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Cutover peatlands: A persistent source of atmospheric CO_2

J. M. Waddington, K. D. Warner, and G. W. Kennedy
School of Geography and Geology, Hydrological Sciences Group, McMaster University, Hamilton, Ontario, Canada

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[1] Peatlands represent an important component of the global carbon cycle, storing 23 g C m^{-2} yr^{-1}. Peatland mining eliminates the carbon sink function of the peatland. In this paper we measure the total ecosystem respiration in a natural, 2 and 3 year (young) and 7 and 8 year (old) postcutover peatland near Sainte-Marguerite-Marie, Québec, during the summers of 1998 and 1999. Although the natural site was a source of CO_2 during the dry 1998 study season (138 g C m^{-2}), CO_2 emissions were between 260 and 290% higher in the cutover sites (363 and 399 g C m^{-2} for young and old, respectively). Cutover site CO_2 emissions were only 88 and 112 g CO_2-C m^{-2} at the young and old sites during the wet 1999 study season. Total ecosystem respiration was more dependent on the water table position than on changes in the thermal regime or the labile carbon of the peat in a dry summer, but the opposite was the case in a wet summer. CO_2 emissions increased with postharvest time regardless of a decrease in labile carbon, demonstrating that cutover peatlands are a large persistent source of atmospheric CO_2. Direct measurement of the net ecosystem CO_2 exchange in cutover peatlands, as opposed to determining the loss of carbon from bulk density determinations, provides a better understanding of how peat drainage and harvesting operations affect the carbon balance in peatlands. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1890 Hydrology: Wetlands; 1610 Global Change: Atmosphere (0315, 0325); 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interaction; *KEYWORDS:* peatland, carbon dioxide, atmosphere, harvesting

1. Introduction

[2] Peatland drainage and harvesting have increased over the last century due to the increased use of peat in the energy, agricultural, and horticultural sectors [*Armentano and Menges*, 1986]. For example, *Jeglum* [1990] estimates that 25,000 ha of peatlands have been drained for forestry in Canada, while *Keys* [1992] estimates 16,000 ha have been drained for Canadian horticultural purposes. In Finland it is estimated that cutover peatlands are increasing at the rate of 2000 ha per annum [*Selin*, 1986]. Although undisturbed natural peatlands play an important role in the global carbon cycle, storing ~20 g C m^{-2} yr^{-1} [e.g., *Gorham*, 1991; *Clymo et al.*, 1998; *Vitt et al.*, 2000], *Gorham*, [1991] estimates that oxidation of peat due to long-term drainage operations results in a net flux of carbon dioxide (CO_2) to the atmosphere of 8.5 Tg yr^{-1}. The combustion of fuel peat adds an additional 26 Tg yr^{-1} [*Gorham*, 1991]. Combined, peatland drainage and peat combustion account for ~45% of the current rate of carbon fixation in peatlands [*Gorham*, 1991]. These global estimates, however, are based on few direct studies of drained or cutover peatlands. Moreover, there are no studies that have considered the interannual variability in these flux estimates. Given that the objective of the Kyoto Protocol [*United Nations*, 1997] is to stabilize greenhouse gas concentrations in the atmosphere through the reduction of fossil fuel emissions and through land use management, there is a need to improve our understanding of the effects of peatland drainage and harvesting on peatland CO_2 release. The general objective of this paper therefore is to determine the effects of peatland drainage and harvesting operations on total ecosystem respiration R_{TOT} in a cutover peatland.

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[3] When peatlands are drained for forestry, primary production is enhanced [*Laiho and Laine*, 1997; *Komulainen et al.*, 1999]; however, in harvesting operations the production component is eliminated. When these cutover peatlands are abandoned, they are often devoid of vegetation, and the hydrological conditions are unsuitable for *Sphagnum* recolonization [*Bugnon et al.*, 1997; *Ferland and Rochefort*, 1997; *LaRose et al.*, 1997]. Peatland drainage enhances organic matter decomposition owing to an increase in the depth of the oxic zone and CO_2 emissions to the atmosphere [e.g., *Glenn et al.*, 1993; *Silvola et al.*, 1996; *Nykänen et al.*, 1997; *Tuittila et al.*, 1999; *Sundh et al.*, 2000]. For example, *Silvola* [1986] found the net release of CO_2 increased ~270–300% when the water table was lowered from ~10 to ~60 cm below the surface in a natural peatland. Moreover, CO_2 emissions in several drained peatlands increased by 100–400% because of the increased oxidation of peat material and the removal of carbon-fixing vegetation through the harvesting of the acrotelm [*Gorham*, 1991; *Nykänen et al.*, 1995; *Silvola et al.*, 1996].

[4] The rate of peat decomposition is a function of moisture content, peat temperature, and substrate quality [*Moore et al.*, 1998] with peat volumetric moisture content (VMC) specified as the dominant control in drained peatlands [*Nykänen et al.*, 1997]. However, there is a paucity of information regarding hydrological processes in cutover peatlands, and by extension, the nature of the carbon balance is uncertain [*Waddington and Price*, 2000]. *Prevost et al.* [1997] and *Price* [1996] both found that VMC was lower in cutover peatlands than in natural peatlands. The range of soil temperatures also increases with peatland drainage [*Prevost et al.*, 1997; *Hokka et al.*, 1997]. Decreased soil moisture content in the upper peat profile results in large diurnal fluctuations in peat temperature in drained peatlands, as the specific heat and thermal conductivity in the upper soil profile are reduced by the loss of water. Consequently, the combined changes in both the hydrological and thermal regimes should be enhanced as the rate of

decomposition increases owing to the aeration of the peat and an increase in peat temperature. The strength of this enhancement will largely be controlled by interannual variability in air temperature, precipitation, and evaporation

[5] R_{TOT} is also expected to vary with time since abandonment owing to changes in peat quality and structure. For example, peat shrinkage and oxidation may increase the bulk density and decrease the specific yield of the peat substrate, increasing the magnitude of water table fluctuations [*Boelter*, 1969; *Bragg*, 1995; *Price*, 1997] and thereby increasing the potential for peat oxidation under dry conditions. Moreover, because the degree of decomposition determines the porosity and pore size distribution [*Boelter*, 1969; *Hillman*, 1997], which controls the water retention, hydraulic conductivity, and water yield characteristics of the peat [*Okruszko*, 1995], the rate of R_{TOT} (oxidation) should vary with postharvest time as the peat properties (e.g., specific yield, bulk density, and porosity) change. Furthermore, without the addition of labile carbon from a vegetation layer, the labile carbon content of the cutover peat should decrease with time, thereby decreasing the rate of peat oxidation. Laboratory experiments, such as those of *Bridgham and Richardson* [1992] in arctic tundra soils and *Nadelhoffer et al.* [1991] in North Carolina pocosin soils, support these findings as low labile carbon has been shown to limit oxidation. Field studies by *Schothorst* [1977] demonstrated that the rate of oxidation decreased with postdrainage and harvest time, with 45% of the total oxidation over a 10 year period occurring within the first 2 years. This contrasts with the findings of *Prevost et al.* [1997] that indicate decomposition rates in the third year of postdrainage were higher than in preceding years.

[6] Nevertheless, the effects of interannual variability in climate and postcutover time on the rate of cutover peatland total respiration have both important global carbon cycle and peatland respiration implications, especially given the global rate of peatland drainage. Despite the importance of these effects, there are no direct measurements of R_{TOT} in cutover peatlands representing various stages of abandonment and in years of varying climatic conditions. Consequently, the objectives of this paper are to gain a better understanding of the hydrological and biogeochemical processes controlling R_{TOT} in a "young" (2 and 3 years) and "old" (7 and 8 years) postcutover peatland in both a wet and dry summer.

2. Materials and Methods

2.1. Study Area

[7] This study was conducted at the Sainte-Marguerite-Marie peatland in the Lac Saint-Jean region of central Québec (48°47′N, 72°10′W), near the town of Mistassini. The average annual temperature is 2.2°C, and the mean annual precipitation is 908.5 mm, of which approximately two thirds occurs as rain. The Sainte-Marguerite-Marie peatland is situated on a terrace of deltaic sands [*Price*, 1997] in the Lac Saint-Jean lowlands, forming a 4315 ha bog-poor fen complex that is classified as a plateau bog [*National Wetlands Working Group*, 1988]. A portion of the peatland has been drained, and the acrotelm has been removed, with operations commencing in 1990. All measurements were made between early May and late August in 1998 and 1999 at a young (drained in the fall of 1996 and cutover in 1997) and old (drained in the fall of 1990 and cutover in 1991) site. The peat depth was 1.8 and 1.7 m at the young and old sites, respectively. Differences in peat thickness at each of the cutover sites are due to differences in both peat extraction (~60–70 cm) and subsidence.

2.2. Total Ecosystem Respiration R_{TOT}

[8] Measurements of total CO_2 respiration R_{TOT} were made with a dark chamber and a PP Systems, EGM-1 or EGM-2 infrared gas analyzer (IRGA) assembly placed and sealed over circular PVC collars inserted ~10–15 cm into the peat. In 1998, five collars were clustered ~5–7 m from the edge of drainage ditch, where the effects of the ditch were minimal [*Price*, 1997], while in 1999 collars at the young and old site were located 1, 3, 5, 7, 9, and 15 m from the edge of the drainage ditch. Cylindrical chambers covered a surface area of 0.05 m^2 with a volume of 20 L. CO_2 concentrations were measured for a 5 min duration at 1 min intervals. Fans mounted inside each chamber ensured well-mixed air during the sampling period. Instantaneous measurements of soil temperature, water table position, and VMC were taken to establish an empirical relationship between these variables and R_{TOT}.

2.3. Environmental Variables

[9] Peat temperature was measured every 30 min at 0, 2, 5, 10, 25, 50, and 100 cm depths at the old site. Manual measurements of air and peat temperature (2, 5, 10, 25, and 100 cm depths) were made three times per week at the young site in 1998 and measured every 30 min in 1999. Continuous 5 cm peat depth temperatures at the young site in 1998 were modeled using a correlation of the manual measurements at the young site and the continuous measurements at the old site (r^2 = 0.96). Water table position was monitored continuously at the natural and old sites in 1998 and at all sites in 1999 using a float attached to a 10-turn potentiometer [see *Waddington and Roulet*, 1996]. Manual measurements of water table position were made three times per week at the young site in 1998, and continuous water table position at the young site was modeled using a correlation of the manual measurements at the young site and continuous measurements at the adjacent old site (r^2 = 0.98). Total rainfall was measured using a tipping bucket rain gauge in 1998 and a manual rain gauge in 1999 at the old site. VMC was measured continuously at both the natural and old sites in 1998 and at all sites in 1999 using Campbell Scientific time domain reflectometer (TDR) probes, inserted at 5, 20, and 100 cm depths. Each probe was individually calibrated in peat removed from the study sites [see *Price*, 1997]. Bulk density and surficial (0–3 cm) gravimetric soil moisture were determined weekly at each of the three sites using a hand cutter that sampled the upper 3 cm of the peat surface. Peat organic content was determined using the loss on ignition technique with a 30 min incubation period and furnace temperature of 550°C.

2.4. Modeling R_{TOT}

[10] Continuous R_{TOT} was modeled at the old and young sites and within the lawn and hummock communities at the natural site using the following equation:

$$R_{TOT} = b_0 + b_1 T_5 + b_2 \text{ WT}. \qquad (1)$$

The respiration response curve was determined using a linear regression relationship between CO_2 exchange and instantaneous peat temperature at 5 cm depth (T_5) and water table position (WT). Water table position was used because VMC did not significantly improve r^2 results using stepwise multiple regression. The coefficients (b_0, b_1, and b_2) were estimated using linear regression.

3. Results

3.1. Soil and Climate Characteristics

[11] Peat bulk density ranged from 0.046 to 0.058 g cm^{-3} (mean of 0.052 g cm^{-3}) at the natural site, from 0.063 to 0.114 g cm^{-3} (mean of 0.084 g cm^{-3}) at the young site, and from 0.098 to 0.141 g cm^{-3} (mean of 0.119 g cm^{-3}) at the old site during the 1998 field season. Bulk density was consistently greater at the old site than at the young site throughout the 1998 study period. The mean organic content (0–2 cm) at the young and old sites was 88 ± 0.1 and 76 ± 0.1%, respectively, while the mean organic content at 5 cm depth

Table 1. R_{TOT} Model Parameters and Corresponding r^2 Values From Multilinear Regression ($R_{TOT} = b_0 + b_1T_5 + b_2$WT) for the Dry (1998) and Wet (1999) Summers[a]

	n		b_0		b_1		b_2		r^2	
Site	1998	1999	1998	1999	1998	1999	1998	1999	1998	1999
Young	120	243	−12.04	−0.59	0.60	0.24	−0.49	0.00	0.79	0.45
Old	120	186	−11.20	0.47	0.80	0.22	−0.33	0.00	0.83	0.65

[a] Here *n* refers to the sample size used in the regression analysis. In the wet year (1999), water table did not improve r^2 over peat temperature on its own.

was 80 ± 0.1 and 78 ± 0.1% at the young and old sites, respectively. Organic content was not determined at the natural site. Von post decomposition values ranged from H3 to H4 in the cutover surface peat (upper 25 cm) and from H1 to H2 in the surface peat of the adjacent natural peatland.

[12] Air temperature was within 1.0°C of the 30 year mean for most of the 1998 summer with the exception of May, where it was 3.3°C higher than normal. In 1999, mean monthly air temperatures were +3.1°C, +1.2°C, +0.2°C, and −1.9°C relative to the normal 30 year mean for May, June, July, and August, respectively. Total rainfall for the 1998 and 1999 seasons was 78 and 116% of the 30 year mean (364 mm) for the May to August period [*Environment Canada*, 1993]. Total rainfall during May, July, and August of the 1998 season was only 54, 79, and 33% of the 30 year mean for these months, while June rainfall exceeded the normal precipitation by 161%. In 1999, June and July rainfall exceeded the normal precipitation by 142 and 146%, respectively. Hereafter, the 1998 and 1999 summer periods will be referred to as the ''dry'' and ''wet'' years, respectively. A comparison of the water table position, peat temperature, and modeled respiration (see Table 1 for model parameters) will be presented to establish the temporal variability in CO_2 exchange at the cutover peatland.

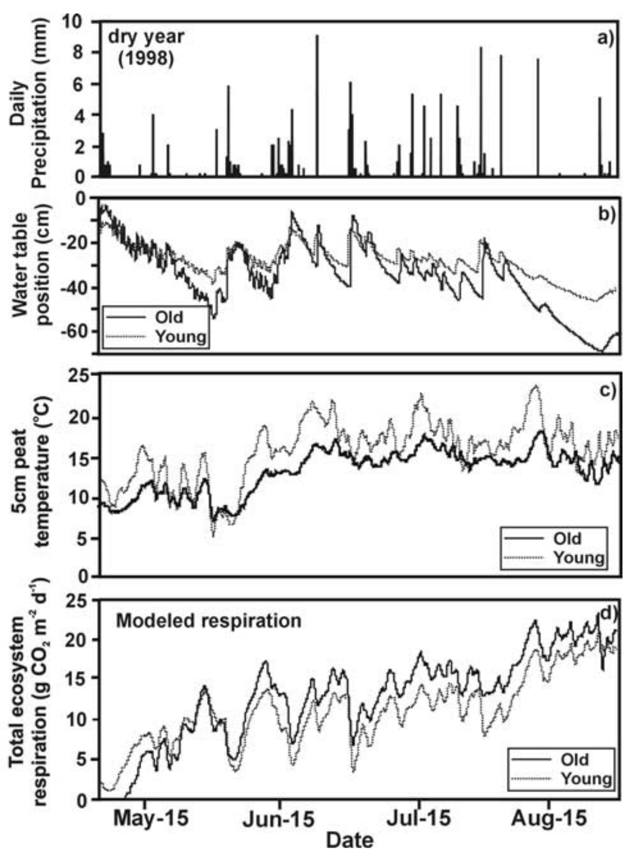

Figure 1. (a) Precipitation (mm), (b) water table position (cm), (c) 5 cm peat temperature, and (d) total ecosystem respiration (modeled R_{TOT}) (g CO_2 m^{-2} d^{-1}) at the young (dotted curves) and old (solid curves) cutover sites during the dry year (1998).

3.2. Interannual Variability in CO_2 Exchange: Dry Year

[13] Rainfall events were small and uniform throughout most of the 1998 study period (dry year) with two dry periods occurring in late May and mid-August (Figure 1a). The two short dry periods resulted in lower water table positions at each of the sites (Figure 1b). The mean water table position at the young and old sites was −30.6 and −35.1 cm, respectively. The water table was never above the surface at either site but had a minimum depth below the peat surface of −2.5 cm at the old site. The water table reached its greatest depth in mid-August during the second dry period with a maximum depth of −40.2 and −68.9 cm at the young and old sites, respectively. The water table remained above −10 cm at the adjacent natural site 55% of the study season but only 5 and 3% of the time at the young and old sites, respectively. Similarly, the water table was above −30 cm for 92% of the study season at the natural site and only 57 and 35% of the study season at the young and old sites.

[14] Mean 5 cm peat temperature was 14.7 and 16.6°C at the young and old sites, respectively. The mean daily 5 cm peat temperature at both sites followed similar patterns to that of the air temperature, with the 5 cm soil temperature at the old site being the closest to the air temperature in both magnitude and fluctuations. Air temperature during the dry study season ranged from −1.6° to 30.7°C, with a mean of 15.9°C. The 5 cm peat temperature reached a maximum of 24.2° and 15.1°C and had a minimum of 5.1° and 6.8°C at the young and old sites, respectively. This is compared to air temperature that ranged from −2.8°C to 31.3°C over the study season and 5 cm peat temperatures at the natural site that ranged from 3.0° to 23.0°C [*Warner*, 1999].

[15] VMC at 5 cm ranged from 59 to 85% with a mean of 70% at the old site, and VMC ranged from 68 to 87% with a mean of 79% at 20 cm depth. As the water table position decreased, the response of volumetric soil moisture to rainfall events also decreased in magnitude, especially at the 5 cm depth.

[16] At the beginning of the dry year study period, modeled R_{TOT} was 0.6 and 0.0 g CO_2 m^{-2} d^{-1} at the young and old sites, respectively (Figure 1d). R_{TOT} at both sites increased rapidly in mid-May when soil temperatures increased and the water table position dropped, which was accompanied by a decrease in peat VMC. Peak modeled R_{TOT} was reached in mid-August, with old and young sites attaining a maximum of 28.0 and 26.6 g CO_2 m^{-2} d^{-1}, respectively. Because R_{TOT} remained high at the end of our measurement period, the seasonal estimates of summer R_{TOT} are conservative. Nevertheless, mean daily modeled R_{TOT} was greater at the old site (12.8 g CO_2 m^{-2} d^{-1}) than at the young site (11.7 g CO_2 m^{-2} d^{-1}). This translates into a seasonal R_{TOT} of 397 and 363 g C m^{-2} at the young and old sites, respectively.

3.3. Interannual Variability in CO_2 Exchange: Wet Year

[17] Two large rainfall events (>50 mm), which occurred on 3 June and 2 July during the 1999 study season (Figure 2a),

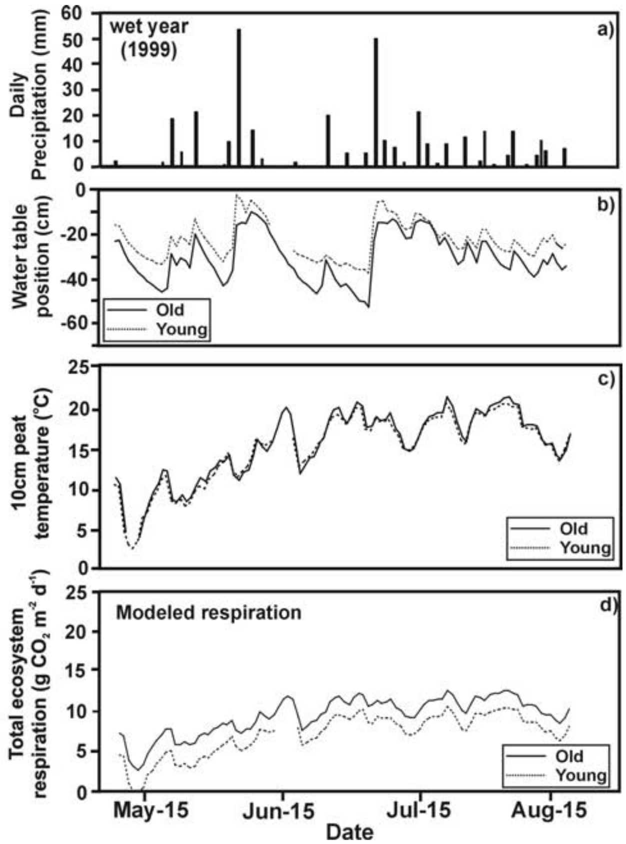

Figure 2. (a) Precipitation (mm), (b) water table position (cm), (c) 5 cm peat temperature, and (d) total ecosystem respiration (modeled R_{TOT}) (g CO_2 m^{-2} d^{-1}) at the young (dotted curves) and old (solid curves) cutover sites during the wet year (1999).

completely saturated the peat, raising the water table position to just below the peat surface at the natural and both cutover sites. There were two short dry periods in mid-May and mid-June but no prolonged periods of drought in 1999. The mean water table position at the young, old, and natural sites was −22.9, −30.5, and −14.0 cm, respectively, which is ∼5–10 cm higher than the dry year means (Figure 2b). Fluctuations in water table position were greatest at the two cutover sites, whereas the water table position at the natural site experienced smaller seasonal variation, ranging from −28 to −2.0 cm. Water table elevation ranged from −38 to −3.0 cm at the young site and from −54 to −8.0 cm at the old site.

[18] Mean 10 cm peat temperature during the wet study year was 15.7° and 15.8°C at the young and old sites, respectively. Mean 10 cm peat temperature ranged from −0.5° to 23.3°C at the young site and from 0.3° to 23.5°C at the old site (Figure 2c). Comparatively, 10 cm peat temperature ranged from 3.7° to 28.2°C at the natural site over the 1999 study season.

[19] Peak R_{TOT} during the 1999 study season occurred in late July, with the old and young sites attaining a maximum of 10.8 and 7.93 g CO_2 m^{-2} d^{-1}, respectively (Figure 2d). It should be noted, however, that the measurement period ended in mid-August when R_{TOT} was typically high. These values for peak R_{TOT} are <30% of the peak values experienced during the dry year. Mean daily modeled R_{TOT} was significantly greater at the old site (3.7 g CO_2 m^{-2} d^{-1}) than at the young site (2.9 g CO_2 m^{-2} d^{-1}). This translates into a seasonal R_{TOT} of 88 and 112 g C at the young and old site, respectively. During this wet year the seasonal flux at the young site was only 24% of the dry year seasonal value, whereas the old site seasonal flux was only 28% of the dry year value.

3.4. Temporal Variability in CO_2 Exchange: Wetting and Drying Events

[20] To illustrate the strong hydrological controls on the temporal variability of R_{TOT}, a time series of mean daily R_{TOT}, and 5 cm VMC content at the old site is presented in Figure 3. R_{TOT} increases as the upper peat layer dries. The wetting event that occurred between 2 and 5 June resulted in a decrease in R_{TOT} from 23.0 to 1.7 g CO_2 m^{-2} d^{-1} as the water table rose from −43.0 to −19.9 cm and 5 cm VMC increased from 69.2 to 74.2%. Within 6 days, R_{TOT} increased to 17.2 g CO_2 m^{-2} d^{-1} as the peat dried again. The second dry period near the end of the study season was represented by a low water table position (−61.5 cm on Julian Day (JD) 233), low 5 cm VMC (60.5%), and high R_{TOT} (30.2 g CO_2 m^{-2} d^{-1}). A rain event that occurred between 21 and 24 August resulted in a decrease in R_{TOT} to 18.6 g CO_2 m^{-2} d^{-1}, when 5 cm VMC increased to 66.0%, despite the water table decreasing to −64.5 cm. The wetting front apparently never reached the water table but, rather, was retained as it infiltrated through the peat profile, resulting in a change in VMC and R_{TOT} but no corresponding change in the water table position.

[21] Two experiments were performed in 1999 to determine the response of R_{TOT} to wetting and drying events. Both experiments simulated a wetting event by adding 1.5 mm hr^{-1} to a collar and leaving an additional collar as a control. In the first experiment a third collar simulated the response to drying after a 24 mm rainfall event, while the second experiment simulated the response to drying after a 34 mm rainfall event.

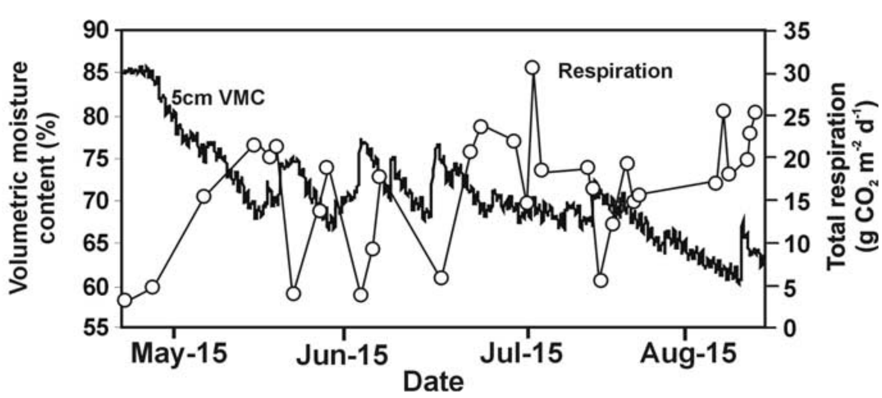

Figure 3. Time series plot of mean daily R_{TOT} (g CO_2 m^{-2} d^{-1}) and VMC at 5 cm depth at the old site during the dry year (1998).

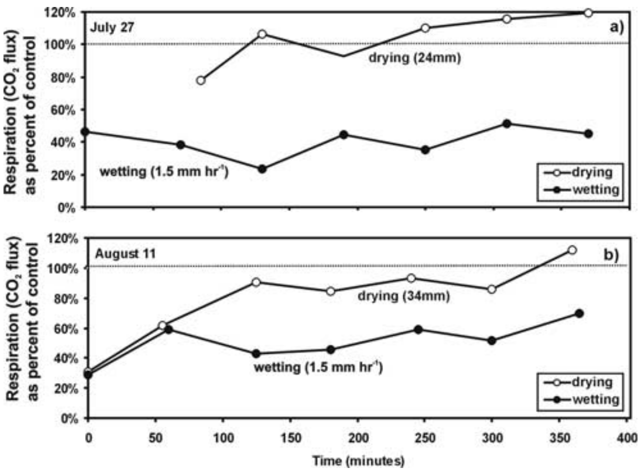

Figure 4. Wetting experiments at the old site during the wet year (1999) on (a) 27 July and (b) 11 August. Respiration values are expressed as a percentage of the control site on.

The wetting curves in Figure 4 illustrate that CO_2 efflux is inhibited when the peat is continually rewetted (15 mm hr^{-1}), with R_{TOT} being ~50% of the control throughout the duration of the experiment. The drying curves demonstrate that R_{TOT} recovers to 100% of the control values within ~150 min of the 24 mm experiment. The addition of more water (10 mm) to the drying collar during the second experiment caused a slower recovery (>300 min) of R_{TOT} compared to the control values.

3.5. Spatial Variability in CO_2 Exchange

[22] Figure 5 shows the spatial variability in CO_2 exchange, soil moisture, water table, and 5 cm peat temperature perpendicular to the drainage ditches at both the young and old sites. The highest mean R_{TOT} values are observed toward the middle of the old transect (4.84 g CO_2 m^{-2} d^{-1}) and young transect (3.46 g CO_2 m^{-2} d^{-1}), which are located 4.9 and 7.1 m from the drainage ditch, respectively. Conversely, the lowest mean R_{TOT} values occur at the old transect (2.39 g CO_2 m^{-2} d^{-1}) and young transect (2.25 g CO_2 m^{-2} d^{-1}), which are located 10.4 and 14.2 m from the drainage ditch, respectively.

4. Discussion

4.1. Environmental Regimes

[23] The mean water table position was 18.8–23.3 cm lower in cutover sites in the dry year and 9–16 cm lower in the wet year than the natural bog. This difference in water table position is consistent with other studies [*LaRose et al.*, 1997; *Price*, 1997]. The old site had the largest fluctuations in water table position in both the dry and wet years, indicating the effect of an increase in bulk density and decrease in specific yield with postharvest time. *Price* [1996] suggests that increased bulk density decreases the specific yield of the peat, thereby resulting in a greater magnitude of water table fluctuations. The bulk density was lower at the young (0.084 g cm^{-3}) than the old site (0.119 g cm^{-3}). The lower water table position in these cutover sites resulted in a deeper aerobic zone than at the natural site [*Waddington and Warner*, 2001].

[24] The rate of gas diffusion through peat is inversely related to VMC content because diffusion of gases in water is ~10,000 times slower than in air. This is especially prevalent in cutover peatlands, which exhibit a wide range of VMC throughout the summer, depending on the frequency and magnitude of precipitation events. Moreover, small diurnal variations in soil moisture at 5 cm depth, likely due to daily evaporation and nightly condensation onto the peat [*Warner*, 1999], along with strong diurnal temperature change caused a correspondingly large diurnal variation in R_{TOT}. An increase in bulk density due to peat subsidence during the summer [*Price and Schlotzhauer*, 1999] can lead to saturation at lower VMC, thereby enhancing R_{TOT} versus VMC hysteresis. Hysteresis due to wetting and drying can lead to large variability in R_{TOT} at similar VMC. Furthermore, VMC also plays an important role in the thermal conditions of the peat. For example, as VMC decreases, the total thermal capacity of the peat decreases, thereby increasing the diurnal fluctuations in surface peat temperatures. Because an increase in peat temperature increases the potential for oxidation by increasing the rate of microbial activity [*Moore and Knowles*, 1987; *Stewart and Wheatley*, 1990; *Hobbie*, 1994], there is a corresponding increase in R_{TOT}. Although direct comparison of model parameter estimates (Table 1) between years is difficult because of the slightly different measurement protocol between years, the differences are likely due to these seasonal and interannual changes in peat characteristics.

4.2. Total Ecosystem Respiration R_{TOT}

[25] Field studies [*Schothorst*, 1977] suggest that CO_2 emissions decrease with postharvest time. Both of these studies suggest that this phenomenon occurs because of a decrease in labile carbon in the peat. Both observed and modeled results in this study in a wet and dry year, however, demonstrate an opposite trend. The rate of loss of CO_2 was greater from the old site than from the young site in both field seasons. Increased decomposition occurring in a peat substrate with greater humification was also reported by *Stewart and Wheatley* [1990], *Prevost et al.* [1997], and *Silvola and Ahlholm* [1989]. Moreover, this study suggests that decomposition was inhibited in wetter peat (wet versus dry year). Considering that *Schothorst* [1977] did not make direct measurements of oxidation, we suggest that the present study provides a better (direct) measure of the effect of postcutover time on R_{TOT}. Given that the organic content of the 0–2 cm layer was significantly greater in the young site (88%) than the old site (76%) and that the organic content in the 5 cm layer was not significantly different between sites

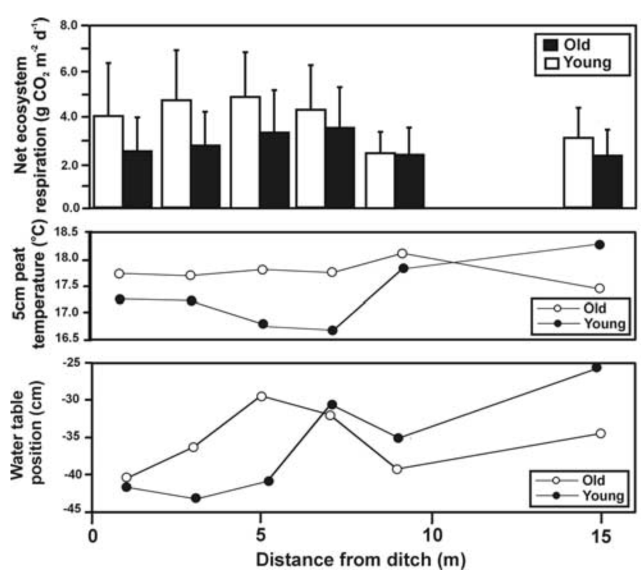

Figure 5. Variability in (a) total respiration, (b) 5 cm peat temperature, and (c) water table position along a transect perpendicular from a drainage ditch at the young and old sites. Error bars in Figure 5a are ± 1 standard deviation.

($\sim$78%), the increase in R_{TOT} with postcutover time observed in this study is not due to organic content. This is substantiated by results from *Waddington et al.* [2001] that found CO_2 production in anaerobic peat incubations of peat from the cutover sites followed the trend: young > old. Instead, differences are likely controlled by the microsite differences in VMC and peat temperature mentioned earlier. As the peat becomes drier, however, substrate quality differences become more important. For example, mean VMC (0–2 cm depth) decreased by 2.5% at the old site (from 59.4 to 56.9%) between the first and second halves of the study period and 11.5% at the young site (from 59.5 to 48.0%). R_{TOT} at the old site increased 27% between the first and second halves of the study period; however, R_{TOT} increased $\sim$90% at the young site owing to a greater decrease in VMC.

[26] The lower R_{TOT} during the wet year and rewetting experiments suggests that with appropriate water management (e.g., rewetting through irrigation) it may be possible to significantly lower the CO_2 source to the atmosphere from cutover peatlands. While this can be a costly endeavor, *Whitehead* [1999] has demonstrated that Sphagnum regeneration on cutover peat surfaces increases VMC. Consequently, R_{TOT} could be lowered naturally once regeneration occurs. However, active restoration through *Sphagnum* reintroduction is needed for *Sphagnum* to grow on these surfaces [*Quinty and Rochefort*, 1997]. Nevertheless, given the high spatial variability in R_{TOT} and high temporal variability in VMC, continuous CO_2 flux measurements using micrometeorological techniques will be essential in developing water (and therefore carbon) management models.

4.3. Global Implications

[27] Seasonal R_{TOT} values in this study were much higher than values reported in other CO_2 source peatlands [*Silvola*, 1986; *Silvola et al.*, 1996; *Waddington and Roulet*, 1996; *Bellisario et al.*, 1998] but are comparable to cutover peatlands in Europe [e.g., *Sundh et al.*, 2000; *Tuittila et al.*, 1999]. The total CO_2 emissions from these cutover sites were $\sim$3 times greater than that of the natural site [*Warner*, 1999]. This was due to a combination of increased R_{TOT} and the reduction of the gross ecosystem production to zero [*Waddington and Warner*, 2001]. Interestingly, any loss of CO_2 through plant and root respiration, which would have been removed by cutover operations, was offset by the large increase in soil respiration.

[28] Currently, peatland drainage in Canada does not contribute to a significant loss of peatlands. *Rebec and Thibault* [1998] estimate Canadian peatlands cover 13.9 $\times$ 10^7 ha, with only 16,000 ha being used for the horticultural peat industry. Consequently, only 0.01% of the total peatland area is currently being drained in Canada for horticultural peat [*Rebec and Thibault*, 1998]. Using current estimate of carbon storage in peatlands of $\sim$20 g C m^{-2} yr^{-1} [e.g., *Gorham*, 1991; *Clymo et al.*, 1998; *Vitt et al.*, 2000], this equates to a net sink of 3200 $\times$ 10^7 kg C yr^{-1} for Canada. Assuming a conservative annual oxidation rate of 4000 kg C ha^{-1} (emissions from the old site over 4 months) from cutover peatlands, there would be a net release of 6.4 $\times$ 10^7 kg C yr^{-1} to the atmosphere (and this does not include the CO_2 released from the cutover peat itself). This would result in a loss of carbon to storage ratio of only 0.2%. Therefore, under current natural to drained/cutover peatland area ratios, drainage and harvesting operations do not result in a significant loss in the net carbon sink in Canada. However, using these same figures, only 5% of peatlands in Canada (or a specific region) need to be drained/harvested to exceed the annual peatland carbon sink of the country (or a specific region). For example, assuming 5% of peatlands in Canada were drained and harvested, the total natural peatland area would be 13.2 $\times$ 10^7 ha, representing a carbon storage rate of 3000 $\times$ 10^7 kg C. Carbon loss from the drained peatland area (765 $\times$ 10^7 ha) using the oxidation rate of peat (4000 kg C ha yr^{-1}) would equal 3100 $\times$ 10^7 kg C. Consequently, the net sink function in Canada would be lost and converted to a net source of CO_2 to the atmosphere if drained/cutover peatlands exceeded 5% of the total peatland area. The net carbon sink in Canadian peatlands is not presently in danger of becoming a net carbon source due to peatland drainage and harvesting activities. However, assuming that these CO_2 evolution rates are representative globally, the global carbon sink is nearing the threshold of being changed from a net carbon sink to a net carbon source. Some regions of Canada (e.g., eastern Québec and New Brunswick) where drainage of peatlands for horticulture is prevalent may already exceed this threshold. Moreover, drainage of peatlands in some countries in Europe already exceeds 5% of the total peatland area [*Gorham*, 1991]. For example, estimates by *Gorham* [1991] suggest that the Fennoscandia region exceeds this 5% drained:natural peatland threshold, with 31.4% of peatlands drained and that other regions are approaching this threshold, such as Russia at 2.6%, United States at 1.1%, and global average at 3.3%. However, many of these peatlands were drained for forestry, which results in an increase in atmospheric CO_2 sequestration [*Laiho and Laine*, 1997]. Considering that the drainage of peatlands for fuel combustion and the horticultural peat industry has increased the annual carbon release sevenfold since 1940 [*Armentano and Menges*, 1986], it is expected that the global loss ratio will only increase in the future. Consequently, land use impacts (in particular drainage and harvesting) will play a greater role in the global carbon budget unless efforts are made to restore these impacted ecosystems or shift their use to forestry [e.g., *Laiho and Laine*, 1997]. However, because methane (CH_4) has a higher radiative forcing potential than CO_2, changes in CH_4 fluxes cannot be overlooked in peatland land use impacts [e.g., *Sundh et al.*, 2000]. *Waddington and Price* [2000] found CH_4 flux at the study cutover peatland decreased to 12–50% of the adjacent natural site value following peatland drainage and during drier conditions. However, CO_2-equivalent emissions were 235–255% greater at the cutover sites than the adjacent natural site [*Waddington and Price*, 2000]. This is especially important in light of the implications of the recent Kyoto Protocol [*United Nations*, 1997].

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G. W. Kennedy, J. M. Waddington, and K. D. Warner, School of Geography and Geology, Hydrological Sciences Group, McMaster University, 1280 Main Street West, Hamilton, Ontario, Canada L8S 4K1. (wadding@mcmaster.ca)