



# Mulch decomposition impedes recovery of net carbon sink function in a restored peatland

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Received 9 October 2002; received in revised form 30 March 2003; accepted 5 April 2003

## Abstract

With the increase in the drainage and extraction of peat for horticultural, agricultural and energy purposes worldwide, there is an increased pressure to restore hydrological conditions essential to the re-establishment of *Sphagnum* mosses and, therefore, carbon sequestration. Measurements of ecosystem CO<sub>2</sub> were conducted at a recently restored vacuum harvested bog in Eastern Québec, Canada. The peatland was restored by blocking the drainage networks to return optimal water table positions for the growth of *Sphagnum* mosses and the spreading of a dense straw mulch layer to reduce evaporative losses and stabilize the surface for the moss re-growth. However, the return of the moss species is a gradual process and previous studies have suggested that initially the carbon loss from the system actually increase as the mulch decomposes. We examined old and new mulch CO<sub>2</sub> production in lab incubations and scaled these results to the ecosystem level in order to determine if mulch decomposition is impeding the net carbon sink function of this peatland. At mean growing season temperatures fresh mulch was observed to release 151.5 μmol CO<sub>2</sub> g<sup>-1</sup> per day, while older mulch released 145 μmol CO<sub>2</sub> g<sup>-1</sup> per day. Furthermore, under moist conditions the CO<sub>2</sub> release increased for all mulches. However, contrary to most assumptions, Q<sub>10</sub> values for all mulches decreased with increasing temperatures and were greater for older mulch than for fresh. Thus, in the short term, the application of a surface straw mulch layer can have significant effects on the carbon balance of a restored peatland. Due to the decomposition of this mulch layer over the first several seasons of restoration, the peatland became a larger source of CO<sub>2</sub>, despite the increase in production of a re-emerging vegetation layer.

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**Keywords:** Peatland; Restoration; Mulch; Decomposition; Carbon dioxide; Carbon storage

## 1. Introduction

Over the past century many peatlands have been drained and extracted for horticultural, energy or agricultural purposes (Armentano and Menges, 1986). Peat extraction results in the removal of the surface vegetation, including *Sphagnum* mosses,

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and ~75–100 cm of peat. After approximately 20–50 years of peat extraction the site is abandoned and the bare cutover peat surface is often left to regenerate on its own devices. These cutover peatlands rarely return to functional peatland ecosystems after abandonment, in part because the viable seed bank has been removed (Rocheffort et al., 1995; Lavoie and Rocheffort, 1996; Ferland and Rocheffort, 1997), but more importantly, the necessary physical and hydrological conditions for *Sphagnum* moss re-establishment and carbon sequestration have been eliminated (Ferland and Rocheffort, 1997; Price, 1997; Van Seters and Price, 2001). Cutover peatlands are not only drier compared with natural peatlands due to the construction of drainage ditches, but there is an additional loss of soil moisture due to enhanced evapotranspiration (Price et al., 1998; Van Seters and Price, 2001). As a result, cutover peatlands become a persistent source of atmospheric CO<sub>2</sub>, due to increases in peat oxidation and decomposition (Petroni et al., 2001; Silvola et al., 1996; Waddington et al., 2002). However, peatland restoration has recently been shown to enhance carbon sequestration on abandoned cutover peatlands (Waddington and Warner, 2001), with the potential to return impacted peatlands to net carbon sinks (e.g. Tuittila et al., 1999).

In order to promote the re-colonization of *Sphagnum* moss, which obtain their water by capillary action (Price, 1997), the hydrology of the peatland must be restored (Quinty and Rocheffort, 1997). This is carried out by blocking the drainage ditches to raise the water table and rewet the surface (Quinty and Rocheffort, 1997; Rocheffort, 2000) and by the creation of dykes and open water ponds (Quinty and Rocheffort, 1997) to hold back spring melt water. Some other interventions to promote *Sphagnum* moss establishment on bare peat surfaces include the active re-introduction of moss diaspores and the application of a protective straw mulch cover to reduce evaporation (Quinty and Rocheffort, 1997; Price et al., 1998; Rocheffort, 2000). This approach has become standard practice in the restoration of Canadian peatlands. A straw mulch cover improves humidity conditions above the soil, moderates the temperature of the peat surface, reduces water tension in the surface

layer, increases soil moisture and promotes a higher water table elevation (Price et al., 1998). Price (1997) determined that applying straw mulch to the surface of bare peat increased the surface soil moisture by 10–15% compared with unmulched sites. Similarly, Price et al. (1998) and Petrone et al. (2001) estimated that the evaporation from mulched covered sites was ~80% of that of the bare peat rate, resulting in a reduction in soil water tension and an increase in water table levels favorable to the establishment of *Sphagnum* moss on abandoned cutover peatlands (Price et al., 1998).

While straw mulch can be removed by wind and/or water erosion, Brady and Weil (1999) noted that when straw mulch is applied to soil surfaces, the fresh decomposable tissue experiences an almost immediate response in microbial decomposition. The decomposition rate of these plant residues is initially rapid and then tends to stabilize (Updegraff et al., 1998; Parshotam et al., 2000) as microbes utilize the more labile carbon pools quickly, leaving the more recalcitrant compounds to decompose more slowly (Wessén and Berg, 1986; Cogle et al., 1989). Moreover, the rate of straw decomposition has been shown to decrease with reductions in pore water (Summerell and Burgress, 1989) and soil moisture content (Leiros et al., 1999), and increase with increasing peat temperature (Summerell and Burgress, 1989).

The decomposition of the mulch cover in restored peatlands has major restoration implications. Not only is the presence of a mulch cover fundamental for plant surface stabilization (Rocheffort, 2000) but the decomposition of the mulch may lead to an enhancement of the persistent CO<sub>2</sub> loss to the atmosphere that is common to cutover peatlands. For example, respiration values from a restored peatland in Eastern Québec approximately doubled in the first year post-restoration, despite active restoration measures, such as rewetting (Petrone et al., 2001). Petrone et al. (2001), suggest that this increase in CO<sub>2</sub> flux post-restoration may be attributed to the decomposing mulch on the peat surface. These claims are substantiated by annual surveys of straw mass remaining on restored cutover bogs in Central Québec (Waddington et al., 2003).

Despite the importance of the mulch cover in peatland restoration, there have been no studies that have systematically investigated the rates and controls on mulch decomposition and no attempts have been made to estimate how much this mulch decomposition contributes to total peatland respiration. Consequently, the objectives of this paper are to: (1) determine the rate of straw mulch decomposition under varying thermal and moisture conditions in a restored peatland, (2) compare decomposition rates of weathered straw that had been decomposing on the surface of the peatland with that of a relatively new straw that was applied to the surface of the bare peat only a few months prior to analysis, and (3) estimate the contribution of straw mulch decomposition to the overall ecosystem scale exchange of carbon dioxide (CO<sub>2</sub>).

## 2. Materials and methods

### 2.1. Study area

This study was conducted at the Bois-des-Bel peatland located in the Bas-Saint-Laurent region of Québec, ~10 km east of Rivière-du-Loup (42°58' N, 69°25' W). The mean annual temperature for the region is 3 °C, with mean January and July temperatures of –12 and 18 °C, respectively. The mean annual precipitation is 926 mm with 27% falling as snow (Environment Canada, 1993).

The Bois-des-Bel peatland is a ~200 ha treed bog of which an 11.5 ha section of the peatland was cutover using the vacuum extraction method from 1973 to 1980 (Fig. 1). This 11.5 ha area was divided into 11 fields (30 m × 300 m), and separated by drainage ditches running parallel to the fields. These ditches drained water to the south end of the peatland into the main drainage ditch. In the autumn of 1999, the eight westernmost fields (fields 1–8) were restored by blocking drainage ditches and constructing bunds that divided the restored section into four zones (1–4), tilling the surface, spreading *Sphagnum* diaspores onto the surface and applying ~3000 kg ha<sup>-1</sup> of straw mulch (Petroni et al., 2001). Field 9 was designated as a buffer zone, while the two easternmost fields, (fields 10 and 11) were left as

controls. In the restored section, zones 2, 3 and 4 were fully treated in the autumn of 1999, while in zone 1 the application of diaspores and mulch was delayed until the autumn of 2000. Consequently, this zone has different characteristics with regards to hydrology, vegetation cover, and the amount and 'age' of straw mulch cover.

### 2.2. Laboratory analysis (CO<sub>2</sub> production rates)

Straw mulch samples for laboratory analysis were randomly removed from zone 2 (hereafter referred to as 'old' straw) and zone 1 (hereafter referred to as 'new' straw). These samples were placed in airtight containers and transported to McMaster University, where samples were frozen until laboratory analysis.

In the lab, both old and new straw mulch, were cut into 3-cm long segments with scissors. The entire straw segment was used including the leaf, node and internodes; to guarantee that different portions of the straw mulch were tested. 25 pieces of straw mulch (~0.3–0.5 g) were then placed in 250 ml incubation jars lids containing a rubber septa. The incubation jars were then placed in a dark Conviron growth chamber for 48 h prior to sampling. Gas samples were extracted initially and every 24 h, thereafter, for a total incubation of 96 h.

Gas samples were injected into a Varian 3800 gas chromatograph (GC), equipped with a thermal conductivity detector (TCD) and Porapak Q packed column, to determine CO<sub>2</sub> concentration. CO<sub>2</sub> concentrations were corrected for changes in standard pressure, temperature and headspace volume and CO<sub>2</sub> production rates were determined using the slope of the gas concentration versus incubation time and expressed as a per final straw dry weight (μmol CO<sub>2</sub> g<sup>-1</sup> per day).

This method for determining CO<sub>2</sub> production rates was used in a 2 × 3 × 3 factorial experiment with two ages of straw (new and old), three different incubation temperatures (4, 12 and 20 °C), and three moisture conditions (dry, moist and wet). There were five replicates of each straw type, at each moisture condition and at each incubation temperature, giving a total of 90 samples. The varying moisture conditions were

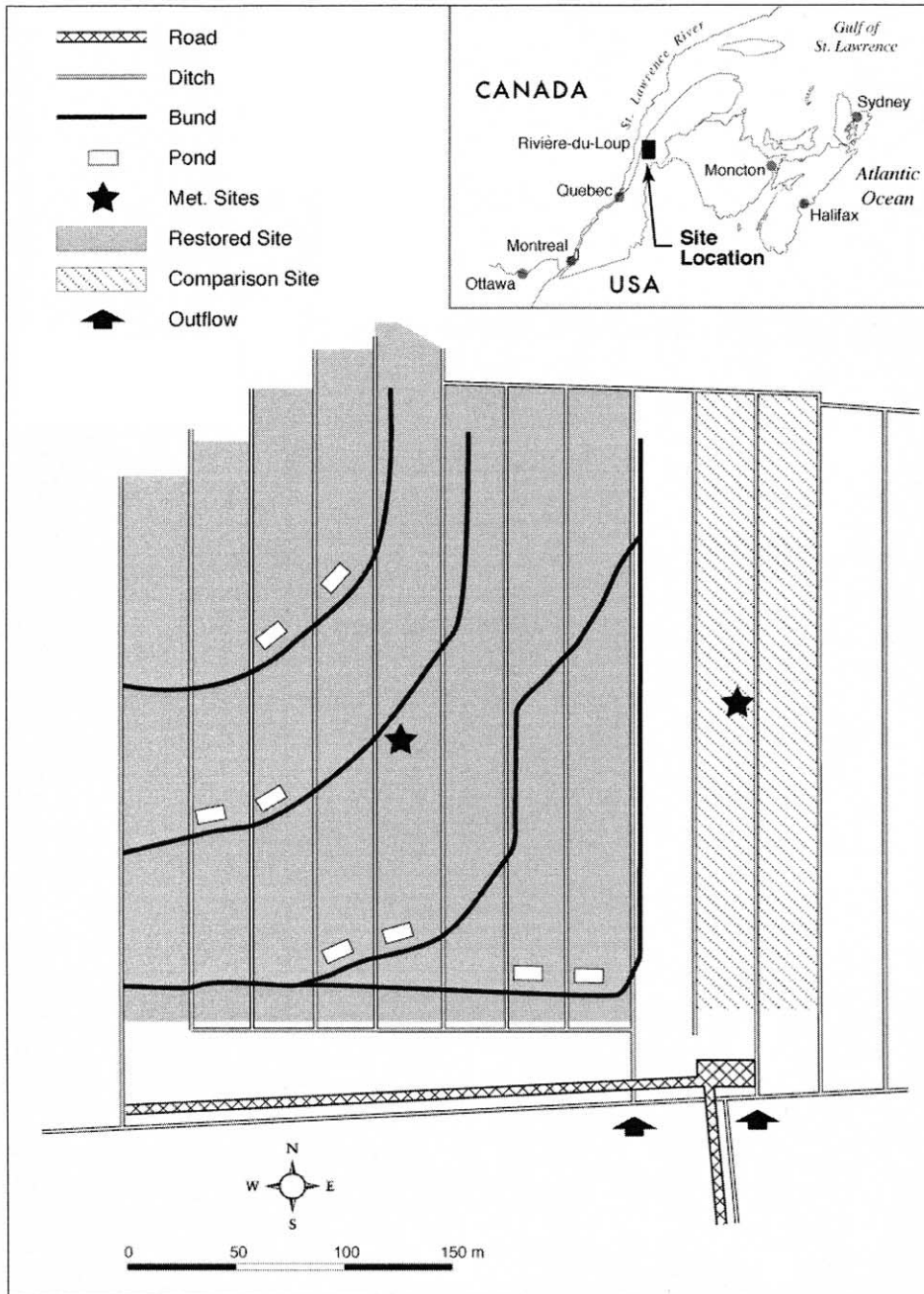


Fig. 1. Bois-des-Bel peatland, Québec, Canada, illustrating the restored and cutover (comparison) and the location of the meteorological tower sites.

‘dry’, (3.2 ml of deionized water sprayed on the mulch and left to dry for 24 h prior to sampling), ‘moist’, (3.2 ml of deionized water sprayed on the

mulch and sealed immediately), and ‘wet’, (30 ml of deionized water added to the mulch in the incubation jar and sealed immediately).  $Q_{10}$  values

were calculated for the rate of change between the 4 and 12 °C and between the 12 and 20 °C temperature incubations.

In order to examine the strength of the relationship between the multiple independent variables (age, moisture and temperature) and the rate of CO<sub>2</sub> produced by the decomposing straw mulch, multiple regression was used. To determine which variable explained the majority of the variance displayed by CO<sub>2</sub> emission rates, the adjusted R<sup>2</sup> value was used since it adjusts for the number of independent variables in relation to the sample size to prevent overestimating the amount of variability explained by the independent variables (Newbold, personnel communication, 2001).

### 2.3. Field measurements

Field data was collected from 5 May to 13 October 2001 at a micrometeorological tower that was located in zone 3 within the Bois-des-Bel peatland (Fig. 1). Net ecosystem CO<sub>2</sub> exchange (NEE) and evapotranspiration fluxes were measured at 1.5 m above the peat surface using the Eddy covariance technique. Measurements were made using a CSAT-3, 3-D sonic anemometer and an open path infrared gas analyzer (IRGA) (LI7500, LI-COR Inc., Lincoln, NE) (Petroni et al., 2001). The height of 1.5 m above the peat surface was chosen to obtain a representative flux of the entire restored peatland, due to its small fetch area (Petroni et al., 2001). Detailed analysis by Petroni et al. (2001) demonstrates that 80% of the measured flux originated from within 77 m of the tower, and the maximum flux was from within 17 m from the tower. Other continuous tower measurements included air temperature, peat temperature (°C) at 2, 5, 10 and 25-cm depths, mulch temperature (°C) and volumetric moisture content (%). Temperatures within the mulch layer were measured continuously within varying age and density of mulch cover located in the proximity of the micrometeorological tower. A detailed description of how NEE was portioned into photosynthesis and total respiration (R<sub>TOT</sub>) is presented in Petroni et al. (2001).

The percent cover of the amount of straw mulch remaining on the surface of the peatland was

surveyed at the end of the study period using the 5 × 12 m Bois-des-Bel grid system and entering this data into the Bois-des-Bel Geographic Information System (Arc View). Each grid was assigned a value between 0 and 4: 0 represented no straw mulch, while 1, 2, 3 and 4 represented 0–15, 15–75, 75–100 and 100% straw coverage, respectively. The average percent straw mulch cover per zone was then determined for each zone using the GIS.

Straw mass (g C) was then measured in five randomly located quadrats for each of new straw (zone 1) and old straw (zones 2, 3, and 4). This data was combined with the weighted percent cover results in the GIS to determine the mean mass of straw in each zone (~630 g m<sup>-2</sup> in zone 1 and ~160 g m<sup>-2</sup> in zones 2, 3 and 4).

To estimate the contribution of straw mulch decomposition to the overall ecosystem level exchange of CO<sub>2</sub>, laboratory results of mulch CO<sub>2</sub> production were scaled to the ecosystem level using the measurements of the mass of old and new straw within Bois-des-Bel, the continuously recorded mulch temperatures, and the laboratory CO<sub>2</sub> production rates. Empirical equations of the CO<sub>2</sub> production rate (g CO<sub>2</sub> m<sup>-2</sup> per day) per gram of dry weight straw were determined from the lab experiment and modeled using continuous mulch temperatures measured near the micro meteorological tower (Table 1).

Table 1  
Ecosystem scaled empirical equations of CO<sub>2</sub> production rates (R) as a function of mulch temperature (T)

Straw type	Moisture regime	Equation	Adjusted R <sup>2</sup>
New	Dry	R = 0.143T - 0.435	0.903
	Moist	R = 0.223T - 0.318	0.988
	Wet	R = 0.182T - 0.630	0.886
Old	Dry	R = 0.008T + 0.065	0.508
	Moist	R = 0.058T - 0.251	0.903
	Wet	R = 0.027T - 0.110	0.903

CO<sub>2</sub> production rate units are (g CO<sub>2</sub> m<sup>-2</sup> per day g<sup>-1</sup> dry weight straw).

### 3. Results

#### 3.1. Laboratory mulch CO<sub>2</sub> production

Fig. 2 summarizes the results of CO<sub>2</sub> production in the 2 × 3 × 3 factorial experiment. Moist, new straw at an incubation temperature of 20 °C had the greatest CO<sub>2</sub> production (151.5 ± 19.9 μmol CO<sub>2</sub> g<sup>-1</sup> per day), while the lowest CO<sub>2</sub> production occurred for wet, old straw at an incubation temperature of 4 °C (6.8 ± 1.5 μmol CO<sub>2</sub> g<sup>-1</sup> per day). In general, CO<sub>2</sub> production tended to increase for both old and new straw at all observed moisture conditions with increasing temperature (Fig. 2a and b). On average, CO<sub>2</sub> production rates at an incubation temperature of 20 °C were 2.4-times greater than rates at 12 °C and 7.5-times greater on average than the rates at 4 °C. How-

ever, similar trends are more difficult to distinguish for the varying moisture regimes. Moist conditions tended to display the greatest CO<sub>2</sub> production rates for both new and old straw under the various incubation temperatures. For example, at 12 °C the CO<sub>2</sub> produced from new, moist straw was 75.8 ± 9.9 μmol CO<sub>2</sub> g<sup>-1</sup> per day and was 151.5 ± 19.9 μmol CO<sub>2</sub> g<sup>-1</sup> per day at 20 °C (Fig. 2a and b). In contrast the old, moist straw at 12 °C had a CO<sub>2</sub> production rate of 39.3 ± 21.1 μmol CO<sub>2</sub> g<sup>-1</sup> per day and increased to 144.5 ± 60.0 μmol CO<sub>2</sub> g<sup>-1</sup> per day at 20 °C (Table 1). However, the dry and wet conditions showed no obvious trends. The average CO<sub>2</sub> production rate of the moist mulch samples was 2.5- and 1.7-times greater than the rates for dry and wet straw samples, respectively. Half of the observed values of CO<sub>2</sub> production were greatest under wet

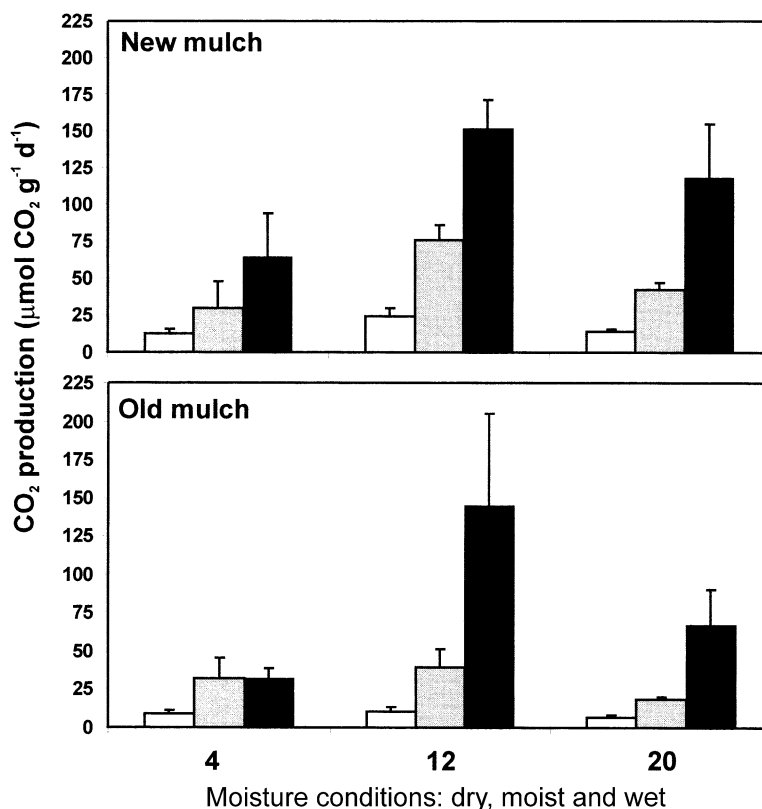


Fig. 2. CO<sub>2</sub> production laboratory incubation experiments using new and old mulch for three different incubation conditions (dry, moist and wet), where white, grey and black bars represent 4, 12 and 20 °C temperatures.



moisture conditions; the other half of the observations displayed the greatest CO<sub>2</sub> production under the dry moisture regime.

Under all moisture regimes and incubation temperatures, new straw had greater CO<sub>2</sub> production and thus straw mulch decomposition, compared with old straw mulch (Fig. 2a and b). For example, at 4 °C, old, dry straw had a CO<sub>2</sub> production rate of 8.7 ± 2.2 μmol CO<sub>2</sub> g<sup>-1</sup> per day whereas new, dry straw was 12.6 ± 3.4 μmol CO<sub>2</sub> g<sup>-1</sup> per day also at 4 °C. On average the rate of straw mulch respiration from the new mulch samples was 1.5-times greater than the rates from old straw samples.

The greatest Q<sub>10</sub> value was 4.8 from moist old straw with a change in temperature from 4 to 12 °C (Table 2). And the lowest Q<sub>10</sub> value observed in this laboratory study was 1.3, from dry, old straw and at a change from 12 to 20 °C. In most cases the Q<sub>10</sub> values tended to decrease as temperature increased from the 4–12 °C range to the 12–20 °C range, which is generally not expected. For example, the Q<sub>10</sub> value of old, dry straw at 4–12 °C was 4.6, where as at 12–20 °C the Q<sub>10</sub> was 1.3. In addition, overall old Q<sub>10</sub> values were also greater than the Q<sub>10</sub> values observed for new straw under the same moisture and incubation temperatures, which is also not expected. In this case, the old, dry straw from 4 to 12 °C was 4.6, and new, dry straw at 4 to 12 °C was only 3.0. It is generally assumed that as temperature increase and as age of straw decreases the Q<sub>10</sub> values would also tend to increase as well.

Results of the multiple regression model indicate that both the age/moisture/temperature and the age/temperature trials explained the majority of the variation in CO<sub>2</sub> productions (R<sup>2</sup> = 0.59)

Table 2  
Q<sub>10</sub> values from laboratory experiments

Straw age	Moisture regime	Q <sub>10</sub> (4–12 °C)	Q <sub>10</sub> (12–20 °C)
New	Dry	3.0	3.9
	Moist	3.9	2.5
	Wet	3.7	3.5
Old	Dry	4.6	1.3
	Moist	4.8	4.6
	Wet	3.4	4.5

suggesting that moisture does not explain a lot of the variance observed in CO<sub>2</sub> production from mulch decomposition. This can be supported by the fact that the model that only uses moisture as the independent variable had an r<sup>2</sup> value of < 0.01 (Table 3). Moreover, all trials that contained moisture as an independent variable all displayed *P*-values > 0.05 (Table 4) indicating that moisture was not significant to the model. In the multiple regression model that contained all three independent variables (age, moisture and temperature), *P*-values obtained were < 0.01 for the age variable, 0.32 for moisture and < 0.01 for temperature. In general, *P*-values for trials using temperature were generally the smallest values, and were much lower than 0.05. This suggests that temperature was the most statistically significant independent variable in all models and had the greatest influence in describing the variation of CO<sub>2</sub> production and hence straw mulch decomposition. The statistical significance of straw age as an independent variable in controlling the variation in straw mulch decomposition falls between that of moisture and temperature. The *P*-values observed for all models are all less than 0.05, making age statistically significant in all models. However, it is not as statistically significant as temperature, when their *P*-values are compared.

### 3.2. Field measurements

Air temperature and inside mulch temperature, used to model ecosystem scale mulch CO<sub>2</sub> flux, between 5 May and 13 October 2001, are shown in Fig. 3. Air temperature progressively increased

Table 3  
A summary of the R<sup>2</sup> values obtained for each combination of independent variables

Independent variables	Adjusted R <sup>2</sup>	Standard error
Age, moisture, temperature	0.59	32.01
Age, moisture	0.04	49.14
Age, temperature	0.59	32.01
Moisture, temperature	0.55	33.75
Age	0.04	49.08
Moisture	0.00	50.12
Temperature	0.55	33.72

Table 4

A summary of the statistical significance of the independent variables from all trials

Multiple regression trials	Independent variables	<i>t</i> -statistic	<i>P</i> -value
Age, moisture, temperature	Age	3.22	0.00
	Moisture	1.00	0.32
	Temperature	10.72	0.00
Age, moisture	Age	2.10	0.04
	Moisture	0.89	0.37
Age, temperature	Age	10.76	0.00
	Temperature	3.21	0.00
Moisture, temperature	Moisture	0.90	0.37
	Temperature	10.17	0.00
Age	Age	2.09	0.04
Moisture	Moisture	0.85	0.40
Temperature	Temperature	10.22	0.00

from early May to a maximum daily average air temperature (29.9 °C) on 12 July. However, shortly after on 16 July the daily average air temperature decreased to 11.2 °C. The air temperature decline continued with some variability until 13 October with the lowest daily average temperature (3.6 °C) recorded on 8 October. Daily average mulch temperatures for the top, inside and bottom of the mulch were 15.6, 15.9 and 15.1 °C, respectively. The maximum daily average inside mulch temperature (25.3 °C) was recorded on 9 August. The lowest observed daily average inside mulch temperature was 3.3 °C on 8 October. Daily average mulch temperatures also follow the same pattern as the daily average air temperature, but with less variation which can be attributed to the ability of mulch to moderate fluctuations in temperature (Price et al., 1998).

### 3.3. Ecosystem scale CO<sub>2</sub> fluxes

Ecosystem scale total respiration ( $R_{TOT}$ ) and the range in ecosystem scale old and new mulch CO<sub>2</sub> flux are shown in Fig. 4. Average growing season  $R_{TOT}$  was 13.7 g CO<sub>2</sub> m<sup>-2</sup> per day, with new mulch respiration being higher than old mulch CO<sub>2</sub> flux. The range in average new mulch CO<sub>2</sub> flux was 1.8–3.2 g CO<sub>2</sub> m<sup>-2</sup> per day, while old mulch CO<sub>2</sub> flux ranged from 0.2 to 0.7 g CO<sub>2</sub> m<sup>-2</sup> per day. On average, the ecosystem scaled respiration rates were 6.2-times greater for the new than old mulch areas. Because the ecosystem scale

mulch CO<sub>2</sub> emissions were modeled with the field inside-mulch temperature values, the maximum respiration values from each age/moisture combination were all observed on 9 August, which had the largest recorded value of inside mulch temperature (25.3 °C). 8 October displayed the minimum ecosystem scaled respiration values, as this was the lowest recorded inside mulch temperature (3.3 °C).

The total seasonal flux was 465 g C m<sup>-2</sup>, while the range in CO<sub>2</sub> flux from the new mulch sites ranged from 80 to 140 g C m<sup>-2</sup>. The total seasonal CO<sub>2</sub> flux from the old mulch sites ranged from 8 to 30 g C m<sup>-2</sup>. We estimate, therefore, that new mulch decomposition accounted for between 17 and 30% of  $R_{TOT}$ , while the old mulch decomposition fraction ranged from 2 to 6% of  $R_{TOT}$ .

## 4. Discussion

### 4.1. Controls on straw mulch decomposition

Under all moisture regimes and incubation temperatures, new straw displayed greater CO<sub>2</sub> production compared with old straw mulch samples. The laboratory rate of new straw mulch decomposition was 1.5-times greater than that of old straw mulch. The ecosystem scale mulch CO<sub>2</sub> flux for new straw mulch was 6.2-times greater than the CO<sub>2</sub> flux from old mulch sites, since the mass of decomposing new mulch is greater than



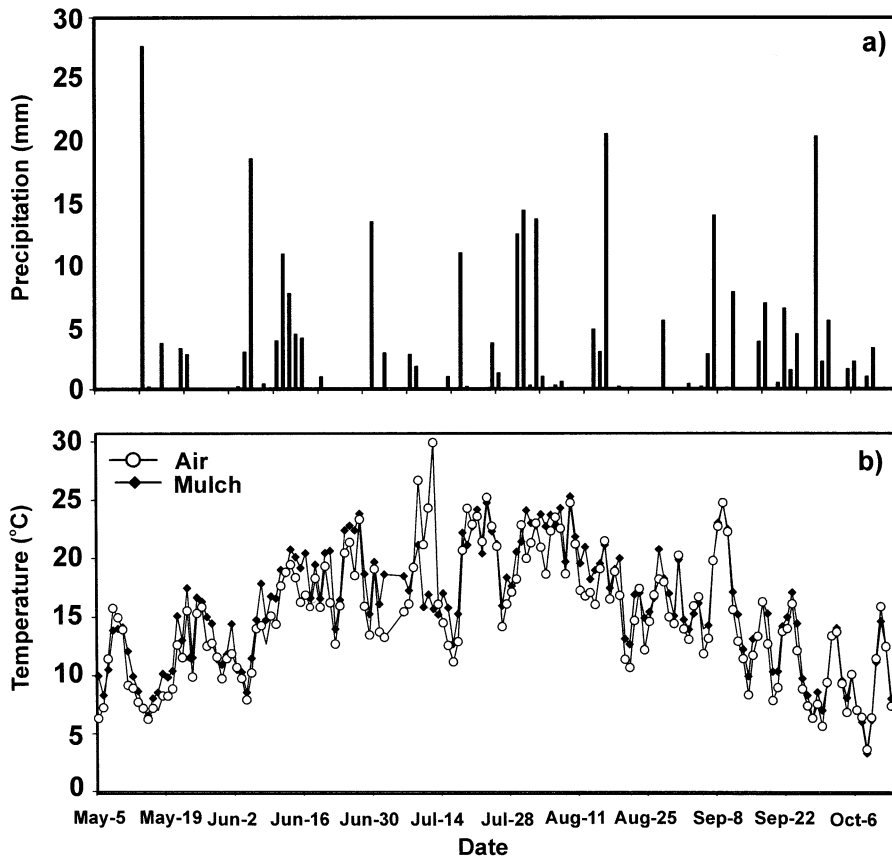


Fig. 3. (a) Precipitation and (b) air temperature and within-mulch temperatures ( $^{\circ}\text{C}$ ) at the meteorological site.

that of old mulch. Maximum new straw mulch  $\text{CO}_2$  flux was  $140 \text{ g CO}_2 \text{ m}^{-2}$  while maximum old mulch  $\text{CO}_2$  flux was  $30 \text{ g CO}_2 \text{ m}^{-2}$ . From multiple regression analysis of all three independent variables used in the laboratory experiments, it was determined that age was a statistically significant variable in determining the rate of  $\text{CO}_2$  production in straw mulch decomposition. These claims are all supported by previous research that states that the amount of labile organic matter plays a pivotal role in the rate of organic matter decomposition. According to Bridgham and Richardson (1992) and Waddington et al. (2001), low labile carbon pools limit soil oxidation. From this study it is evident that the newly mulched sites still contain

some labile carbon pools that microbes target and are thus decomposed at a much faster rate compared with more recalcitrant residues. When straw mulch is first applied to soil surfaces it provides “temporal hot spots” for microbial activity (Gaillard et al., 1990), and therefore, initial decomposition rates tend to be rapid and once labile materials are consumed, decomposition rates tend to decline (Updegraff et al., 1998).

Lignin is a recalcitrant compound found in most plant residues, such as straw mulch. It tends to restrict many easily decomposable polysaccharides (Bowen and Harper, 1990) and thus has much slower rates of decay compared with their labile counterparts (Bridgham et al., 1998). Since the old

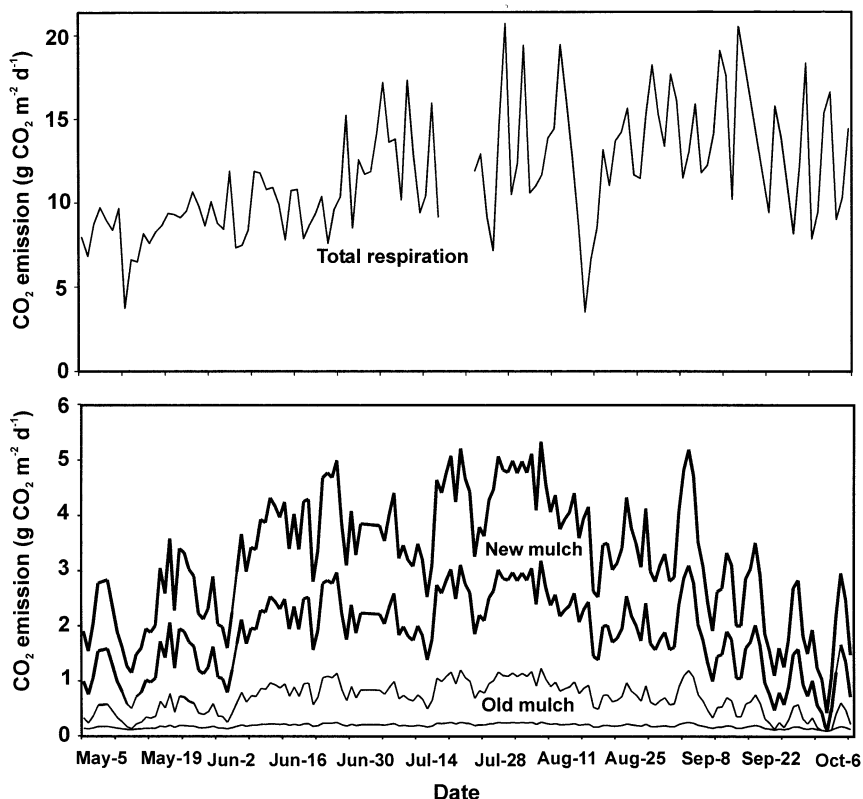


Fig. 4. (a) Ecosystem-scale total respiration ( $R_{TOT}$ ) and (b) the range in ecosystem-scale new and old mulch  $CO_2$  flux.

straw used in this study had been decomposing for an entire year on the surface of the peatland before it was used for analysis, much of this mulch should be comprised of more recalcitrant sources of carbon.

Temperature was used as a control on the rate of straw mulch decomposition in both the laboratory experiment and ecosystem scale flux modeling. Moreover, in both cases temperature proved to be the strongest variable in determining the rate of straw mulch decomposition over all moisture conditions and straw ages. For both old and new straw at all moisture conditions in laboratory analysis, the rate of  $CO_2$  flux increased with increasing temperature. On average the rates of respiration from mulch samples incubated at 20 °C were 2.4-times greater than the rates of respiration

observed at 12 °C, and were 7.5-times greater than the rates observed at 4 °C. The calculated  $Q_{10}$  values from this study ranged from 1.3 to 4.8. However,  $Q_{10}$  values showed an unexpected decline as the temperature range increased from 4–12 to 12–20 °C. In addition, multiple regression analysis from laboratory independent variables further support the dependence of straw mulch decomposition on temperature. Temperature was determined to be the most statistically significant variable compared with both age and moisture. Many previous studies show that temperature is a stronger correlate compared with moisture in determining  $CO_2$  flux (Bridgham and Richardson, 1992; Moore and Dalva, 1993; Zak et al., 1999). However, other studies suggest that both temperature and moisture play an important role. Accord-

ing to Douglas and Rickman (1992), microbial activity is greatest during moist, warm spring and fall seasons. In contrast, typical low temperatures in winter and dry soils in the summer tend to limit microbial decomposition of surficial plant residues. Warmer soils provide ideal conditions for decomposers, which in turn enhance rates of CO<sub>2</sub> production (McKenzie et al., 1998; Waddington et al., 2001).

The rate of CO<sub>2</sub> production from moist mulch samples was observed to be 2.5-times greater than dry mulch samples and 1.7-times larger than wet straw samples. The greater rates of respiration from moist straw mulch is also evident from ecosystem scale mulch CO<sub>2</sub> fluxes. Fig. 4b shows that moist CO<sub>2</sub> production rates were ~2-times greater than dry sites and 1.5-times greater than wet sites. However, based on multiple regression of the independent variables studied in laboratory experiments, moisture was shown not to be statistically significant in determining CO<sub>2</sub> flux. Higher soil moisture content limits the available pore spaces for O<sub>2</sub> (Brady and Weil, 1999) thus reducing the rate of aerobic microbial activity. Anaerobic conditions tend to exhibit slow rates of decomposition, leading to organic matter accumulation (Clymo, 1984). This study demonstrates that both wet and dry conditions have lower rates of decomposition as compared with moist straw mulch, suggesting a possible threshold value of moisture content which is optimal for microbes during decomposition of surface residues, straw mulch in particular. That is, some moisture is necessary to the metabolism of the organic material, but too great an increase will lead to anaerobic conditions.

#### 4.2. Peatland restoration and carbon cycling implications

The application of straw mulch to assist in plant surface stabilization has been deemed to be a fundamental practice in peatland restoration (Quinty and Rochefort, 1997; Rochefort, 2000). According to Price et al. (1998), this straw mulch cover improves the humidity conditions above the soil, reduces water tension in the surface layer, and increases soil moisture and water table elevation.

In addition due to its high surface albedo, straw mulch also acts to moderate peat temperatures: for example, Duiker and Lal (2000) stated that noon-time soil temperature was up to 14 °C higher under unmulched soils compared with those with a surface mulch cover. All these benefits provided by straw mulch on the surface of restored peatlands, appears to make the application of straw mulch a positive step towards *Sphagnum* moss regeneration, and ultimately towards peatland restoration.

However, from a carbon balance perspective, the application of straw mulch provides the potential for increased organic matter decomposition resulting in increased CO<sub>2</sub> fluxes to the atmosphere (Waddington et al., 2003). Previous studies found ~80% of straw had decomposed after the first 3 years of a restored plot in a cutover peatlands. For example, assuming an initial mulch cover of 300 g m<sup>-2</sup>, only ~50 g m<sup>-2</sup> would remain after the first 3 years after application. Based on the mulch quadrat data, we estimate that ~75% of the straw mulch had decomposed in the present study in only 2 years time. Petrone et al. (2001) suggested that an approximate doubling in post-restoration respiration values from a restored peatland receiving active restoration measuring can be attributed to decomposing mulch on the peat surface. Results from this study indicate that mulch decomposition can account for up to 30% of R<sub>TOT</sub>. Hence, the potential for straw mulch to provide a positive flux of CO<sub>2</sub> is large, especially with new mulch under moist, warm conditions.

#### Acknowledgements

We wish to thank Sarah Day and Karola Toth for assistance in the field and lab. Comments and suggestions by the anonymous reviewers are greatly appreciated. This research was funded by an NSERC Industrial grant to J.M.W. and J.S.P. with the financial assistance of the Canadian *Sphagnum* Peat Moss Association and many of its member companies.

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