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Atmospheric CO_2 sequestration in restored mined peatlands[1]

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Abstract: This study comparing the net ecosystem CO_2 exchange in natural, restored, and naturally regenerated peatlands assesses the significance of peatland restoration as a global biotic offset under the Kyoto Protocol. Maximum gross photosynthesis (GP_{max}) at the restored peatland (-17.5 g CO_2 m^{-2} d^{-1}) was more than two times that at lawns in the natural peatland (-8.2 g CO_2 m^{-2} d^{-1}) and almost three times that of the naturally regenerated peatland (-6.5 g CO_2 m^{-2} d^{-1}). However, GP_{max} at hummock sites (-18.1 g CO_2 m^{-2} d^{-1}) in the natural peatland exceeded that of the restored peatland. Total rainfall during the study period was ~75% of the 30-year mean and these drier conditions resulted in all sites being a net source of atmospheric CO_2 during the summer. From May 5 to August 23, 1998 respiration followed the trend: mined (398 g C m^{-2}) > restored (169 g C m^{-2}) > natural (138 g C m^{-2}) peatland. While restoration did not return the net carbon sink function, it resulted in a significant decrease in the source of atmospheric CO_2 (229 g C m^{-2}) over the summer season. Approximately 70% of this decrease was due to the increase in gross ecosystem production, while the remaining 30% was due to a decrease in total respiration. The presence of *Sphagnum* mosses at the naturally regenerated peatland also resulted in a ~45% decrease in total respiration (soil and plants), indicating that an increase in volumetric soil moisture content during restoration has the potential to lower soil respiration at abandoned mined peatlands. Considering the area of drained and mined peatlands globally, peatland restoration on abandoned mined peatlands has the potential to represent an important biotic offset through enhanced carbon sequestration.

Keywords: peatland, restoration, carbon sequestration, hydrology, carbon dioxide, Kyoto Protocol.

Résumé : Cette étude compare les échanges nets de CO_2 dans les tourbières naturelles, restaurées et naturellement revégétées et évalue l'importance de la restauration des tourbières dans le contexte du Protocole de Kyoto. La photosynthèse brute maximale (GP_{max}) de la tourbière restaurée (-17.5 g CO_2 m^{-2} d^{-1}) était deux fois plus élevée que celle des tourbières naturelles (-8.2 g CO_2 m^{-2} d^{-1}) et presque trois fois plus élevée que celle de la tourbière revégétée naturellement (-6.5 g CO_2 m^{-2} d^{-1}). Cependant, GP_{max} dans les buttes des tourbières naturelles (-18.1 g CO_2 m^{-2} d^{-1}) était supérieure à celle de la tourbière restaurée. Pendant la période étudiée, les précipitations totales équivalaient à ~75 % des précipitations moyennes sur 30 ans. En raison de ces conditions plus sèches, tous les sites sont devenus une source nette de CO_2 atmosphérique pendant l'été. Du 5 mai au 23 août 1998, la respiration a suivi la tendance suivante : tourbière exploitée (398 g C m^{-2}) > restaurée (169 g C m^{-2}) > naturelle (138 g C m^{-2}). Quoique la restauration n'ait pas permis à l'écosystème de redevenir un puit net de carbone, celle-ci a tout de même résulté en une baisse significative du CO_2 atmosphérique émis au cours de l'été (229 g C m^{-2}). Approximativement 70 % de cette diminution est attribuable à l'augmentation de la production brute de l'écosystème, tandis que le 30 % restant est dû à la diminution de la respiration totale. La présence de sphaignes au site revégété naturellement a aussi entraîné une baisse de la respiration totale de ~45 % (sol et plantes), ce qui indique qu'une hausse du contenu en humidité volumétrique du sol pendant la restauration a le potentiel de réduire la respiration dans les sites abandonnés après exploitation. En considérant de façon globale la superficie des tourbières drainées et exploitées, la restauration des tourbières après exploitation représente potentiellement une compensation biotique importante par une plus grande séquestration du carbone.

Mots-clés : tourbière, restauration, séquestration de carbone, hydrologie, gaz carbonique, Protocole de Kyoto.

Introduction

The objective of the Kyoto Protocol (UNFCCC, 1997) is to stabilize greenhouse gas concentrations in the atmosphere through the reduction of fossil fuel emissions and through land-use management designed to increase biotic carbon sinks and/or reduce carbon sources. Peatlands represent an important component of the global carbon cycle, containing ~33% of the world's soil carbon (Gorham, 1991) despite covering only ~5% of the global land area (Matthews & Fung, 1987). Peatlands function as a persistent sink for atmospheric carbon dioxide (~23 g C m^{-2} yr^{-1}); however, direct and indirect land-use impacts can change the natural carbon sink strength of peatlands (Armentanao & Menges, 1986; Nykänen *et al.,* 1995). This has important implications for the Kyoto Protocol (Roulet, 2000). Peatland drainage and mining, for example, increase total respiration (R_{TOT}) and reduce gross ecosystem production (GEP) to zero as the water table is lowered and *Sphagnum* mosses and other vegetation are removed. This substantially changes the carbon balance of a peatland, increasing CO_2 emissions to the atmosphere by ~300% (Waddington *et al.*, 2001a). The natural net carbon sink function in these impacted peatlands is therefore reduced or eliminated.

Recent research indicates it is possible to partially restore *Sphagnum* peatlands (Rochefort, Gauthier & Lequere, 1995; Campeau & Rochefort, 1996; Quinty & Rochefort, 1997) indicating there is the potential to increase biotic carbon sinks and/or minimize the current persistent atmospheric CO_2 source from abandoned peatlands. However, the rate at which the carbon balance of restored

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peatlands will return to natural conditions is unknown. The goal of this study is therefore to compare the net ecosystem CO_2 exchange (NEE) between restored, naturally regenerated, and natural peatlands to determine if mined peatland restoration practices have restored the net carbon sink function common to natural peatlands.

Prior to restoration, during peatland abandonment, peat undergoes significant structural changes (Price & Schlotzhauer, 1999). Water is removed from the peat, resulting in subsidence, enhanced peat oxidation, and enhanced compression of the peat below the water table as the overburdening peat layer loses its buoyancy and the weight of the drained peat compresses the underlying peat (Schothorst, 1977; Mulqueen, 1986). Combining these factors results in an increase in bulk density and a decrease in specific yield, which leads to increases in the magnitude of water table fluctuations in response to wetting and drying events (Price, 1996). During dry conditions, the depth of the aerobic zone and the potential for increased oxidation can be substantial (Waddington *et al*., 2001a). To alleviate these conditions, peatland drainage ditches are often blocked after abandonment (Eggelsmann, 1988). Although blocked drainage ditches aid in rewetting the peatland, water tension in the surface layers of the peat can often exceed –100 mb (Price, 1997), the threshold where *Sphag-num* can no longer generate enough suction to hold water in their cells, causing desiccation of the plant (Hayward & Clymo, 1982). Therefore, if *Sphagnum* is to successfully regenerate (recolonize) on mined peatlands, suitable moisture and surface tensions must be established on these abandoned surfaces.

Most vegetation regeneration on abandoned mined peatlands includes plants typical of peatlands such as ericaceous shrubs (*Kalmia angustifolia*, *Ledum groenlandicum, Vaccinium angustifolium*), cotton grass (*Eriophorum vaginatum*), tamarack (*Larix laricina*) and black spruce (*Picea mariana*), with exotic tree species such as birch (*Betula papyrifera*, *B. populifolia*). Lavoie and Rochefort (1996) report *Sphagnum* has naturally regenerated on block-cut abandoned mined peatlands in eastern Canada; however, total coverage within these peatlands are low and *Sphagnum* regeneration is mainly limited to areas of low topography such as wet trenches. Rochefort and Campeau (1997) suggest that microtopography within these peatlands provide shelter and a viable seedbank for regeneration. In modern mined sites, however, the upper 40 to 60 cm of peat is cut and removed, leaving a flat, barren surface with no viable seedbanks (Salonen, 1987; Huopalainen *et al.,* 1998). Consequently, re-wetting the surface and plant re-introduction (restoration) is needed to re-establish *Sphagnum* mosses at these sites.

The goal of peatland restoration is to bring back a natural functioning self-sustaining peatland ecosystem with *Sphagnum* peat forming species (Heikkila & Lindholm, 1995). Several studies have investigated various methods for restoring *Sphagnum* mosses onto these harsh conditions by developing techniques to improve water tension near the surface. These techniques include open water reservoirs (LaRose, Price & Rochefort, 1997), surface profiling (Bugnon, Rochefort & Price, 1997), microtopography development (Price, Rochefort & Quinty, 1998), companion species (Ferland & Rochefort, 1997), and straw mulch application (Quinty & Rochefort, 1997). A combination of blocking ditches and broad trenches, coupled with the use of straw mulch, provide the highest water table and soil moisture conditions most favourable for restoration (Price, Rochefort & Campeau, 2000). *Sphagnum fuscum* and *S. capillifolium* diaspores are then placed on the surface below the straw mulch.

Based on previous productivity studies (Campeau & Rochefort, 1996), regrowth of the re-introduced *Sphag-num* due to the aforementioned rewetting techniques should increase the rate of atmospheric CO_2 fixation in restored peatlands. Total respiration, however, may also increase due to an increase in labile organic material. Komulainen *et al.* (1999) determined that a restored fen returned to a net carbon sink within two years post restoration; however, much of the carbon was fixed by *Eriophorum vaginatum* and not *Sphagnum* spp. Tuittila *et al.* (1999) found that re-wetting an abandoned mined peatland decreased total respiration and increased GEP resulting in a net carbon sink. Dry sections of the peatland remained a source of atmospheric CO_2 during dry summers, highlighting the sensitivity of CO_2 exchange dynamics to both the temporal and spatial variation in environmental factors (Tuittila *et al.,* 1999). Minkkinen *et al.* (1999) indicate that planting forests on drained peatlands can enhance atmospheric CO_2 sequestration. However, this CO_2 is stored in the above-ground biomass (trees) but does not lead to an accumulation of peat or growth of *Sphagnum*. Nevertheless, there is the potential to return these ecosystems to net atmospheric CO_2 sinks while restoring the peat accumulating system. The specific objective of this study is therefore to determine if restored and/or naturally regenerated peatlands have returned to a net carbon sink by comparing differences in net ecosystem CO_2 exchange between these peatlands and a natural peatland.

Material and methods

This study was conducted at two mined peatlands: *i*) the Sainte-Marguerite-Marie peatland (labeled SM hereafter) in the Lac-Saint-Jean region in central Québec (48° 47' N, 72° 10' W) near the town of Mistassini; and *ii*) the Cacouna bog (labeled C hereafter) in the Lower St. Lawrence region in eastern Québec (47° 53' N, 69° 27' W) near the city of Rivière-du-Loup.

SAINTE-MARGUERITE-MARIE PEATLAND

The average annual temperature at the Sainte-Marguerite-Marie peatland is 2.2°C and the mean annual precipitation is 909 mm, of which two-thirds occurs as rain (Environment Canada, 1993). 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, 1997). A portion of the peatland has been drained and the acrotelm mined, with operations commencing in 1990. Post-mining, the drainage ditches were blocked manually and/or through peat slumping to rewet the sites. Three sites were monitored within the peatland between May 5 and August 27, 1998: a natural site (SM-natural), a bare seven-year post-mined site (SM-mined), and a restored peatland (SM-restored) adjacent to the mined site. The SM-natural site is located east of the SM-mined site and the water table position is not impacted by the adjacent mined peatland.

The SM-natural site consists of lawn and hummock (~10 to 25 cm above the lawn surface) microtopography. Hummocks and lawns each cover ~50% of the natural bog surface area. Lawn vegetation consists of *Sphagnum magellanicum*, *S. angustifolium*, *Vaccinium oxycoccos*, and *Andromeda glaucophylla*, while hummock vegetation is dominated by *Sphagnum magellanicum*, *S. angustifolium*, *Polytrichum strictum*, *Ledum groenlandicum*, *Kalmia angustifolia*, and *Larix laricina* (S. Campeau, pers. comm.). The bog is generally open with some sparse cover of *Picea mariana* and *Larix laricina*. The depth of peat is approximately 2.7 m. Due to the presence of an iron hardpan near the mineral substrate, the bog is isolated from regional groundwater flow (Price, 1996). The SM-mined site was drained in the fall of 1990 and mined in 1991, leaving a peat depth of approximately 1.70 m (Waddington *et al*., 2001a). The SM-restored site is a field within the mined peatland and was also drained in the fall of 1990, mined in 1991, and then restored in the spring of 1997 with *Sphagnum fuscum,* and some *S. capillifolium* (Campeau, pers. comm., 1998). There was ~ 5% cover of *Eriophorum vaginatum* at both the SM-mined and SM-restored sites prior to restoration.

CACOUNA PEATLAND

The Cacouna peatland, (83 m a.s.l.) is a domed bog of the Low Boreal Wetland Region (NWWG, 1997) and has an average annual temperature (1963-1990) of 3.3°C and a mean annual total precipitation (1963-1990) of 924 mm, of which three-quarters occurs as rain (Environment Canada, 1993). The bog originally covered an area of 203 ha in 1930 but was reduced to 173 ha by 1995 (Girard, 1999) due to agricultural land encroachment and road building through the east and west margins. More than 50% of the original surface of the Cacouna peatland (102 ha) was mined (block-cutting of peat) ~1 m deep between 1942 and 1975 (Bérubé & Lavoie, 2000), leaving a series of peat ridges and trenches (Van Seters, 1999). Drainage ditches were blocked manually or through peat slumping to rewet the sites. Various tree and shrub species and cotton grass (*Eriophorum vaginatum*) have invaded the abandoned sites at the bog, with *Sphag-num* moss cover being sparse, occurring mostly in the wet trenches (Lavoie & Rochefort, 1996, Van Seters, 1999). Two sites were monitored during an early, middle, and late period (June 23 to 26, July 23 to 27, and August 12 to 15, respectively) for the summer of 1998: a naturally regenerated site (C-regenerated), and an adjacent non-regenerated bare peat surface (C-mined). The regenerated *Sphagnum* cushions were composed primarily of *S. capillifolium*, *S. magellanicum*, and some *S. fuscum*. Ericaceous shrubs were cut and removed in order to study the net ecosystem CO_2 exchange only from naturally regenerated *Sphagnum* mosses. Both the C-regenerated and C-mined sites are located within 2 m of each other and were mined and abandoned ~25 years ago.

CO_2 EXCHANGE

Measurements of net ecosystem CO_2 exchange (NEE) were made with a climate-controlled enclosure (see Whiting, 1994) and a PP systems EGM-1 or EGM-2 infrared gas analyzer (IRGA) several times a week. The enclosure was placed and sealed over PVC collars set into the peat. At the SM-natural site, two sets of three collars were placed approximately 100 m from the edge of the mined area to prevent the water table position from being affected by the drainage ditch. The collars in the SM-natural site were subdivided into micro-topographic units of lawns (SM-natural lawns) and hummocks (SM-natural hummocks) based on the differences in vegetation cover and microtopography. Three to five collars at each of the SM-restored, SM-mined, C-regenerated and C-mined sites were clustered approximately 2 to 5 m from the ditch edge where the water table position was flat. Total respiration (R_{TOT}) was measured using an opaque chamber. The chambers covered a surface area of 0.05 m^2 with a volume of 20 L. CO_2 concentrations were measured for a five-minute duration at one-minute intervals. Fans inside each chamber ensured well-mixed air during the sampling period. The clear chamber utilized a cooling device, consisting of a manual pump circulating cold water through a copper piping radiator inside the chamber, to ensure air temperature inside the chamber remained within 1°C of ambient air temperature. Instantaneous measurements of soil temperature and water table position were taken to establish an empirical relationship between these variables and R_{TOT}. Gross ecosystem CO_2 production (GEP) was determined several times a day every two days during the study period using a clear chamber, with a series of neutral density shrouds to measure GEP under low light conditions. A relationship between photosynthetically active radiation (PAR) and GEP was developed.

ENVIRONMENTAL VARIABLES

Peat temperature was measured continuously at 0, 2, 5, 10, 25, 50, and 100 cm depths at both the SM-natural and SM-mined sites. Manual measurements of air and peat temperature (2, 5, 10, 25, and 100 cm depths) were made three times per week at the SM-restored, C-regenerated and C-mined sites. Continuous 5 cm peat depth temperatures at the SM-restored site were modeled using a correlation of the manual measurements at the SM-restored site and the continuous measurements at the SM-mined site ($r^2 = 0.96$). Water table position was monitored continuously at the SM-natural and SM-mined sites using a 10-turn potentiometer (Waddington & Roulet, 1996). Manual measurements of water table position were made three times per week at the SM-restored, C-regenerated and C-mined sites. Continuous water table position at the SM-restored site was modeled using a correlation of the manual measurements at the SM-restored site and continuous measurements at the adjacent SM-mined site ($r^2 = 0.98$). Total rainfall was measured using a tipping bucket rain gauge at the SM-mined site. Photosynthetically active radiation (PAR) was monitored continuously at the SM-natural site using a LI-COr quantum light sensor (units: W m^{-2}). Volumetric soil moisture content was measured continuously at both the SM-natural and SM-mined sites using Campbell Scientific TDr probes at 5, 20 and 100 cm depths. Each probe was individually calibrated in peat removed from each study site at the end of the study period. Bulk density and surficial (0 to 3 cm) gravimetric soil moisture content were determined weekly at each of the three sites using a hand cutter that sampled the upper 3 cm of the peat surface.

Modeling CO$_2$ exchange

Continuous NEE was modeled at the SM-restored, SM-mined, SM-natural lawn, and SM-natural hummock communities using the following equation:

$$\mathrm{NEE} = \mathrm{GEP} + R_{TOT} \qquad [1]$$

where GEP and R_{TOT} refer to gross ecosystem production and total respiration, respectively. GEP was modeled using a rectangular hyperbolic curve fit of gross photosynthesis to PAr using the equation:

$$\mathrm{GEP} = \left[\frac{mT_{5cm}}{msT_{5cm}}\right] \times \left[\frac{\alpha * \mathrm{PAR} * \mathrm{GP}_{max}}{\alpha * \mathrm{PAR} + \mathrm{GP}_{max}}\right] \qquad [2]$$

The asymptote, GP_{max}, of the curve fit is the maximum rate of atmospheric CO$_2$ fixation and the α coefficient (the apparent quantum yield) is the initial slope of the curve. The seasonal ecophysiological parameters (α and GP_{max}) were determined using software created by Dundee Scientific, UK. Equation 2 adopts a seven-day running mean of the daily peat temperature (mT_{5cm}) divided by the seasonal average (msT_{5cm}) (Trumbore *et al.*, 1999) to provide a factor of seasonality on the GEP model. R_{TOT} was modeled using a multi-linear regression relationship between CO$_2$ exchange (at PAR values of zero) and instantaneous peat temperature at 5 cm depth (T_5) and instantaneous water table position (WT). The coefficients (b_0, b_1, b_2) were estimated using linear regression according to equation 3.

$$R_{TOT} = bo + b_1 * T_5 + b_2 * \mathrm{WT} \qquad [3]$$

All model parameters are listed in Table I.

Results

Environmental variables

Total rainfall during the study period at the Sainte-Marguerite-Marie peatland was 286.5 mm, approximately three-quarters of the 30-year mean (Environment Canada, 1993). Although there was less total rainfall throughout the study period, most of the rain events were small and uniform (Figure 1a). The mean water able position at the SM-mined and SM-restored sites was -35.8 cm. The water table remained near the surface in the SM-natural site for most of the study period (mean = -11.8 cm) except during a dry period in mid-August, when the water table reached its lowest point of the study season (-40.9 cm) (Figure 1b). The water table position at the SM-mined and SM-restored sites was consistently lower than the SM-natural site and also reached its lowest position (-64.2 cm) during the dry period in August (Figure 1b). The water table remained above -10 cm at the SM-natural site 55% of the study season, but only 3% of the time at the SM-mined site. Similarly, the water table was above -30 cm for 92% of the study season in the SM-natural site and only 35% in SM-mined site (Waddington *et al.*, 2001a). Mean 5 cm peat temperature was lowest at the SM-natural and SM-restored sites (14.1°C) and greatest at the SM-mined (15.0°C) (Waddington *et al.*, 2001a). Peat temperature ranged from 7.1 to 19.7°C, 6.7 to 19.6°C, and 7.6 to 20.6°C in the SM-natural, SM-restored and SM-mined sites, respectively. The coolest temperatures occurred in early June, whereas the warmest peat temperatures occurred in early August (Figure 1c).

Total rainfall during the study period at the Cacouna peatland was 218 mm (Whitehead, 1999), approximately 90% of the 30-year mean (Environment Canada, 1993). Average evapotranspiration for the C-regenerated and C-mined region of the peatland was estimated to be 2.8 ± 1.1 mm d^{-1} (Van Seters, 1999). A net water deficit of over 60 mm for the summer resulted in an ~40 cm drop in the water table during the summer (Figure 2). Mean water table position for the early, middle, and late measurement periods were -19, -20 and -39 cm, respectively. The 5 cm peat temperature during the early, middle, and late measurement periods ranged from 18.1 to 18.6°C at the C-regenerated site and from 16.3 to 17.1°C at C-mined site. Mean water table position was -26.0 cm. Volumetric soil moisture content at 2 cm peat depth from early June to late August was significantly greater below the C-regenerated site *Sphagnum* cushions (86.6 ± 4.0%) than the adjacent bare areas at the C-mined site (77.8 ± 8.0%) (Whitehead, 1999).

CO$_2$ exchange model parameters

The seasonal ecophysiological parameters created from GEP-PAR light response curves are presented in Table I. The empirical relationship between PAR and GEP varied throughout the summer at the SM-natural site and between

Table I. Net CO$_2$ exchange model parameters including the light response curve fit parameters with standard deviations given in brackets (GP_{max} units are g CO$_2$ m^{-2} d^{-1}) and variables and corresponding r^2 values from multi-linear regression ($R_{TOT} = b_o + b_1{*}T_5 + b_2{*}\mathrm{WT}$). *n* refers to the number of chamber deployments.

Site	Gross ecosystem production (GEP) parameters			Total respiration (R_{TOT}) parameters			
	n	α	GPmax	b_0	b_1	b_2	r^2
Sainte-Marguerite-Marie							
SM-natural lawn	132	0.008 (0.001)	-8.2 (2.6)	-1.47	0.33	-0.23	0.66
SM-natural hummock	82	0.064 (0.032)	-18.1 (2.6)	-8.52	1.08	0.38	0.63
SM-restored	180	0.023 (0.006)	-17.5 (2.9)	-0.13	0.38	-0.15	0.60
SM-mined	120	n/a	n/a	-11.20	0.80	-0.33	0.78
Cacouna							
C-regenerated	78	0.011 (0.005)	6.6 (1.7)	-9.65	0.94	-0.14	0.54

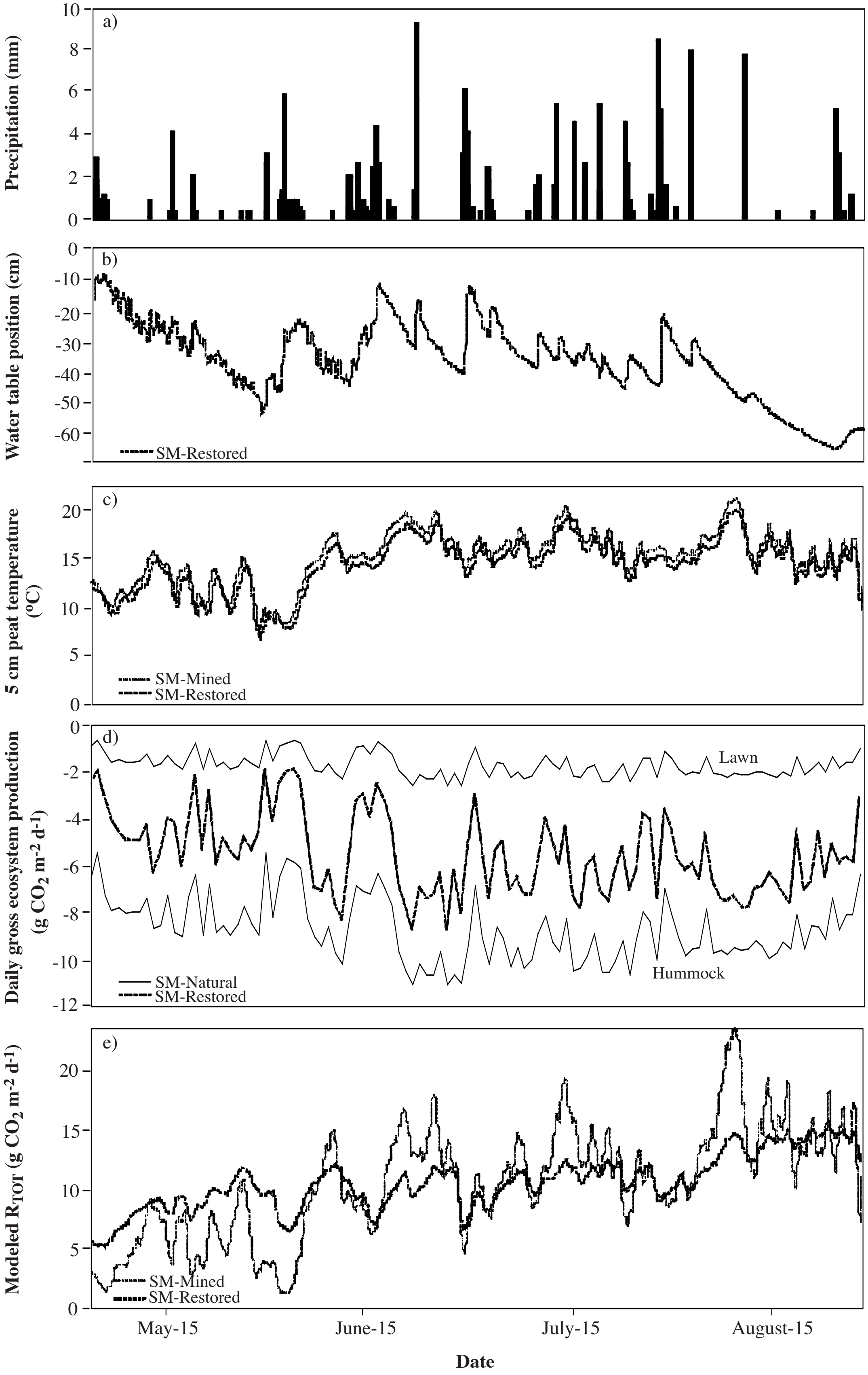

FIGURE 1. Sainte-Marguerite-Marie peatland: a) precipitation (mm), b) water table position (cm), c) 5 cm peat temperature (°C), d) modeled GEP (g CO$_2$ m^{-2} d^{-1}), and e) modeled R$_{TOT}$ (g CO$_2$ m^{-2} d^{-1}). SM-natural lawns and SM-natural hummocks are shown separately. See text for a description of the modeling procedure.

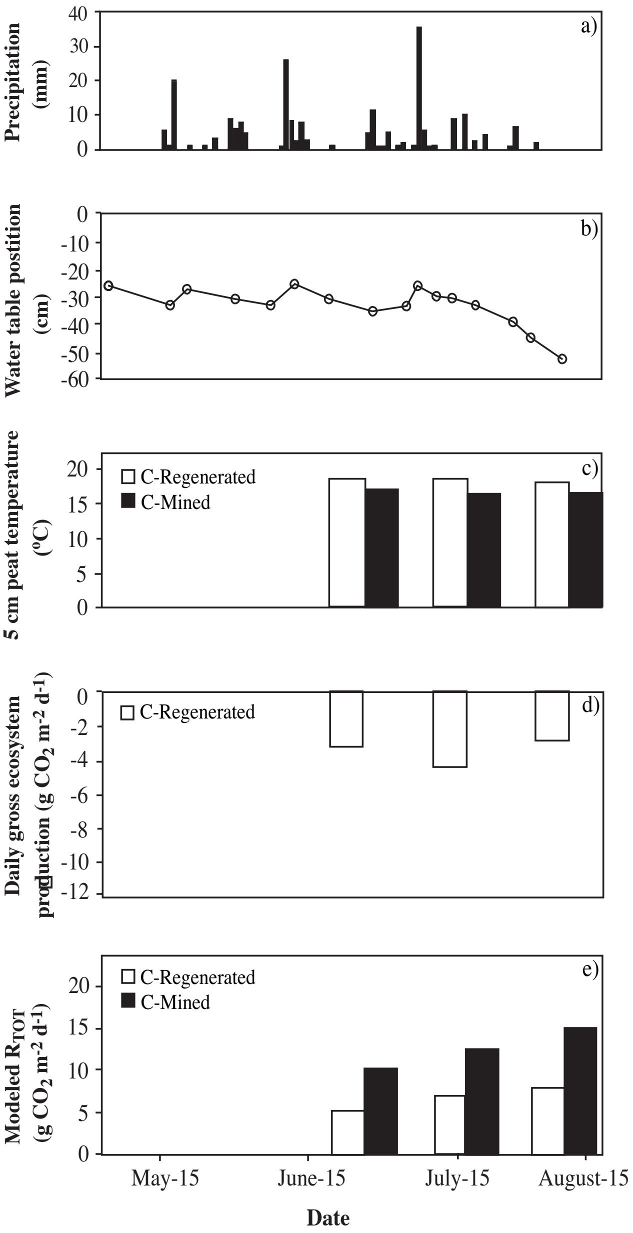

FIGURE 2. Cacouna peatland: a) precipitation (mm), b) water table position (cm), c) 5 cm peat temperature (°C), d) average GEP (g CO_2 m^{-2} d^{-1}), and e) average R_{TOT} (g CO_2 m^{-2} d^{-1}). Average GEP and R_{TOT} are for the early (June 23 to 26), middle (July 23 to 27) and late (August 12 to 15) measurement periods only.

different topographic units (hummocks *versus* lawns). The correlation between GEP and PAR ($r^2 = 0.63$ to 0.66) falls within the range found in other studies (Bubier *et al.,* 1998; Frolking *et al.,* 1998; Waddington & Roulet, 1996) and is considered a strong relationship given that it represents a seasonal relationship combining early, middle, and late periods of the growing season. The apparent quantum yield (α) is the initial slope of the light response curve and was low in all of the sites, (SM-natural lawns, SM-natural hummocks, SM-restored and C-regenerated sites; 0.008 ± 0.001, 0.064 ± 0.032, 0.023 ± 0.006, and 0.011 ± 0.05 g CO_2 d^{-1} W^{-1}, respectively) when compared with those found by Waddington and Roulet (1996), but are similar to values found by Frolking *et al.* (1998) and Bubier *et al.* (1998). The α coefficient was the greatest in the SM-natural hummocks, indicating that they had the greatest uptake of CO_2 with increasing PAR. Comparing the sites with *Sphagnum* cover only, the α coefficient was highest at the SM-restored site and more than two times greater than the C-regenerated and SM-natural lawn sites (Table I). The point of light saturation or maximum gross photosynthesis (GP_{max}) was also greatest in the SM-natural hummock site (-18.1 ± 2.6 g CO_2 m^{-2} d^{-1}), followed by the SM-restored (-17.5 ± 2.9 g CO_2 m^{-2} d^{-1}), SM-natural lawn (-8.2 ± 2.6 g CO_2 m^{-2} d^{-1}) and C-regenerated sites (-6.6 ± 1.7 g CO_2 m^{-2} d^{-1}, respectively). The values of the SM-natural hummocks fall within the range of those found by Frolking *et al.* (1998) and Bubier *et al.* (1998), but the lawns are lower than those found by Waddington & Roulet (1996). GP_{max} at the SM-restored site was more than double that of the natural lawn.

R_{TOT} was positively correlated to peat temperature at all sites with the SM-natural hummock, with C-regenerated sites being the most sensitive to peat temperature variation (Table I). All sites with the exception of the SM-natural hummocks were negatively correlated to mean water table position. Waddington and Roulet (1996) found a similar relationship with natural lawns and ridges (large hummocks) at a patterned boreal peatland in northern Sweden.

MODELED CO_2 EXCHANGE

Daily-modeled GEP varied both spatially between sites and temporally throughout the growing season (Figure 1d, 2d). Maximum daily GEP occurred in late June / early July at all SM-sites and followed the trend: SM-natural hummock (-11.0 g CO_2 m^{-2} d^{-1}) > SM-restored (-5.4 g CO_2 m^{-2} d^{-1}) > SM-natural lawn (-2.6 g CO_2 m^{-2} d^{-1}). Minimum daily GEP occurred at all sites in early June (Figure 1d). The mean daily GEP was -8.7, -5.1, and -1.7 g CO_2 m^{-2} d^{-1} at the SM-natural hummock, SM-restored, and SM-natural lawn sites, respectively. The mean daily GEP at the C-regenerated site was greatest during the middle measurement period (-4.5 g CO_2 m^{-2} d^{-1}) and lowest during the late measurement period (-2.9 g CO_2 m^{-2} d^{-1}) (Figure 2d). A seasonal comparison of GEP between the C-regenerated and SM-restored sites is not possible because continuous PAR and air temperature were not measured at the Cacouna peatland. Weighting the GEP equally for SM-natural lawns and SM-natural hummocks (each topographic unit covered ~50% of the peatland surface), the seasonal SM-natural peatland GEP was -164 g C m^{-2}. Recall that because the mined sites were devoid of vegetation, they had a seasonal GEP of 0 g C m^{-2}.

Modeled R_{TOT} was both spatially and temporally variable between sites (Figure 2b) with mean R_{TOT} greatest in the SM-mined site (12.8 g CO_2 m^{-2} d^{-1}), followed by SM-natural hummocks (12.4 g CO_2 m^{-2} d^{-1}), SM-restored (10.5 g CO_2 m^{-2} d^{-1}), and SM-natural lawn (6.9 g CO_2 m^{-2} d^{-1}) sites. Mean daily-modeled R_{TOT} was consistently higher in the SM-natural hummocks than the SM-natural lawns. The greatest R_{TOT} occurred during mid-summer in the SM-natural hummocks, except during the low water table periods in both late May and mid-August. R_{TOT} ranged from 1.5 to 19.1, and 2.3 to 13.5 g CO_2 m^{-2} d^{-1} in the SM-natural hummocks and SM-natural lawns, respectively. R_{TOT} was more variable at the SM-mined site than the SM-natural site, ranging from 5.4 to 15.6, and 1.3 to 23.1 g CO_2 m^{-2} d^{-1} in the SM-natural and SM-mined sites, respectively. The magnitude of the fluctuations in the SM-mined site was also much greater than in the SM-restored site, with R_{TOT} increasing as the summer progressed.

Seasonal R_{TOT} was the greatest in the SM-mined site, with a cumulative summer loss of 398 g C m^{-2}. Seasonal R_{TOT} from the SM-natural hummocks, SM-natural lawns and SM-restored sites were 386, 215, and 326 g C m^{-2}, respectively. Seasonal R_{TOT} at the SM-restored site was 82% of the SM-mined site. The similarity in R_{TOT} values between the SM-restored and SM-mined sites was not found in the C-regenerated and C-mined sites. Despite equal water table positions and higher temperatures at the C-regenerated site, R_{TOT} at the C-regenerated site was 50 to 55% of the C-mined site during the different measurement periods (Figure 2e). Mean daily R_{TOT} was greatest during the late measurement period at both the C-regenerated and C-mined sites (8.1 and 15.2 g CO_2 m^{-2} d^{-1}, respectively) during the period of lowest water table position.

Adding the season modeled R_{TOT} and GEP results, all SM sites were net sources of CO_2 to the atmosphere. The SM-natural site lost 138 g C m^{-2} to the atmosphere, whereas the SM-mined site lost over 2.8 times more CO_2 to the atmosphere during the summer (398 g C m^{-2}). The SM-restored site source was 58% of the SM-mined site (170 g C m^{-2}) and only 23% greater than the SM-natural site.

Discussion

NET CO_2 EXCHANGE AT THE SAINTE-MARGUERITE-MARIE PEATLAND SITES

R_{TOT} was high in the SM-natural site when compared with other studies (Whiting, 1994; Waddington & Roulet, 1996; Alm *et al.,* 1997; Bellisario *et al.,* 1998; Bubier *et al.,* 1998) due to the drier than normal (78% of the 30-year mean rainfall) study period. Despite this, R_{TOT} at the SM-mined site was still ~33% greater than the SM-natural site due to the lower water table position and volumetric soil moisture content (Waddington *et al*., 2001a). This increase in CO_2 emissions from drained sites is similar to other drained peatlands reported in Silvola (1986). Moreover, this net source of atmospheric CO_2 is significantly greater, with a change in sign, than Gorham's (1991) estimate of long-term carbon storage in northern peatlands (23 g C m^{-2} yr^{-1}). R_{TOT} increased at the SM-natural lawns as the water table position decreased, while R_{TOT} at the SM-natural hummocks decreased with a decrease in water table position. These opposite relationships resulted in little variation in the SM-natural modeled R_{TOT} with changes in water table position, and this has been documented in other studies of natural peatlands (Waddington & Roulet, 1996). The low variation in modeled R_{TOT} at the SM-natural site (2.2 to 17.3 g CO_2 m^{-2} d^{-1}) also reflects the low degree of variability in water table position and peat temperature at this site.

SM-restored site GEP was greater than the SM-natural lawn but lower than the SM-natural hummocks (SM-natural hummocks > SM-restored > SM-natural lawns). Considering that plant re-introduction and restoration only occurred at the SM-restored site one year before measurements, *Sphagnum* production was high especially since there were two summer dry periods in 1998. The presence of the shrubs on the SM-natural hummocks resulted in a greater GP_{max} than the sites with only *Sphagnum* moss cover. Despite this, however, the GP_{max} at the SM-restored site was almost equal to that of the SM-natural hummocks. This indicates that the SM-restored *Sphagnum* had a higher gross productivity during the study season than the SM-natural sites devoid of vascular shrubs. In fact, the SM-restored GEP was more than two times greater than the SM-natural lawn. The SM-restored site was dominated by *Sphagnum fuscum*, which is not as productive in comparison to other *Sphagnum* species when at the same water content; however, *Sphagnum fuscum* is a hummock species that is less sensitive to water table position and less prone to desiccation (Grosvernier, Matthey & Buttler, 1997). Moreover, the high GEP at the SM-restored site may be due to the relatively more minerotrophic conditions usually found in mined peatlands, since increased decomposition leads to increased concentrations of NH_4-N, NO_3-N, and PO_4 which can act as fertilizers and enhance production.

Waddington and Price (2000) indicate that although blocking drainage ditches reduces water loss, the water table position remains low in mined peatlands due to evaporative loss and a low specific yield. This results in a large persistent source of atmospheric CO_2 (Waddington & Price, 2000). Consequently, to increase volumetric soil moisture content, Price, Rochefort and Campeau (2000) suggest that in addition to blocking ditches, the construction of broad trenches, and the application of straw mulch are also necessary to provide the most favourable moisture conditions for *Sphagnum* establishment. Because R_{TOT} at the SM-restored was 82% of that at SM-mined sites, the *Sphagnum* re-establishment has created moisture conditions suitable to reduce CO_2 production and gas diffusion. Nevertheless, the high GEP at the SM-restored site helped offset the high R_{TOT} values, resulting in a mean NEE slightly less than half that of the adjacent SM-mined area. This demonstrates the importance of restoration on the CO_2 balance of mined peatlands.

NET CO_2 EXCHANGE IN THE C-MINED AND C-REGENERATED PEATLANDS

Although the water table was at the same position for the C-regenerated and adjacent C-mined sites, and the 5 cm peat temperature was greater under the *Sphagnum* hummocks, R_{TOT} was more than two times greater at the C-mined sites than at the C-regenerated sites. Despite the addition of plant and root respiration, as well as an input of more labile carbon from plant material and newly fixed carbon at the C-regenerated site, R_{TOT} was still less than at the C-mined sites that have a lower amount of labile carbon. This suggests that the lower volumetric soil moisture content at the C-mined sites resulted in greater peat aeration and increased decomposition and CO_2 gas diffusion. Consequently, despite more than 25 years of abandonment, a substantial CO_2 source still exists at the bare peat areas in the Cacouna peatland. This suggests that some abandoned peatlands may still be a large source of CO_2 after the first few years of drainage and mining. Schothorst (1977) suggested that most peat oxidation occurs during the first few years of abandonment; however, Waddington *et al*. (2001a) found that a seven-year post mined site had a greater CO_2 flux to the atmosphere than a two-year post mined site, despite lower substrate quality (Waddington *et al*., 2001b).

Currently *Sphagnum* species have recolonized only trenches and moist depressions at the Cacouna peatland (Lavoie & Rochefort, 1996). The block-cut method of peat extraction appears to aid in revegetation by providing a viable seed source for regeneration, as well as the trench-ridge topography providing natural windbreaks and trees providing a shading function (Whitehead, 1999). GEP was low in the C-regenerated site when compared to other studies (Whiting, 1994; Waddington & Roulet, 1996; Alm *et al.,* 1997; Bellisario *et al.,* 1998; Bubier *et al.,* 1998). Moreover, GEP at the C-regenerated site was much lower than the restored peatland at the Sainte-Marguerite-Marie peatland (SM-restored). Although differences in biotic (species composition) and abiotic (moisture, temperature, growing season) factors make direct comparisons difficult, several causes may have led to this difference. For example, the naturally regenerated *Sphagnum* cushions (C-regenerated) may be under more moisture stress due to drier conditions (Whitehead, 1999). Van Seters (1999) found that, unlike the sites at the Sainte-Marguerite-Marie peatland where the drainage ditches were blocked, ditches were only partially blocked from natural slumps and some minor ditch blocking activity at the Cacouna peatland. Grosvernier (1997) has demonstrated that *Sphagnum* photosynthesis is positively correlated to *Sphagnum* moisture content; consequently, drier conditions will lead to lower GEP. As such, the *Sphagnum* cushions were not as productive as *Sphagnum* at the SM-restored site. However, the processes controlling the supply of moisture to *Sphagnum* cushions on cut-over peat surfaces is currently unknown. Moreover, the cushions studied in this research were among many of the larger cushions found in the Cacouna peatland. It is possible that larger cushions are drier, and because *Sphagnum* cushion moisture content controls both photosynthesis and decomposition, the larger cushions have reached a steady state in growth. Natural peatlands also reach a growth limit (Clymo, 1984) when surface production equals total peat decomposition. This limit to peat bog growth is controlled by the position of the water table (Ingram, 1982), which controls surface productivity, acrotelm decomposition, and catotelm decomposition (Clymo, 1984). The limits and processes controlling naturally regenerated *Sphagnum* cushion growth, however, are also currently unknown.

Peatland drainage results in a shift towards forest species (Laine, Vasander & Laiho, 1995) that results in the transfer of peatland productivity from the moss and shrub level to the tree layer (Laiho & Laine, 1997). Forest presently covers ~20% of the Cacouna peatland (Van Seters, 1999) and forest cover has increased since abandonment (Lavoie & Rochefort, 1996). Although NEE has not been measured above the tree canopy at Cacouna, it is likely that tree productivity is also offsetting much of the persistent atmospheric CO_2 source from the non-vegetated mined regions within the Cacouna peatland.

GLOBAL IMPLICATIONS

The objective of the Kyoto Protocol (UNFCCC, 1997) is to stabilize greenhouse gas concentrations in the atmosphere through the reduction of fossil fuel emissions and through land-use management designed to increase biotic carbon sinks and/or reduce carbon sources. Direct and indirect land-use change, however, can have the opposite effect and change the natural carbon sink strength of peatlands (Armentanao & Menges, 1986; Nykänen *et al.,* 1995). For example, Waddington *et al.* (2001a) suggest, based on direct measurements of peat oxidation in mined peatlands, that only 5% of peatlands in a specific region need to be drained/harvested to exceed the annual carbon sink of the region. In this study, while neither the restored nor the regenerated sites have restored the natural carbon sink function of peatlands, *Sphagnum* peatland restoration with plant re-introductions (Campeau & Rochefort, 1996) reduced the loss of carbon to the atmosphere by increasing GEP. The results from this study, therefore, permit an estimate of the potential magnitude of carbon sequestration possible with the restoration of abandoned peatlands. For example, in a Canadian context, only 16 000 ha of the 13.9×10^7 ha of peatlands in Canada are used for the horticultural peat industry. Although these drained and harvested peatlands represent only 0.01% of the total peatland area in Canada, they represent an annual net release of ~0.06 Tg C to the atmosphere (Waddington *et al*., 2001a). If restoration was undertaken on all abandoned drained/harvested peatlands in Canada, however, it could potentially reduce this loss by ~0.04 Tg C yr^{-1}, through an increase in GEP and reduction in R_{TOT}. The loss would likely be further decreased with time, since results from the C-regenerated site indicate that R_{TOT} decreases as *Sphagnum* re-colonization increases volumetric soil moisture content in the underlying peat substrate. In countries where a larger number of peatlands have been drained (*e.g.,* Finland, Sweden, Russia) the potential to sequester carbon in restored peatlands will be even greater. Peatland restoration, either on abandoned peatlands or drained peatlands for agriculture, can therefore represent an important biotic offset under the Kyoto Protocol. This is analogous to the reforestation of deforested areas (Roulet, 2000).

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