the study period by considering a 100-year timescale and weighting the warming potential of CH<sub>4</sub> at 23 times that of CO<sub>2</sub> [*Intergovernmental Panel on Climate Change*, 2001]. After three growing seasons, the quotient of GWP (experimental/control) increased by 152 and 40% at hummocks and lawns and declined by 70% at hollows (Table 4). Thus, if these microforms are evenly distributed across the peatland (33% cover each) a water table drawdown of ~20 cm is expected to increase the GWP of the peatland by 40%. However, if a hypothetical peatland initially has a composition with 23% hummocks, 17% lawns and 60% hollows, water table drawdown would result in no net change in GWP. In fact, prior to disturbance, the average cover of hummocks, lawns and hollows was 30, 30 and 40%, respectively. On the basis of these values the expected increase in GWP for this site is 29%. Thus peatland microform composition is important when predicting the response of peatlands to climate change due to differences in the relative contributions of CO<sub>2</sub> and CH<sub>4</sub> to the carbon balance and the differential potential for lower water tables to enhance ecosystem productivity between microforms.

## 6. Conclusions

[36] Water table drawdown induced peat subsidence which maintained water tables close to the surface particularly at lawns and hollows. The changing hydrology in-

duced an increase in vascular plant cover, especially at hollows, while moss cover was unaffected.

[37] Following three seasons of persistent water table drawdown there was no significant difference in CO<sub>2</sub> exchange from any microform, although increases in GEP and Rtot were observed at hollows. Since significant shifts in CO<sub>2</sub> exchange were evident at another pool drained for eight seasons it is probable that the vegetation community at the experimental site is continuing to respond to the water table drawdown. This suggests that short-term drought studies will not capture the full vegetation community response to persistent hydrologic changes.

[38] Methane efflux was reduced by water table drawdown. However, CH<sub>4</sub> emission from hollows at the experimental site remained similar to the control site after three seasons of water table drawdown.

[39] Changes in CO<sub>2</sub> and CH<sub>4</sub> exchange varied between microforms owing to spatial variability in peat subsidence and vegetation changes related to initial ecohydrological differences between microforms. Therefore, in order to predict the response of northern peatlands to disturbance, the distribution and composition of microforms should be considered.

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